DISCUSSION PAPER

.9

World energy markets and uncertainty to the year 2100:

implications for greenhouse policy

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Australian Bureau of Agricultural and Resource Economics

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Foreword

The possibility of climate change induced by human activity is now an issue of concern, but the appropriate response to that concern is as yet far from clear. What is certain is that the energy sector is providing a focus for much early attention. Given the importance of energy for all economies, the implications of possible climate change policies directed at the energy sector is of wider significance. As a major energy exporter, Australia will be affected by any policies put in place by our trading partners and others which have the effect of changing their energy systems.

In this paper, some possible implications for world energy markets and the world economy of climate change policies directed at the energy sector are discussed. The global and regional consequences of a range of assumptions concerning economic growth, cooperation in taking policy action, and factors internal to energy markets are analysed in some detail. The paper highlights the fact that the uncertainty which pervades consideration of climate change issues is of central importance in the design of effective policies. Uncertainty, and the consequences of operating in an uncertain environment, must be considered by policy makers.

The modelling approach used in the paper concentrates on linkages within the energy sector across regions of the globe. In future research it is planned to extend this approach in order to more formally examine the links between the energy sector and other sectors of the global economy. The impact of greenhouse policies directed at the energy sector on the agriculture, mining, manufacturing and services sectors, and on domestic and international resource flows, can then be determined.

BRIAN FISHER
Executive Director

Australian Bureau of Agricultural
and Resource Economics

August 1991

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Climate change is a considerable policy concern

The possibility that climate change will result from the buildup of greenhouse gases in the atmosphere as a result of human activity is the focus of considerable international policy concern. Much attention is being paid to the contribution of energy industries to greenhouse gas emissions. There has tended to be a strong link between energy consumption and economic growth, so the future paths of economic development and energy consumption growth are key factors in greenhouse policy formulation.

Carbon dioxide is the major greenhouse gas

Taking into account the large differences which exist in the warming potentials, atmospheric lifetimes and sources and sinks of the various greenhouse gases, carbon dioxide is estimated to be responsible for between 50 and 60 per cent of the total enhanced greenhouse effect. For this reason, carbon dioxide has received more attention than the other greenhouse gases with the exception of chlorofluorocarbons, which also affect the ozone layer. The burning of fossil fuels accounts for around 75–80 per cent of human induced carbon dioxide emissions.

Fossil fuels dominate energy markets

Fossil fuels dominate the world primary energy market. This is explained in part by the widespread availability of large, low cost reserves of these fuels. While reserves of coal are far larger than those of other fuels, crude oil is the most widely used fuel. The share of crude oil in energy markets has fallen, however, since the oil price rises of the 1970s. Asian economies still tend to have relatively high use of oil, apart from China, whose energy system is dominated by coal. Since the energy price rises of the 1970s, the link between energy consumption and economic activity has weakened, but this has been more marked in the industrial economies with access to more advanced technology. In many developing countries, the ratio of energy consumption to economic activity is rising as their economic structure changes from an agricultural base to more industry.

Need for efficient policies

The link between greenhouse gas emissions, energy consumption and economic growth has important practical implications for greenhouse abatement strategies. There are important theoretical considerations also. An efficient policy will limit greenhouse gas emissions up to the point where the net cost of reducing emissions by an extra tonne is equal to the additional benefit obtained by so doing. There are considerable problems in identifying these costs and benefits in practice, however. The extent of uncertainty surrounding the greenhouse problem is a major source of such difficulties.

Range of policy instruments

There is a range of alternative policy instruments which might be used to achieve greenhouse gas emission reductions if this is desirable. One option is to put a tax on emissions so that emitters must take into account the costs of using the atmosphere as a sink for their pollution. Uncertainty means that the size of such a tax is not known. Another option is to create property rights in the use of the atmosphere by specifying a level of greenhouse gas emissions considered acceptable, and distributing shares in this total. These rights could be traded to ensure that the reduction in emissions is achieved in the most efficient manner.

Practical problems

A practical problem with any policy response is that international cooperation will be required, yet the incentives facing different countries to cooperate vary widely. The extent to which global cooperation is required to achieve a workable solution is an important issue.

The long run impact on global and regional energy markets of the imposition of a carbon tax designed to reduce carbon dioxide emissions was examined using a long run dynamic partial equilibrium model of world energy markets and fossil fuel use. A long time horizon, extending to the year 2100, was used because of the very long time lags involved in climate change. The effect of various assumptions regarding economic growth and technological transfer were examined.

Continued emission growth in absence of policy action

In the absence of any policies designed to reduce carbon dioxide emissions from the energy sector, such emissions can be expected to continue to grow over the period to 2100 as population and economic growth continue. The rate of growth of these variables can be expected to slow, however. Economic growth is expected to be strongest in non-OECD Asia. While some convergence in regional income relativities can be expected, wide differences are projected still to exist by 2100. Projected growth in carbon dioxide emissions is less than projected global economic growth due mainly to energy conservation rather than energy switching. Reflecting depletion of known resources, growth in demand for coal is projected to be much stronger than for oil and gas, but growth in use of renewable and nuclear fuels is projected to be stronger still. However, in all regions coal is projected to dominate energy use in 2100 in the absence of greenhouse policy initiatives.

Carbon tax effectiveness increases with greater international cooperation

A 100 per cent *ad valorem* carbon tax introduced in 2000 is projected to reduce carbon dioxide emissions, but projected overall reductions in atmospheric concentrations of carbon dioxide are much less over the period to 2100. The effectiveness of the tax increases as more regions cooperate in its imposition. In 2100, a tax in the OECD alone is projected to reduce emissions by 24 per cent in that year, a tax in the world excluding China reduces emissions by 47 per cent and a global tax reduces emissions by 63 per cent. Cumulative emissions, which determine atmospheric concentrations, are projected to decline by only 7–20 per cent, depending on how many regions adopt the tax. As modelled, carbon taxes introduced in 2000 have only a slight effect on the level of economic activity by 2100. They operate to switch energy consumption from coal to carbon free or renewable energy sources, but have little effect on oil and gas use. Fossil fuel prices are projected to decline relative to baseline when a carbon tax is introduced, and the decline is greatest for oil.

A carbon tax imposed in the OECD alone is projected to have little effect on the level or composition of energy demand in regions outside the OECD. However, energy exports from the Soviet Union and Eastern Europe are projected to fall considerably under this scenario.

Overall, changes in the growth rates of per person income, and relative per person incomes, are fairly insensitive to the degree of global cooperation in carbon taxation.

Technological transfer important

The extent to which technological transfer effects economic growth in developing countries appears to be an important determinant of carbon dioxide emission growth. The greater the rate of transfer to developing countries, the faster the projected rate of world emission growth. Transfer of energy efficient technologies acts as a useful brake on emission growth, but as the degree of per person income convergence over time increases, energy efficiency transfers must rise much more sharply to prevent the level of cumulative emissions rising markedly. It is apparent that even marginal inaccuracies in estimating long run world economic growth will be strongly magnified in terms of estimating the long run outcome for the absolute level of cumulative emissions. Setting an appropriate carbon tax rate depends critically on estimating accurately the level of world economic activity and the degree of convergence in per person incomes between regions.

Responsiveness of energy consumption also important

The degree to which energy consumption is responsive to changes in economic activity and to changes in energy prices is also important in setting tax rates. The rate of carbon tax required to achieve a particular emission target is projected to rise sharply with income elasticity and fall with the price elasticity of demand for energy services. The way in which these responses will change over time as countries develop is a major area of uncertainty in greenhouse policy analysis. A policy implication is that carbon tax regimes may have to be administered flexibly over time in response to changing circumstances.

Technology breakthroughs alone may not be enough

The effects of technology breakthroughs were also examined. Cumulative emissions were not found to decline markedly as a result of sharply reduced solar energy costs, even though the share of solar energy in the overall demand mix may increase considerably. This highlights the effect of lags in translating emission levels to atmospheric concentrations of greenhouse gases, the critical measure for global warming concerns. If the adjustment lag to a solar advance amounts to decades then other policy measures would be needed to curtail the increase in emissions during the adjustment period if it is decided that action must be taken to curtail the enhanced greenhouse effect. All other things being equal, an increase in the efficiency with which coal is converted to electricity is projected to reduce the electric power generation costs of coal, and thus promote substitution away from relatively less carbon intensive fuels and towards coal. Under some circumstances carbon dioxide emissions could rise as a result of such a technological advance.

CHAPTER 1

Introduction

Global concern over the possible consequences of climate change arising from human activities augmenting the natural greenhouse effect is driving current international debate. Proposed solutions, however, have potentially far reaching effects on the world economy, and particularly on the world energy system. Many complex issues remain to be resolved. At the heart of these issues is the current wide disparity in income, population, and growth prospects between the various nations and regions of the globe.

The objective in this study is to analyse the implications for long run world and regional economic growth and energy markets of possible international action to counter the enhanced greenhouse effect and to gain insights into designing effective policy responses that will be acceptable to all nations. Particular attention is paid to the role of uncertainty in policy formulation. The climate change issue is characterised by uncertainty at many levels, and this uncertainty affects the design of policy instruments to deal with climate change. As Australia is a major energy exporter, the implications for energy trade of greenhouse policy responses will also be of considerable importance for this nation.

The central issue examined is the effect of responses to possible climate change directed at the energy sector on energy markets and economic growth. A very long run timeframe is used, for several reasons. First, atmospheric concentrations of greenhouse gases are such that action to limit emissions will take time to change the total concentration to an appreciable extent. Second, to be effective, policy responses to the prospect of climate change must operate indefinitely. The implications of these policies for national economic growth prospects for many years into the future is such that agreement on global action is only likely if developing countries can be assured that not only the current generation, but also future generations, will not be disadvantaged relative to the more affluent countries by such agreement. Third, policies must be designed to be effective in the long term, so that pressures for development do not negate the effect of poorly designed policies introduced now.

The approach taken is to simulate regional and global economic growth, and energy demands and supplies, using the model developed by Edmonds and Reilly (1983, 1985, 1986). This model, hereafter described as ERM, is a long run partial equilibrium model of world energy markets and fossil fuel pollution. Specifically designed to address problems of policy responses to issues such as climate change, it has been widely used in similar studies. The effect on world energy markets and the world economy of various levels of carbon taxes is examined, with differing assumptions as to the degree of international cooperation gained in implementing the tax. The effect of differing assumptions regarding economic growth rates, and particularly regarding the degree to which incomes in developing countries converge towards those in more affluent countries, are also examined. The impact of technological change as a means by which the efficiency of energy use can vary over time is also examined, and assumptions regarding the speed with which innovations are transferred between developed and developing regions are tested. Finally, the importance of uncertainty in affecting the choice and effectiveness of policy responses is highlighted by means of sensitivity analyses regarding key assumptions.

In the next section, the nature of the greenhouse effect and human influences on it are described, and the current structure of world energy markets is outlined, as background to the analysis. The following section contains a discussion of the economics underlying responses to the greenhouse problem. The ERM model is then described and the key assumptions made in the analysis are given. Finally, the results of the analytical exercise are described in detail, and their key implications outlined. Details of the modelling exercise are given in appendixes.

CHAPTER 2

The greenhouse effect, energy markets and economic growth

2.1 The greenhouse effect

The greenhouse effect defined

The term 'greenhouse effect' refers to the general warming of the earth's surface and its atmosphere. This warming is caused primarily by the insulating effect of 'greenhouse' gases in the Earth's atmosphere. When the climate system, which comprises the atmosphere, oceans, land surface, cryosphere and some aspects of the biosphere, is in equilibrium, the short wave energy absorbed by the Earth from solar radiation is balanced by outgoing long wave infrared radiation from the Earth and its atmosphere. Any change in this energy balance is called a radiative forcing on the climate. Any factor which can disturb this balance, and thus potentially alter the climate, is called a radiative forcing agent.

One important radiative forcing agent is the amount of solar radiation reaching the Earth. This may vary because of changes in the Earth's orbit around the sun, or because of changes in total solar irradiance. Other sources of radiative forcing on the climate include the absorption of solar radiation and outgoing long wave radiation by aerosols in the upper and lower atmosphere, and changes in the reflective capacity of the land induced by desertification, salinisation, urbanisation and deforestation. Apart from solar radiation, the most important source of radiative forcing is the greenhouse effect. Over the next few decades, greenhouse gases are expected to alter radiative forcing more than any other natural or human-based factor (Houghton, Jenkins and Ephraums 1990).

Greenhouse gases

The major greenhouse gases on Earth are water vapour and carbon dioxide. Other important gases are chlorofluorocarbons (CFC-11, CFC-12, and HCFC-22), methane, nitrous oxide and low altitude (tropospheric) ozone. These gases allow short wave radiation from the sun to pass through the atmosphere and warm the Earth's surface, but absorb some of the long wave infrared radiation which the Earth reradiates into space. They subsequently emit this radiation both upwards to space, and downwards to the Earth's surface. This absorption and re-emission of infrared radiation by greenhouse gases alters the atmospheric radiation balance and raises the temperature of the lower atmosphere and the surface of the Earth.

In considering the greenhouse effect, it is essential to distinguish between the natural greenhouse effect and the enhanced greenhouse effect. The latter is due to human activities. Greenhouse gases have trapped part of the earth's radiant heat for millions of years, and this natural greenhouse effect has meant that the average global surface temperature is about 33°C warmer than it would be in their absence. Their presence throughout this period has prevented Earth from becoming a colder, and probably lifeless planet.

The current high level of concern about possible global climate change has come about because human activities are not only augmenting naturally occurring concentrations of greenhouse gases in the earth's atmosphere, but are also adding new and powerful gases such as chlorofluorocarbons. Present day levels of the main greenhouse gases are compared with their pre-industrial (1750–1800) levels in table 1. Concentrations of carbon dioxide and methane have risen sharply since pre-industrial times, largely as a result of human activities. Carbon dioxide levels have increased by around 25 per cent and methane levels have doubled. Concentrations of nitrous oxides have also increased, with much of the change taking place in the last few decades (Houghton, Jenkins and Ephraums 1990). Chlorofluorocarbons were not present in the atmosphere before the 1930s.

Water vapour and ozone are important greenhouse gases, but are not included in table 1. Water vapour concentrations are determined largely within the climate system rather than by human activities. The major source of water vapour emissions is evaporation of the oceans. The net contribution to water vapour emissions from human-induced activities is very small. It is difficult to quantify changes in ozone concentrations since pre-industrial times.

The effectiveness of a greenhouse gas as a radiative forcing agent depends not only on its atmospheric concentration, but also on its ability to absorb outgoing long-wave terrestrial infrared radiation, and on its atmospheric lifetime (Pearman 1991). When a greenhouse gas initially enters the Earth's atmosphere, it alters the Earth's radiation budget, that is, the balance between the shortwave radiation coming in from the sun, and the long wave radiation passing from the Earth's surface into space. Each molecule of gas is capable of causing a specific amount of radiative forcing in the earth's atmosphere. The radiative forcing or heat trapping capacity of each gas varies considerably and depends on how much infrared radiation is absorbed by each molecule of that gas (table 2).

To obtain a more accurate estimate of the contribution of each gas to global warming, it is necessary to take into

1 **Atmospheric concentrations of greenhouse gases**

Gas	Unit a	Pre-industrial concentration	Present concentration	Current rate of change a year	
Carbon dioxide	ppmv	280	353	1.8	(0.5%)
CFC-11	pptv	0	484	17	(4%)
CFC-12	pptv	0	280	9.5	(4%)
Methane	ppbv	800	1720	15	(0.9%)
Nitrous oxide	ppbv	288	310	0.8	(0.25%)

a ppmv = parts per million by volume; ppbv = parts per billion by volume; pptv = parts per trillion by volume.
Source: Houghton, Jenkins and Ephraums (1990).

2 Relative contributions of greenhouse gases to the greenhouse effect

Gas	Relative forcing capabilities per molecule a	Atmospheric residence time greenhouse	Relative global warming potential a	Relative contribution to effect
		years		%
Carbon dioxide	1	2–250 b	1	55–60
CFC-11	12 000–22 000	60–70	4000–11 000	12–25
CFC-12	15 000–25 000	110–130	7100–20 000	
Methane	21–30	10–15	4–63 c	12–15
Nitrous oxide	200	150–160	180–300	5–8
Tropospheric ozone	2000	0.1	4	8

a Relative to carbon dioxide. **b** Low estimate refers to that portion of carbon dioxide which is quickly absorbed by the atmosphere, biosphere and oceans. **c** Higher estimate includes indirect effects.
Sources: Houghton, Jenkins and Ephraums (1990); Lashof and Ahuja (1990); Rodhe (1990); US Department of Energy (1990).

account the length of time a molecule of the gas will remain in the Earth's atmosphere. The estimates in table 2 vary considerably with respect to the residence time of carbon dioxide. The relatively low estimate of 2 to 3 years, refers to that portion of carbon dioxide which is quickly absorbed by the atmosphere, animal and plant life, and the ocean (Rodhe 1990). Carbon dioxide molecules which stay in the atmosphere can last from 120 to 250 years, making it the longest-lived of the greenhouse gases.

Because greenhouse gases have different atmospheric residence times, the relative cumulative impact of each gas on the global climate may be quite different from its relative initial radiative forcing. An effective measure of the global warming potential of a gas is one which takes into account both the radiative forcing for each molecule of the gas, and the atmospheric residence time of the gas. This approach results in a measure of the radiative impact of the gas, over time (Lashof and Ahuja 1990).

The chlorofluorocarbons, CFC-11 and CFC-12, clearly the most potent gases, are up to 20 000 times as effective as carbon dioxide in cumulative global warming. The chlorofluorocarbon HCFC-22, increasingly used instead of other chlorofluorocarbons because it causes less damage to the ozone layer, still has a global warming potential 810 times greater than that of carbon dioxide (Lashof and Ahuja 1990). Nitrous oxide is 180 times more powerful than carbon dioxide as a potential warming agent.

Estimates of the relative contributions of each of these gases to the total greenhouse effect take into account the global warming potential of the gas and its atmospheric concentration. The differences in estimates in table 2 result mainly from differences in estimates of the residence times and the radiative forcing capabilities of each gas. While carbon dioxide is currently the major source of human-based greenhouse gas emissions, over time, it is likely that the combined effects on the global climate of chlorofluorocarbons, methane and nitrous oxide could exceed that of carbon dioxide. These gases were responsible for an estimated 43 per cent of the increase in radiative forcing during the 1980s (Hansen, Lacis and Prother, cited in Lashof and Ahuja 1990). As the largest single contributor, however, carbon dioxide has received more attention to date than other greenhouse gases.

Major sources of carbon dioxide

The principal human source of carbon dioxide emissions is energy production and use. The burning of fossil fuels (coal, oil, and natural gas) for industrial, commercial, residential, transportation and other purposes accounts for around 75 to 80 per cent of annual carbon dioxide emissions. Deforestation, which alters carbon and nitrogen cycles, is another source of increased carbon dioxide levels in the atmosphere, and is estimated to contribute 20 to 25 per cent of total emissions (Pearce and Turner 1990; US Department of Energy 1990).

While carbon dioxide is released into the atmosphere in the production and consumption of all fossil fuels, different fossil fuels release carbon dioxide at different rates for the same level of energy production. Natural gas has the lowest rate of carbon dioxide release. Coal combustion releases 1.7 times as much carbon dioxide and oil combustion 1.4 times as much carbon dioxide as natural gas, in producing the same amount of energy (Edmonds and Reilly 1985; Rodhe 1990; US Department of Energy 1990).

Total global emissions of carbon dioxide to the atmosphere from the combustion of solid, liquid and gas fuels, from gas flaring, and from the production of cement are presented in table 3. Solid and liquid fuels (primarily, but not exclusively coals and petroleum) are responsible for most of these carbon dioxide emissions, producing about 80 per cent of total emissions in 1987. Gas flaring, the practice of burning off gas which is released during petroleum extraction, is a minor and declining source of carbon dioxide emissions, accounting for just under 1 per cent of total carbon dioxide emissions in 1987. Cement production, which involves the calcining of calcium carbonate to produce calcium oxide, accounts for a small but increasing share of carbon dioxide emissions. Comprising one per cent of total emissions in 1950, it now accounts for around 2.5 per cent.

3 Relative global emissions of carbon dioxide from energy related sources a

Year	Solid fuel	Liquid fuel	Natural gas	Gas flaring	Cement production
	%	%	%	%	%
1950	65.8	25.8	5.9	1.4	1.1
1960	54.7	32.7	9.0	1.5	1.7
1970	38.4	44.9	12.6	2.1	1.9
1980	36.5	45.8	13.8	1.7	2.3
1987	40.3	40.5	15.8	0.9	2.5

a Percentage contributions to total carbon dioxide emissions.
Source: World Resources Institute (1990).

Carbon dioxide emissions by country

Carbon dioxide emissions from the use of fossil fuels and from cement production for the ten largest contributors in 1987 are shown in table 4. Together these countries comprise 70 per cent of total emissions. The United States and the Soviet Union are by far the largest contributors, accounting for 21.2 per cent and 18.0 per cent of total emissions respectively. The United States, the Soviet Union and China are responsible for half of all carbon dioxide emissions from the use of fossil fuels and from cement production.

The wide diversity between these major emitting countries in terms of per person income, population and economic systems underscores the problems in negotiating global reductions in carbon dioxide emissions.

4 Carbon dioxide emissions by country

Country	Carbon dioxide emissions	Relative country contribution
	Mt carbon	%
United States	530	21.2
Soviet Union	450	18.0
China	260	10.4
Germany a	118	4.7
Japan	110	4.4
United Kingdom	69	2.8
India	67	2.7
Poland	56	2.2
Canada	48	1.9
Italy	45	1.8
World	2500	100

a Includes the former F.R. Germany and German D.R.
Source: World Resources Institute (1990).

Uncertainty and the greenhouse effect

In 1988, the United Nations Intergovernmental Panel on Climate Change (IPCC) was set up to advise on: the climate changes which might be induced by the increase in greenhouse gas concentrations; the environmental and socioeconomic implications of these changes; and possible response strategies. The general conclusion of the Panel was that, if nothing is done to curb current greenhouse gas emissions, there is a high probability that the average global temperature will rise at a rate of 0.3°C a decade (with an uncertainty range of 0.2–0.5°C a decade) over the next century (Houghton, Jenkins and Ephraums 1990). This could be accompanied by a general rise in the global mean sea level of about 6 cm a decade (with an uncertainty range of 3–10 cm a decade). If these predictions are roughly correct, global temperatures could be around 3°C higher, and sea levels some 65 cm higher, by the end of the next century. However, the Panel has qualified its findings by referring to the many uncertainties in its predictions.

The uncertainty surrounding the greenhouse effect derives from a lack of knowledge concerning the physical nature of the greenhouse effect and the climate system itself, and from uncertainty over future human activities. The Panel identified the following areas of uncertainty in particular: the sources and sinks of greenhouse gases, which affect predictions of future concentrations of these gases; clouds, which play a large part in determining the magnitude of climate change; oceans which influence the timing and pattern of climate change; and polar ice sheets, which affect predictions concerning rises in sea levels. Changes in water vapour, sea-ice, clouds and the oceans have been identified as the main sources of feedbacks within the climate system. As the climate begins to get warmer, some processes, through positive feedbacks, will amplify the warming, while others, through negative feedbacks, will reduce the warming. The net impact of such feedbacks is unclear. The potential for feedback effects from the biosphere is also considerable, but not very well understood (D. Lashof, cited in Taylor 1990).

Even in the absence of policy actions in response to concern over global warming, there is considerable uncertainty over the impact of future human activities on concentrations of greenhouse gases. Some sources of uncertainty include the rate of use of fossil fuels, the nature of forest management programs, the nature of agricultural practices, the level and impact of technological advances, the extent of technology transfer from developed to developing nations, and the rate of growth of the human population (Henderson-Sellers 1991). Current indications are that in the absence of policy actions, many of these indicators would point to rising concentrations of greenhouse gases in the atmosphere as populations grow, economies develop and the level of energy use increases.

Given the importance of carbon dioxide as a greenhouse gas, and the importance of energy consumption as a source of greenhouse gas emissions, an understanding of the factors influencing energy consumption is critical in both determining the likely impact of and responses to the possibility of climate change. In the next section the current structure and recent developments in world energy markets are described, to provide background information to the simulation study.

2.2 The role of energy in the world economy

Sources of energy

Fossil fuels, comprising oil, gas and coal, have dominated the world primary energy market since the 19th century. Fossil fuels are finite in nature and extracted from deposits formed ultimately by energy deriving from the sun. The sun is also the ultimate source of potentially renewable forms of primary energy such as solarpower, hydropower and windpower, and enables the growth of plant material or biomass which is also burned for energy (Davis 1990). The emergence of nuclear power in the mid 1950s provided another alternative primary energy source to fossil fuels.

Oil dominates the world energy market, with a 38.7 per cent share of current total primary energy consumption. Coal accounts for 27.8 per cent, natural gas 21.3 per cent, hydropower 6.6 per cent and nuclear 5.6 per cent (BP 1990). Published data such as these, however, tend to understate the contribution of renewable sources of energy. The United Nations estimates that 10–50 per cent of energy demand in developing countries is supplied by noncommercial energy sources, including fuelwood, animal waste, peat and agricultural residues. As a large proportion of such supplies are not purchased in markets, but gathered by end users, they are difficult to include in official statistics.

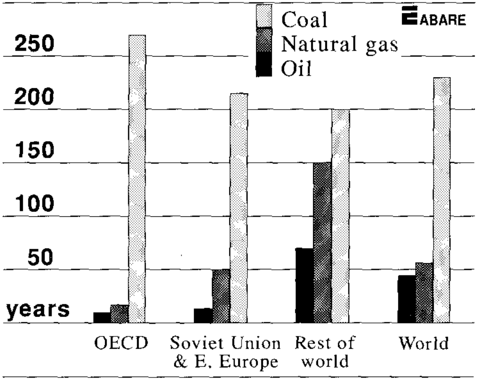
Fossil fuel reserves and production

The dominance of fossil fuels can be explained in part by the widespread availability of large, low cost reserves. In 1989 the world's proven fossil fuel reserves were 815 billion tonnes of oil equivalent (Gtoe), a 20 per cent increase from the 1985 reserves of 680 Gtoe. Seventy per cent of the 1989 reserves were coal, of which three quarters was anthracite and bituminous and the remaining quarter was sub-bituminous and lignite. Oil's 17 per cent share does not include shale oil, which represents a large potential resource. Natural gas's share has remained at 13 per cent since 1985, but over the period from the late 1970s until 1985 gas had the largest growth in reserves.

Reserve/production ratios indicate the length of time it would take to diminish currently known reserves if the current rate of production were to continue, and are an indicator of relative scarcity. Based on 1989 estimates, coal has a world reserve/production ratio of 230 years, oil 44 years and gas 56 years (figure A). It is worth noting that 20 years ago the oil reserve/production ratio was 35 years. This illustrates that reserves are not static. New discoveries, improved geological and engineering techniques, and changing costs mean additions to the reserve base and reevaluation of existing reserves.

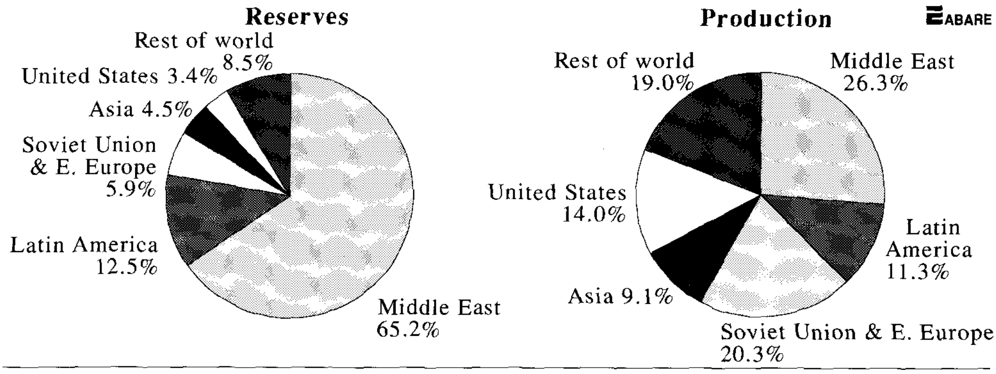
World oil reserves are concentrated in the Middle East and a few other nations belonging to the Organisation of Petroleum Exporting Countries (OPEC) (figure B). At the end of 1989, the world's proven reserves of oil were estimated at approximately 1011.8 thousand million barrels. Oil production, driven by the regional distribution of reserves, is dominated by the Middle East. In 1975 world production was 55.7 million barrels a day (mbd), of which the Middle East contributed one third and OPEC (including some Middle East producers) half. By the mid 1980s the Middle East share had been reduced to one quarter and OPEC's share was under one third due to production cuts by OPEC in the early 1980s in a bid to keep prices buoyant. Following the oil price decreases of 1986, and reflecting the low cost nature of OPEC reserves, the Middle East and OPEC share began rising again as marginal production elsewhere was shut in.

A Ratios of fossil fuel reserves to yearly production at end of 1989



Coal reserves are dominated by the United States with 24 per cent of the total, the Soviet Union with 22 per cent, and China with 15 per cent (figure C). Australia, the world's largest exporter of coal has an 8 per cent share of reserves (ABARE 1990). Based on current world production rates, coal reserves, approximately four times as large as oil reserves on an energy equivalent basis,

B **World oil reserves and production**

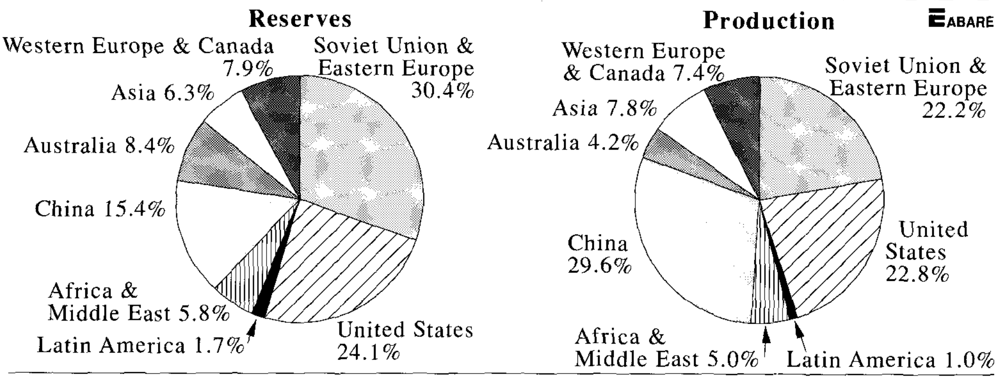


will outlast both oil and gas by a large margin.

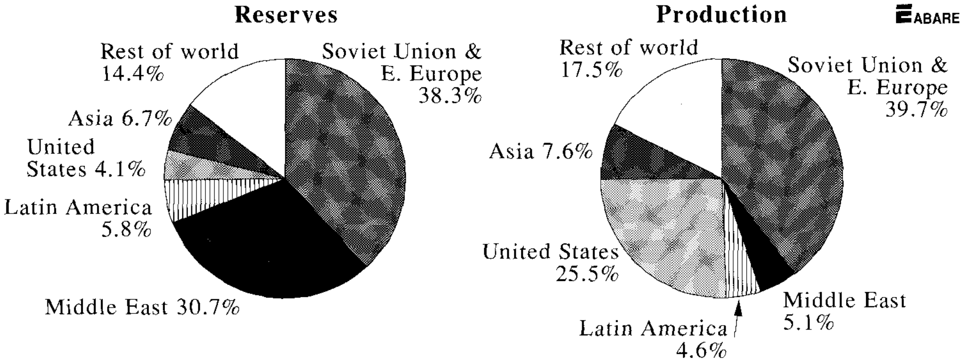
Notwithstanding the importance of a few countries, the regional distribution of coal reserves is more evenly dispersed than gas and oil. Production again reflects the reserves position. World production of hard coal in 1990 was 3295 Mtoe, up 10 per cent from 1985 and 45 per cent on 1975. The United States increased production by 10 per cent between 1985 and 1989 to maintain an approximate 23 per cent share of production over the period. By contrast, the Soviet Union's share dropped from 18 per cent to 16 per cent in the same period. Australia increased production by 26 per cent, driven by increased demand from the Japanese steel industry, while China experienced a 21 per cent growth in production in the same period to represent 30 per cent of 1989 world production (ABARE 1990).

Proved natural gas reserves increased 55 per cent over the past decade to reach 101.7 Gtoe at the end of 1989. Gas reserves are regionally unbalanced, with the Soviet Union and the Middle East (especially Iran), accounting for two-thirds of the world's total (figure D).

C **World coal reserves and production**



D **World natural gas reserves and production**



World gas production was 1721 Mtoe in 1989, up 15 per cent from 1985 and up 51 per cent from 1975. The Soviet Union, with 38 per cent of world production, and the United States, with 26 per cent, are the largest producers.

Energy consumption

Generally, the level of economic activity in an economy, especially in the industrial sector, has played a major role in determining the level of energy consumed. In the past, increases in gross domestic product (GDP) were usually matched by strong growth in energy consumption, and as an economy moved into recession, energy demand has fallen (Hansen 1990). However, more recently the link between energy consumption and the level of economic activity has weakened. From 1966 to 1972 world consumption of fossil fuels grew 50 per cent but from 1973 to 1985 it increased by only 23 per cent, with a stronger increase from 1985 to 1989 as the real price of fossil fuels eased. In most of the industrialised nations, this slow down in energy consumption in the 1970s and 1980s was greater than the slowdown in economic growth. The result has been a reduction of the energy to GDP ratio, the amount of energy required to produce a unit of economic growth and a popular measure of energy conservation (Hansen 1990).

From a regional perspective the industrial nations with access to more advanced technology have been more successful in reducing the energy intensities of their economies than the developing nations. Selective energy intensity ratios from 1955 to 1989 are given in table 5. Japan has achieved one of the lowest energy-to-GDP ratio of the industrialised countries in 1989, requiring 1.75 toe to produce US$1000 worth of GDP. Japan's energy-to-GDP ratio dropped 30 per cent in the period 1975 to 1985, but in the period since 1985 lower real energy prices have resulted in a drop of only 5 per cent. The majority of change occurred in the early 1980s, and was associated with high energy prices and a shift offshore of some energy intensive manufacturing industries. From 1975 to 1985 the energy intensity of the United States fell 26 per cent, and from 1985 to 1989 a further 5 per cent. The energy intensity of OECD Europe fell 25 per cent from 1975 to

5 Regional energy intensities

	1955 boe/$1000 a	1965 boe/$1000	1975 boe/$1000	1985 boe/$1000	1989 boe/$1000
OECD	3.72	3.53	3.46	2.69	2.51
– United States	4.11	3.87	3.88	2.89	2.76
– Japan	1.82	2.29	2.54	1.85	1.75
– OECD Europe	3.40	3.30	3.16	2.65	2.38
– Other OECD	3.93	4.03	4.07	3.51	3.37
Centrally planned economies (Soviet Union, China and Eastern Europe)	15.12	16.21	14.22	13.27	12.59
OPEC	1.08	1.42	1.42	2.66	3.07
Developing countries	2.60	3.12	3.53	3.80	3.92
World excluding centrally planned economies	3.50	3.39	3.32	2.85	2.75
World	4.22	4.31	4.31	3.87	3.74

a Barrels of oil equivalent per US$1000 GDP at 1985 exchange rates and prices.
Source: Paga and Brennand (1990).

1985. These changes were driven by higher energy prices. Higher prices encouraged a change in the mix of goods and services produced in the economy by depressing the demand for energy intensive products mostly concentrated in the industrial sector, such as steel and ship building, and enabling higher growth in low energy intensive industries — electronics, information systems and various service industries. This structural change from an economy dominated by the industrial sector towards an economy with a larger tertiary sector was already taking place within the industrial economies and higher energy prices was an added impetus. Energy efficiency gains were also made in the form of more energy efficient technologies and energy management programs. However, the rates of decrease in energy intensity have slowed markedly in recent years due to lower real energy prices.

By contrast, the newly industrialised economies have had limited success with the decoupling of energy consumption and economic growth. In 1987 industry consumed 30–40 per cent of total energy consumption in most of these counties (James and Fesharaki 1990). However, between 1980 and 1985 slower world economic growth dictated a lower level of demand for their export driven industrial sector which is heavily reliant on petroleum. For this reason, coupled with high oil costs, their energy consumption growth slowed, but energy intensities changed little. Since 1986 lower energy prices and higher economic growth has resulted in a higher energy to GDP ratio. Latin America, southern Asia and Africa, indicative of developing nations, had low energy to GDP ratios relative to the United States and East Asia until the mid 1980s, attributable to their low industry base. Since the late 1970s however, their energy to GDP ratios have risen as the economic structure has shifted to an industry base and away from agriculture. Between 1975 and 1985 the energy to GDP ratio for developing countries in aggregate rose 8 per cent. Energy consumption between 1979 and 1989 rose 37 per cent in Latin America, 43 per cent in Africa and 101 per cent in South Asia (BP 1990). High population growth rates also contributed to the high energy consumption growth rates in these regions.

The centrally planned economies are the least energy efficient and consume over three times the amount of energy to produce one unit of GDP. Steady gains, however, have been made, with energy intensity falling by 11 per cent in the period 1975 to 1985.

Energy switching

Oil price increases have played a major role in encouraging energy conservation in the 1980s, but they have also encouraged considerable substitution of other fuels for oil in many applications. As illustrated in figure E, the change in energy sources has also varied across nations, influenced by their resource endowments as well as prices.

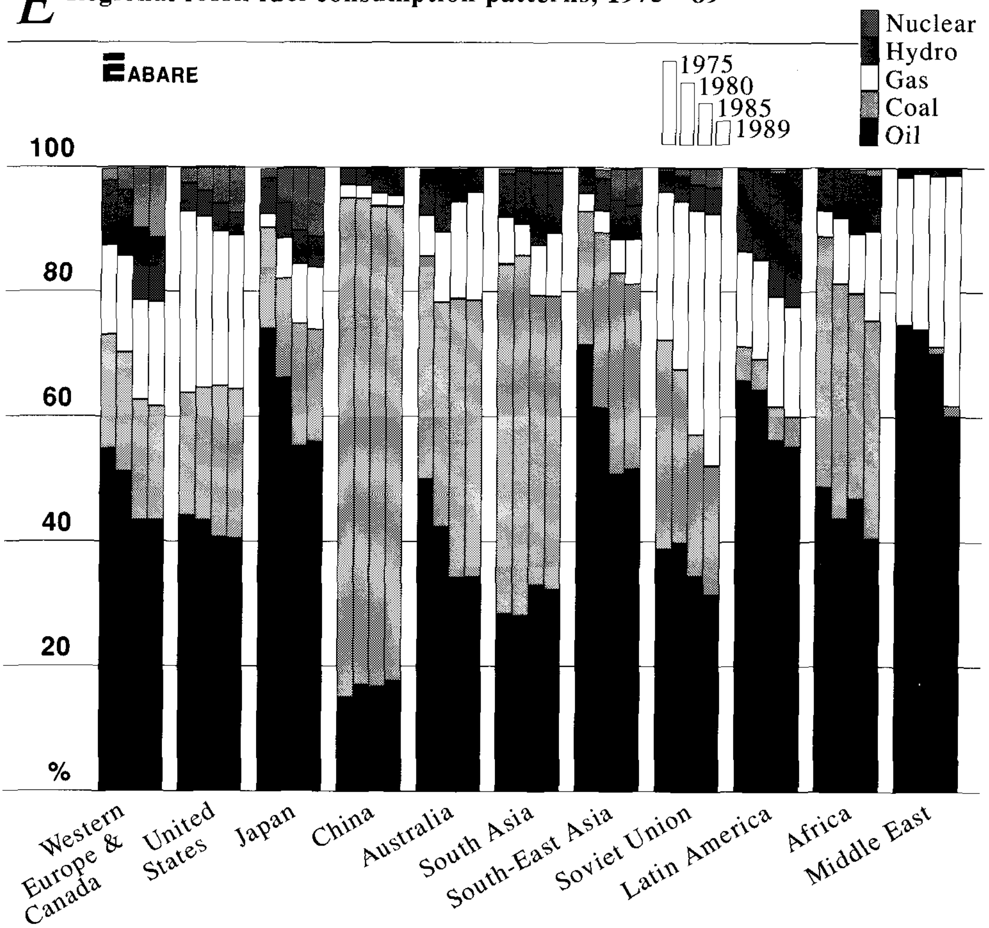
The oil price shocks of 1973 and 1979 made oil substitution a major issue in energy planning and policy formation worldwide. The result was a reduction in oil use as a percentage of total energy consumed from 46 per cent to 36 per cent. However, except for the period 1979–83, when consumption fell by 11 per cent, oil consumption has continued to trend upwards (BP 1990).

Increased oil consumption has been heavily influenced by the trend in Asia. From the mid to late 1970s, there was a very high dependence on oil in Asian economies, ranging from 65 per cent of total energy consumption in South Korea and 72 per cent in Japan to 94 per cent in Thailand. Structural change and a lower dependency ratio was not visible until the early 1980s (James and Fesharaki 1990). By 1985 dependency on oil had fallen to 51 per cent in Korea, 55 per cent in Japan and 65 per cent in Thailand, with similar falls throughout the region. After 1985, when oil prices fell, the pace of structural change slowed and oil dependency ratios had increased again by 1988 (Ang 1990).

Western Europe adopted a policy of oil switching immediately after the 1972 price shock and continued this trend into the 1980s. The result was a fall in oil's percentage of total energy consumed from 61 per cent to 45 per cent. The United States, Australia and to a lesser extent the African and the Latin American countries have followed suit.

Within the economies undergoing the oil switching process, these changes were more easily achieved in the fuel conversion sector (mostly electricity generation) than by very large numbers of final users (Rhys 1985). Trends in the last three decades show electricity consumption to be growing at a faster rate than energy in aggregate, driven mostly by the increasing size of the services sector. The proportion of primary energy being used for electricity generation is also on an upward trend (Rhys 1985). Coal and increasingly natural gas have been the substitutes for

E **Regional fossil fuel consumption patterns, 1975 - 89**



oil within the electricity sector. The switch to coal in Europe began after the first oil price shock while the switch in Japan did not gather pace until after the second oil shock.

Interfuel substitution in the electricity generating sector is not just confined to fossil fuels. France has reduced dependence on fossil fuels by pursuing the development of nuclear power as a source of electricity generation, to the extent where its primary energy pattern is now dictated by the rate of growth in electricity consumption (Rhys 1985).

Hydropower as a substitute for fossil fuels consumption has not experienced growth similar to nuclear energy, mainly due to financial and environmental constraints, maintaining a percentage share in total consumption of 6 per cent.

In addition to price, income growth also has an impact on the energy mix of a country. As incomes rise, urban concentration also tend to rise, particularly in the fast growing Asian economies. This in turn puts pressure on the demand for electricity already increasing as higher incomes encourage the use of electrical appliances, which increases the role for gas or coal. Furthermore households purchase motor vehicles as incomes rise, increasing the demand for petroleum.

World energy trade

The increased price of oil and the increased demand for oil substitutes has had a positive effect on the level of world energy trade.

Exports of coal increased 41 per cent between 1981 and 1988 (table 6). Favoured as a substitute for oil in electricity generation, and with electricity experiencing a large increase in demand world wide, steaming coal trade has increased almost sevenfold since the first oil shock in 1973. Japan's policy of energy switching from oil to coal power generation has been a driving force behind the 323 per cent increase in Australia's steaming coal trade since 1981, which has put Australia at the top of the exporters of coal worldwide. The move away from oil demand in Europe has also led to a large increase in the flow of coal from South Africa to Europe. However, the increasing flow of Colombian coal to Europe may slow this trend. The United States despite its domestic price being greater than the world export price is a large exporter of coal. Yet its steaming coal exports have dropped in the 1980s as domestic demand for electricity generation has increased. Canada has also increased its share in world coking coal trade. This has been in line with the expansion of the Asian steel industry.

6 World coal exports

Exporters	1981	1985	1989
	Mt	Mt	Mt
Coking coal			
Australia	40.8	49.8	55.6
United States	59.2	54.7	59.1
Western Europe and Canada	23.0	28.2	33.1
China	1.4	2.8	3.5
Soviet Union	8.8	10.6	18.6
Rest of world	11.8	16.9	13.9
World	145.0	163.0	183.5
Steaming coal			
Australia	10.2	38.1	43.1
United States	42.9	29.3	32.4
South Africa	26.4	42.5	42.6
Colombia	–	2.4	12.7
China	2.3	3.4	11.2
Rest of world	44.2	58.3	57.9
World	126.0	174.0	199.9

Source: ABARE (1990); International Energy Agency (1991).

The oil trade is dominated by the Middle East and from the distribution of reserves this trend could be expected to continue, especially as oil trade has increased 14 per cent since 1987 after falling steadily by 39 per cent between 1979 and 1985 (OPEC 1989) (table 7). Western Europe was the main importer of oil in 1985 and 1989. The Soviet Union, Latin America and Africa, driven by the demand for foreign exchange took advantage of OPEC's lower production in the early 1980s and moved in to the oil export market. Again the high level of reserves in this area would indicate a continued high level of trade in the future.

Natural gas exports have grown 283 per cent between 1972 and 1989, with much growth in the mid-1970s attributable to the Soviet Union and Western Europe, and since then by Africa and Asia as well as the Soviet Union (table 8) (OPEC 1989).

Well endowed with natural gas reserves, Indonesia and Malaysia have gained from the increase in trade levels as gas became the favoured oil substitute in the Asian region from the late 1970s. The majority of these exports flow to Japan which absorbs 95 per cent of Asian Pacific gas exports (OPEC 1989).

The Soviet Union with the world's largest reserves has taken advantage of Europe's stringent energy conservation and switching policies to increase its gas exports by 50 per cent in the past 5 years (OPEC 1989). The United States, a major producer and consumer of gas, has a monopoly on Canadian gas imports and had a 14 per cent share of 1989 world trade. As indicated above, much of the gas trade is intraregional and in Europe and the United States, both large producers of natural gas, total production is absorbed domestically.

The potential for further growth in gas trade is constrained by high transport costs and by the geographic imbalance between centres of current and probable future gas consumption and the location of reserves, which are mainly concentrated in countries with low levels of infrastructure and capital. To transport gas over long distances and keep the cost within limits, large volume contracts are required which in turn requires large installations, large pipelines and costly financing.

7 World oil trade

	1985 kbd	1989 kbd
Exporters		
Middle East	7 073.6	11 305.6
Latin America	2 614.1	2 701.9
Africa	3 663.0	4 067.2
Asia and Far East	1 248.8	1 248.8
– Brunei	148.0	142.0
– Indonesia	705.7	675.7
– Malaysia	351.4	428.2
North America	687.5	853.9
Soviet Union	2 152.0	2 563.4
World	20 472.6	25 764.0
OPEC	10 926.4	15 128.8
Importers		
United States	3 208.4	5 808.0
Western Europe	7 928.1	8 938.2
Asia and Far East	5 720.6	6 602.1
– Japan	3 336.9	3 558.8
– South Korea	542.9	809.0
Latin America	1 483.1	1 650.9
World	21 921.9	27 078.9

Source: OPEC (1989).

8 World natural gas trade

	1985 million m^3	1989 million m^3
Exporters		
United States	1 439	2 170
Western Europe	68 135	64 640
Canada	26 223	37 910
Middle East	3 036	6 710
Africa	22 870	30 760
Asia and Far East	35 509	40 700
– Indonesia	20 250	24 870
– Malaysia	5 997	8 740
Soviet Union	69 050	102 460
World	228 672	288 550
Importers		
United States	26 893	31 900
Western Europe	123 835	148 510
Asia and Far East	37 517	46 340
–Japan	37 517	43 680
Centrally planned economies	37 470	46 650
World	228 672	288 550

Source: OPEC (1989).

CHAPTER 3

Economic issues in relation to greenhouse warming

3.1 Optimal greenhouse gas emissions

Any policy response to the greenhouse effect must take into account two sets of costs: the costs of abating the greenhouse effect and any costs from damages associated with the greenhouse effect. The optimal level of greenhouse emissions is that which minimises the total cost associated with the greenhouse effect. The total cost from the greenhouse effect equals the sum of the cost of abatement and the cost of any damage from the greenhouse effect. Costs are measured net of any benefits that result from either climate change or abatement initiatives.

Both abatement and damage costs depend on a range of factors. At the global level the total cost of greenhouse damage represents the costs to the world economy from climate change and is a function of such factors as changes in crop yields, recreational amenities and sea levels which are associated with the greenhouse effect. The total cost of greenhouse abatement represents the costs to the world economy to prevent or reduce the consequences of the greenhouse effect. For example, the cost of abating carbon dioxide emissions depends on such factors as the ease with which labour, capital and clean fuels can be substituted for fossil fuels in production and consumption activities, and the availability or relative scarcity of low cost alternatives to fossil fuels.

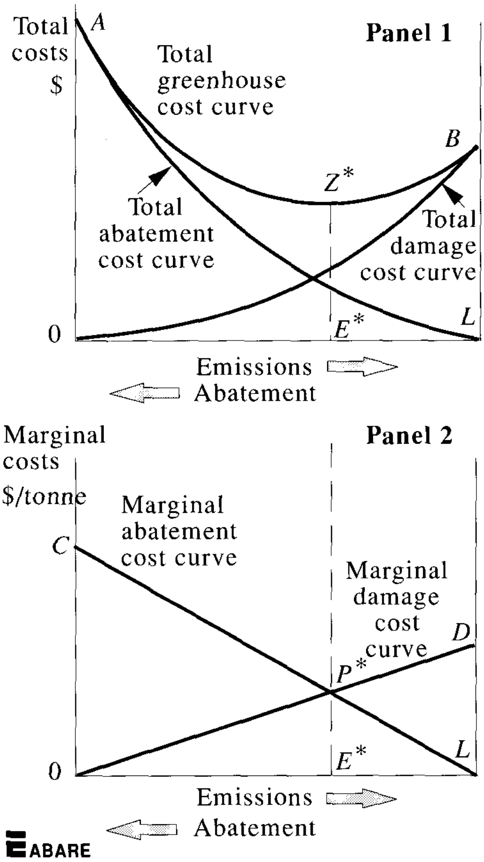
In the following graphical analysis the determination of the globally optimal level of greenhouse gas emissions is illustrated under a number of simplifying assumptions. Key simplifications are that the location and shape of the greenhouse cost curves are known and that markets are competitive. In the remaining sections of this chapter complications to this analysis are discussed.

In figure F the total and marginal greenhouse effect cost curves are shown. The vertical axes measure costs expressed in current dollars or dollars per tonne of greenhouse gas emissions. Measured from left to right the horizontal axes represent the level of emissions, and from right to left represent the level of emissions abated. Point *L* is the level of emissions that would occur if no action were taken to abate emissions. In panel 1 the total cost functions associated with the greenhouse effect are illustrated. The total cost of abating emissions is represented by the curve *AL*. This curve increases from right to left to represent the fact that total abatement costs increase as greenhouse gas emissions are abated. Curve *OB* represents the total cost of damage incurred as a result of greenhouse gases. It is depicted as rising from left to right, which embodies an assumption that the negative effects of the greenhouse effect outweigh any positive effects. It is assumed that with zero net emissions there is zero damage associated with the greenhouse effect.

The total cost of greenhouse gas emissions is the vertical sum of the total abatement and total damage cost curves. Total greenhouse costs are minimised at *Z** where emissions are *E**. Hence, as drawn, zero net emissions at point *O*, where costs equal *A*, or zero abatement at *L*, where costs equal *B*, are not optimal responses to the greenhouse effect.

To further highlight the reason why *E** represents the optimal level of greenhouse emissions the marginal abatement and damage cost curves are shown in panel 2. The marginal abatement cost curve *CL* traces the absolute slope of the total abatement cost curve from zero abatement at *L* to zero damages at *O*. From right to left the marginal abatement cost curve represents the cost of abating emissions by a further tonne. The marginal cost of abatement increases from the right with emissions abated. This reflects the plausible assumption that it becomes increasingly more difficult to substitute other inputs for inputs which generate greenhouse gas emissions in production and consumption. The marginal damage cost curve *OD* traces the slope of the total damage cost curve from zero damage at O to zero abatement at *L*. From left to right the marginal damage cost curve represents the damage caused by each extra tonne of greenhouse gas emitted. As drawn, the marginal cost of damage increases from the left as emissions rise.

F **Greenhouse abatement and damage cost curves under certainty**



A movement from *O* to *E** reduces the marginal cost of abatement, or, equivalently, increases the marginal benefit from not abating emissions, by more than it increases the marginal cost of damage from emissions. Symmetrically, a movement from *L* to *E** reduces the marginal cost of damage, or, equivalently, increases the marginal benefit from damage avoided, by more than it increases the marginal cost of emission abatement. Since the net difference between marginal costs falls with movements toward *E** from the left and also falls with movement toward *E** from the right, the total costs from greenhouse are minimised at *E**. Hence, total costs from the greenhouse effect are minimised where the marginal damage caused by an extra tonne of greenhouse gas emitted equals the marginal cost of abating emissions by an extra tonne, at *P**.

Difficulties in calculating optimal emission levels

While the above framework is useful for organising thoughts about appropriate policy reactions to the greenhouse effect, it is very difficult to use in practice. The costs of abating greenhouse gas emissions can be identified and some attempts have been made to calculate marginal abatement cost curves for a range of emission reduction (Nordhaus 1990). However, very little is known about the damage costs of different levels of greenhouse gas emissions. As noted in the previous chapter there is a great deal of uncertainty about the aggregate effect of greater concentrations of greenhouse gases in the atmosphere. The costs arising from rising sea levels, the effect which is probably best known, are difficult to evaluate. Many other important potential effects, including the changes to local ecologies, agricultural systems, and comfort levels, require information about changes in regional climates, and on this issue scientists are very uncertain.

Another issue which makes the calculation of the optimal levels of greenhouse gases and their emissions difficult is related to when the damage costs will accrue and when abatement costs are incurred. The concepts outlined in relation to figure F ignore this timing aspect. Yet, timing is central to the problem. While current generations may obtain some benefits in the form of reduced pollution, significant reductions in emissions are likely to be costly, and the bulk of any costs of reducing emissions are paid in the short term. However, any benefits of this reduction, that is the reduced damage resulting from a less severe greenhouse effect, will accrue as much as fifty years into the future.

To arrive at an optimal level of emissions for the current period, the costs resulting from future global warming must be converted into current dollars so that they can be compared with the largely current costs of reducing emissions. In this problem much depends on the choice of a discount rate, that is the rate at which society prefers one dollar of benefits now to one dollar of benefit at some time in the future. The usual practice in evaluations of policy proposals is to choose some real rate of interest that is thought to represent society's rate of time preference. The long time scale that is relevant in dealing with the greenhouse effect, including intergenerational aspects, makes such a choice difficult (Collins and Young 1991). Nordhaus (1990) suggests that the minimum rate possible is one equal to the expected rate of increase in economic welfare throughout the period. The reason for this choice is that future generations may have higher living standards as a result of the growth in incomes in the intervening period. This minimum discount rate takes into account this growth in incomes, and reduces the weighting that is given to the benefits and costs experienced by future generations relative to those experienced by present generations. Normally the rate of economic growth would be chosen to represent the growth in economic welfare; however, this proxy measure should be adjusted if it is thought that other influences on people's welfare not included in the economic growth calculation, for example, the costs resulting from environmental degradation, are significant.

As noted above, the uncertainty that exists about the timing of damage caused by greenhouse gas emissions is a further complication to this analysis. A more accurate idea of the lags involved is crucial to any assessment of what the optimal level of greenhouse gas emissions is for any given year. This is because when a positive discount rate is used, the present value of a future benefit or cost depends on how far into the future it is experienced.

It is also difficult to value some of the potential costs (or benefits) resulting from greenhouse gas emissions. It is relatively straightforward to place a value on some costs, such as those associated with variations in agricultural yields, costs of flood protection or the costs of cutting back on energy use. Output declines resulting from these actions can be measured using the market price for the agricultural goods, construction services and so on involved, as these are equivalent, under competitive conditions, to the value placed on these goods and services by society. However, many things that society places value on do not have prices. In this category is much that is prominent in the debate about the greenhouse effect, such as the continued existence of species, aesthetic appeal and the greater comfort of a less harsh climate. Consequently, it is difficult to include changes in these 'goods' in calculations of the optimal levels of greenhouse gases. Methods are available for attempting to put a value on these items, but they have a number of unresolved problems (R. Rose 1990).

One other point should be noted about the costs at issue here. Up until this point the discussion has been confined to the concepts of global net costs associated with different levels of greenhouse gases or the global net costs of abating greenhouse gases. Issues of distribution are ignored in these concepts. In principle, these distributional effects could be offset by transfers from gaining to losing groups. If transfers are unlikely to occur to compensate the losers, attention should be given to determining which groups will experience the costs and benefits of the greenhouse effect. Distributional issues and the determination of which groups stand to gain or to lose are likely to prove fundamental in negotiating a solution to the potential problems caused by greenhouse gas emissions.

3.2 Policy responses to the greenhouse effect

Much of the problem posed by emissions of greenhouse gases is that the costs of these emissions is not known with any certainty. This uncertainty becomes even greater when assessing the effect of climate change on particular communities. However, it is the prospect of catastrophe that weighs most heavily, a prospect which the possibility of positive outcomes does not fully offset. Hence, the enhanced greenhouse effect is an event against which many would wish to insure themselves. The result is that attempts are already being made to reach international agreements to reduce greenhouse gas emissions. The question then becomes what are the best ways that these reductions can be achieved.

In the absence of a coordinated international response to the greenhouse effect, action by individual countries to reduce emissions is unlikely to be attractive or effective. This is because they may suffer large losses in competitiveness, as the cost of energy increases for domestic industries, while only marginally reducing the greenhouse effect. It is possible, though, that the leadership by example of one country may be important in leading to an international agreement to curb greenhouse gas emissions (Haynes, Fisher and Jones 1990).

Given that an international response to the greenhouse effect is appropriate, the issue then becomes what are the best policies to achieve a reduction in greenhouse gases. The most straightforward way to achieve a reduction in greenhouse gases is to arrive at a common target of reductions for each country to achieve. The problem with this approach is that it is a costly way of achieving a given reduction in greenhouse gases. For instance, consumers in some countries may place less value on energy efficiency than consumers in other countries. For example, drivers in countries where long distance trips are common may prefer larger cars for safety and comfort reasons, cars which often are less fuel efficient (Haynes, Fisher and Jones 1990). A uniform restriction does not take into account these differences in preferences, and thus introduces extra costs for consumers in some countries. It may be possible in principle for an international agreement to adjust any greenhouse gas emission reduction targets according to the particular characteristics of different countries. However, the information required to make this choice is difficult to obtain. In addition such a system would be unlikely to allow the world to efficiently adapt to changes in the competitiveness of different countries. Other policy options rely on market incentives, which automatically take into account these differences in preferences. As a result they can achieve a given goal in greenhouse gas emission reduction at lower cost.

Greenhouse gas taxes

The greenhouse problem, in common with other pollution problems, arises because the polluter does not pay the full cost of the damage incurred by society. In the case of the greenhouse effect, the cost of emitting greenhouse gases into the atmosphere is negligible to individual firms, consumers or even countries. Yet, if the negative aspects of the greenhouse effect outweigh the positive aspects, greenhouse gases impose a cost on the world. In terms of figure F, because the marginal cost to the emitter of greenhouse gases is zero, emissions of L occur, which is not optimal. The common resource of the atmosphere is overused as a dump for emissions.

One policy option, therefore, is to put a tax on greenhouse gas emissions worldwide so that individual emitters must take into account the cost of greenhouse gas use. A tax would ensure that the optimal amount of greenhouse gases would be emitted if it was set at a level where the marginal cost of abatement equals the marginal cost of emissions per tonne of greenhouse gas. (A tax levied at rate P^* per tonne corresponds to the optimal level of emissions E^* in figure F.) In this case, the degree to which each country reduces its emissions of greenhouse gases will be different, with the market automatically and efficiently taking into account the difference between countries. For example, if one country's consumers have a strong preference for large cars, they are free to maintain them, and they express this preference by paying the higher costs of running these cars.

There are some practical difficulties with such a tax. The sums of money that would be collected by such a tax would be very large for even moderate reductions in greenhouse gases (Haynes, Fisher and Jones 1990). This money must then be distributed according to some criteria, and there are doubts about the willingness of sovereign governments to surrender this sum of money to an international organisation (Bertram, Stephens and Wallace 1990). There are several options for the disbursement of such tax revenues. One is to reduce the level of other taxes and direct greenhouse tax revenue to normal functions of government. This option could serve to offset the effectiveness of the greenhouse tax, however. Alternatively, revenues could be directed to a fund established for the purpose of reducing environmental problems, including climate change. This idea has already been raised in international forums (see for example Japan Petroleum and Energy Trends 1991). Tax revenue could also be spent on development of reproducible capital to increase future wealth.

In addition to the uncertainty about the optimal level of emissions (which will be dealt with below), the degree to which a particular tax level discourages greenhouse gas emissions would not be known with precision. Consequently, the tax may have to be levied in a trial and error fashion, until the desired level of greenhouse gas emissions was reached. However, the fact that the tax may be varied in future introduces uncertainty into economic decisions. This uncertainty is in addition to that resulting from the possibility that better information about the greenhouse effect may come to hand, necessitating changes in tax rates.

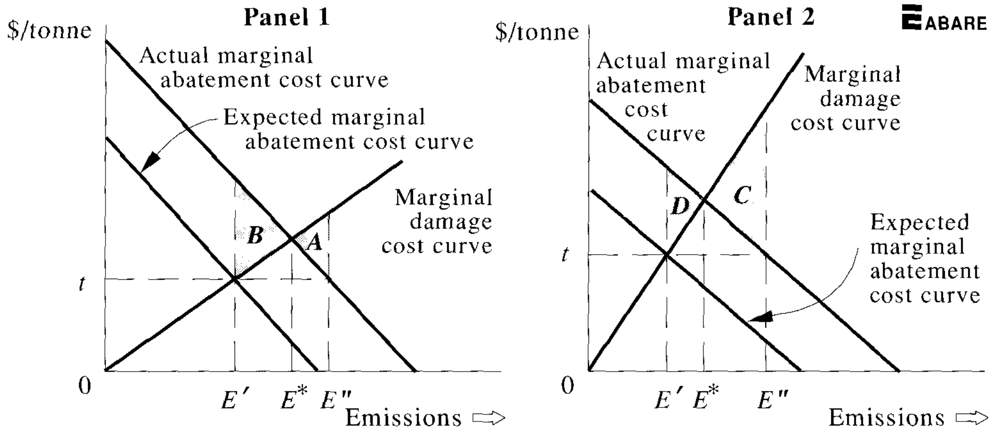
Tradable emission permits

Another way of viewing pollution problems such as the greenhouse effect is that they arise because of an absence of property rights. When property rights are defined clearly, scarce resources such as labour, capital and natural resources attract a price as users bid for them. Producers using these resources have an incentive to economise on the use of them and, under competitive conditions, markets for these resources will allocate them in an efficient way, that is in a way that maximises the community's welfare. In the case of the greenhouse effect, the scarce resource is the the ability of the atmosphere to absorb greenhouse gases. Yet at present this resource is treated as unlimited, and thus is overused. A way around this problem is to specify a total level of greenhouse gas emissions which is considered acceptable, and distribute shares in this total to sovereign nations. These rights to emit could then be traded between countries to ensure that the reduction in greenhouse gases occurs in the most efficient manner. Individual countries would then be free to choose a combination of regulation, emission charges and quotas to restrict greenhouse gas emissions within the total quota they each had accumulated.

In a world of complete knowledge about costs of damage caused by pollution and the costs of abatement, there is little to distinguish between tradable permits to emit greenhouse gases and a greenhouse gas tax on efficiency grounds. In figure F either a tax is set at P^* and emissions of E^* result or a quota for total permits is set is at E^* and a permit price of P^* results. Both allow the flexibility necessary for greenhouse gas emissions to be reduced in the most efficient manner. Thus the choice between the two would be determined by practical considerations. However, if uncertainty exists about the location and/ or the shape of the curves depicted in figure F then this conclusion changes (Tietenberg 1988; Hartwick and Olewiler 1986). Specifically, if it is thought that the absolute slope of the marginal abatement cost curve is steeper than that of the marginal damage cost curve, even though the location of each is not known, then it will be desirable to be able to control abatement costs more accurately. This is because it is more costly to be wrong about the cost of abatement than it is to be wrong about the level of greenhouse emissions. In this case emission taxes will be superior to tradable emission permits. Conversely, if the marginal damage cost curve is thought to be steeper, then tradable emission permits are superior.

The above arguments are illustrated in figure G. It is assumed that the actual marginal abatement cost curve is to the right of expectations. In panel 1 a tax of t results in excessive emissions at E'' relative to the optimum at E^* and results in a cost of uncertainty of area A. A permit system results in too few emissions at E' and results in a cost of uncertainty of area B. Since the absolute slope of both marginal abatement cost curves is steeper than the damage cost curve the cost of uncertainty is smaller under the tax. Conversely, in panel 2 the absolute slope of the marginal damage cost curve is steeper than the marginal abatement cost curve such that a permit system minimises the cost of uncertainty, that is, area C exceeds area D.

G Marginal abatement and damage cost curves with unexpected shift in abatement



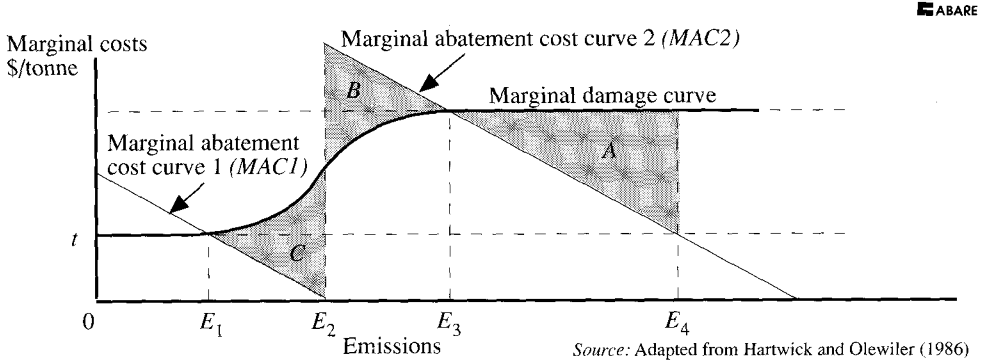
Source: Hartwick and Olewiler (1986)

A combined system of transferable emission permits and carbon taxes could be preferable in more complicated circumstances. For example, the marginal damage curve could be S shaped such that for low levels of emissions damage costs are relatively flat but beyond some threshold, determined by scientists, damages escalate rapidly until a higher saturation level of marginal damage is reached. In this circumstance a tax which operates below the threshold level could be used to minimise the cost of uncertainty associated with overestimating marginal abatement costs, due for example to weaker than expected demand for inputs which generate greenhouse emissions. A permit system with total quota set at the damage threshold for greenhouse emissions could minimise the cost of uncertainty associated with underestimating the marginal abatement costs and generating excessive damage costs.

These propositions are illustrated in figure H. The threshold level of emissions is at point E_2. If a tax of t is the only policy instrument to contain emissions then if the marginal cost of abatement curve is correctly estimated to be *MAC1* the resulting emissions of E_1 are optimal. If, on the other hand, the actual marginal cost of abatement is *MAC2*, then optimal emissions ate at E_3 and the tax causes excessive emissions of E_4 with a cost of uncertainty equal to area A under the single tax instrument. However, if a permit system comes into effect at E_2 then the cost of uncertainty is reduced to area *B*. Conversely, if a permit system alone were in place at the threshold level and the correct marginal abatement cost curve is *MAC1* then the cost of uncertainty is area *C* under a permit and zero under the tax. Hence in both cases the cost of uncertainty from under or overestimating the marginal cost of abatement are minimised by the combined policy of a tax and tradable permit system.

A further difference between emissions trading and taxation is that an emissions trading system avoids the problem of what to do with the revenues raised. However, there is still a significant issue associated with the initial allocation of tradable permits.

H Marginal abatement and damage cost curves given a damage threshold level and uncertainty



Source: Adapted from Hartwick and Olewiler (1986)

Equity and the workability of an international greenhouse policy

From an efficiency perspective, if certain conditions are met, it does not matter how the permits are allocated. These conditions are that there must be low transactions costs and the markets for the permits must be competitive, that is no country or group of countries must be able to exercise market power. When these conditions hold, the permits will be allocated efficiently regardless of the initial allocation. Countries without the desired number of permits would offer to buy permits from other countries. The outcome of this trading, under competitive conditions, would be that the price of a permit reflected the true scarcity value of the permits, that is the cost of the greenhouse emissions it permitted. A country which had received a large amount of permits would have incentive to sell them until it did not stand to benefit more from the sale than it did by keeping the marginal permit. Alternatively, if that country had received no permits, it would be in its interests to buy permits until the cost of the permit was just less than the benefit it gained from the permit. The final amount of permits the country owned would be the same in each case.

Obviously, however, the allocation of permits will confer additional wealth on countries, and thus the equity of this allocation must be considered. For instance, some have suggested that permits should be allocated to countries on the basis of population (Bertram 1990). This allocation criterion would alter the world distribution of wealth in favour of the poor. Another conceivable distribution criterion is to allocate permits on the basis of existing emissions. This would produce the opposite result, that is, it would widen world wealth disparities (Haynes, Fisher, and Jones 1990).

Choices made about the criteria chosen to distribute quotas also have implications for the workability of the scheme. The degree to which countries agree with the initial allocation will have a great bearing on the commitment they show to the system, and thus its ultimate effectiveness. A high degree of commitment is essential for any scheme to work because there will be a strong incentive for countries to 'free ride', that is, take the benefits of greenhouse abatement without incurring any of the costs of doing so and indeed profiting from the cost disadvantages other countries are incurring. Also, the equity principle shown must have wide acceptance because, whatever the principle chosen, some countries will be favoured relative to others. This is further complicated by the fact that the greenhouse effect will not impose uniform costs on countries. Indeed, some countries may benefit from the greenhouse effect. As a result, countries have differing incentives to participate in a scheme to mitigate global warming. The same information that will enable a more accurate calculation of the marginal damage caused by greenhouse gases, that is, more information about specific regional impacts, will make an agreement more difficult because the divergent interests of countries become clearer. Thus a set of principles must be found that obtain a general acceptance, such that these equity notions are strong enough to offset the clear difference in national interests that arise in any international policy.

It must be pointed out, though, that the issues of equity and the workability of schemes to reduce greenhouse gas emissions are not confined to the tradable quotas system, although here they are bought into sharp focus. They apply equally to carbon taxes, where the revenue raised by any international greenhouse gas tax must be distributed in some manner. Also, any agreements to limit the greenhouse gas emissions by an agreed amount across nations implicitly makes equity judgements (A. Rose 1990).

For any of the above policies there are a number of practical problems to overcome. Each policy requires accurate and prompt measurement of emissions of greenhouse gases, which is complicated in some cases where the processes are poorly understood. There also need to be effective mechanisms to bring about compliance, including a capacity to enforce sanctions against countries which break the agreement. These problems, though, are of a similar magnitude for any international agreement, and thus these considerations do not favour the choice of one type of policy over another.

Dealing with new knowledge about the greenhouse effect

It is likely that there will be rapid advances in knowledge in the next decade about the likely consequences of the greenhouse effect. As a result, the optimal level of greenhouse gas emissions will be calculated with more accuracy. As new information comes to hand it is therefore likely that greenhouse gas tax levels or the size of emission quotas would be changed, possibly by large amounts. This prospect introduces uncertainty into investment and consumption decisions. A partial solution to this problem would be to institute reviews of the greenhouse gas tax on a regular basis, say every ten years, so that decision makers could plan with some certainty in the intervening period. In the case of emission permits, the equivalent policy would be to create permits which gave a country the right to emit a certain level of greenhouse gas emissions for a specified number of years. Additional permits could be distributed at the end of each period, reflecting more up to date views on the optimal level of greenhouse gas emissions. With each of these options a tradeoff has to be made between the cost of the greater uncertainty engendered by short review periods, and the cost of emitting greenhouse gases at a non-optimal level for a number of years.

Uncertainty about the seriousness of the greenhouse effect is one reason why attention has been given to relatively cheap methods of reducing greenhouse gas emissions. It is argued that there are many examples of market failure within nations which, if corrected, would bring national benefits and have the side effect of reducing greenhouse gas emissions. Examples are given of instances where technologies in common use are not energy efficient even though more efficient technologies are readily available. However, this does not constitute prima facie evidence of market failure, because economic efficiency is a broader concept, and requires the minimisation of total costs, rather than simply the energy costs of a technology (Haynes, Fisher, and Jones 1990). There are other more unambiguous instances where there is potential to increase national economic welfare at the same time as reducing greenhouse gas emissions. Energy use is above what would be economically efficient in many countries because of the existence of large technical inefficiencies in energy generation and distribution and the common practice by governments of subsidising energy use. Also, in some cases, pollution and traffic congestion problems within countries may mean that higher taxes on fuel would bring benefits for that country. Thus, there may be considerable scope to reduce greenhouse gas emissions at low cost or even net benefit to national economies.

Policies based on correcting existing national market failures do little to tackle the long run and global consequences of the greenhouse effect as countries are not forced to take into account the additional global costs brought about by greenhouse warming. However, policies of this type may have an important role to play when considerable advances in knowledge about the costs of greenhouse warming can be expected in the next ten years. If it is found that the cost of greenhouse warming is small then policies of this nature have still been worthwhile. Hence, this approach is known as a 'no regrets' greenhouse policy strategy. If, on the other hand, it is found that greenhouse gas emissions have significant costs, then the fact that greenhouse gas reductions have taken place in the intervening years will make the adjustment required less harsh. Of course, the international approaches to reducing greenhouse gas emissions outlined above leave individual countries free to adopt 'no regrets' national policies.

CHAPTER 4

The simulation study

4.1 Overview

The main objective of the simulation study is to examine the long run impact on global and regional energy markets of a range of policy responses designed to reduce CO_2 emissions in the energy sector, under various assumptions about world economic growth and its regional distribution. Particular attention is given to the role of uncertainty in influencing the effectiveness of carbon management initiatives.

From chapters 2 and 3, it is apparent that, over the last decade scientific evidence has mounted which suggests that emissions of greenhouse gases arising from human activities, if left unconstrained, will lead to an enhanced greenhouse effect which may have a significant effect on global climatic patterns. Economic management of the greenhouse effect requires balancing the costs of policies to reduce the effect against the potential damage caused from the effect, to ensure that the net expected benefits from greenhouse policy initiatives are maximised. An optimal solution to the greenhouse problem requires consideration of all possible trade-offs between activities that alter the atmospheric concentration of greenhouse gases. Hence, emission management requires analysis of greenhouse gas emissions from all human and natural sources and of the interaction between these activities. All possible mechanisms to reduce emissions need to be considered in deriving the optimal policy response to greenhouse concerns.

The complexity of the greenhouse management problem presents a major challenge to economic modelling. Hence, several simplifying assumptions have been made to gain some key insights into this problem. One such simplification is that only CO_2 emissions from the energy sector are to be considered. As noted in section 2.1, carbon dioxide is currently the major contributor to the enhanced greenhouse effect, and the principal human source of carbon dioxide emissions is energy production and use.

Past economic development in the industrialised regions has tended to be based on increased use of fossil fuels. Of central concern to the carbon management problem is the risk that future economic growth in developing regions will be similarly based on increased fossil fuel use which would substantially increase global CO_2 emissions. Proposed policy initiatives to limit CO_2 emissions in the energy sector therefore require analysis to determine their consequences for regional economic growth and energy use. Over the next century economic growth is likely to be strongest in the Asia–Pacific region where developing regions can be expected to change their technologies of production.

CHAPTER 4

The greenhouse problem is surrounded by uncertainty regarding its scientific causes and consequences and economic impacts. Uncertainty pervades long term forecasting of energy requirements, CO_2 emissions and climatic feedback effects. These uncertainties may affect the choice of policy instruments in carbon management. For example, as noted in chapter 3, to maximise the net benefits from reducing CO_2 emissions a carbon tax is preferred to a permit instrument when the costs of being wrong are more sensitive to marginal changes in control costs rather than damage costs. The sensitivity of CO_2 impacts in the energy sector to four major sources of uncertainty are examined in this paper. These sources involve: the effect of technology transfer from industrialised to developing regions on regional income growth; the timing and extent to which energy efficient technologies are transferred between regions; the responsiveness of energy demand to relative prices and income changes; and the development of new energy technologies.

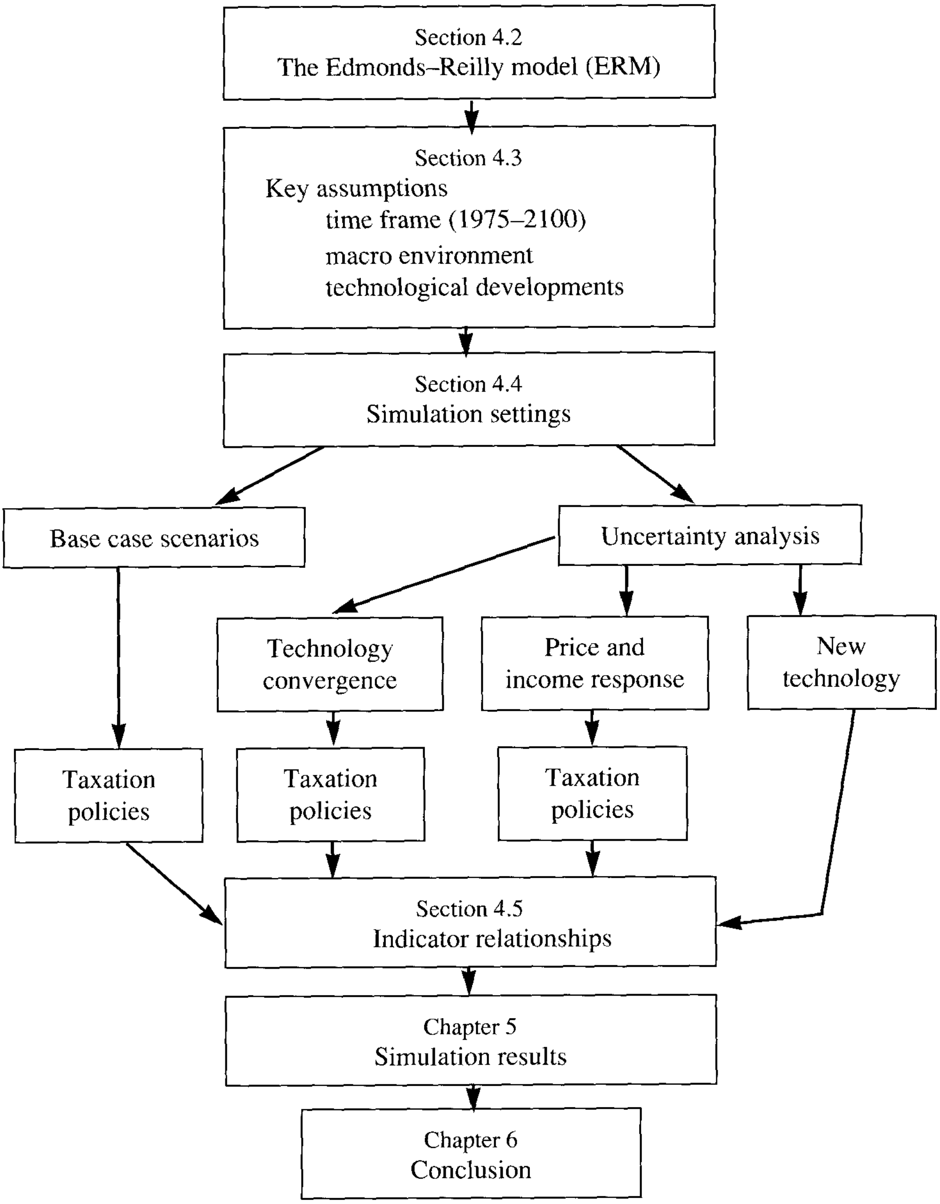
An overview of the simulation study is presented in figure I. At the top of this figure is the Edmonds–Reilly modelling framework which underpins the simulation study. This framework, known as the ERM model, comprises a set of economic relationships which are outlined in section 4.2. ERM is a long run dynamic partial equilibrium model of world energy markets and fossil fuel use. The method of analysis is to simulate regional and global CO_2 emissions, and energy demands and supplies, using this model. ERM has been a key model used in applied economic research of the international greenhouse effect (Mintzer 1987; Chandler 1988; Environmental Protection Agency 1989; Awata, Hattori and Ogawa 1990). ERM provides a consistent conditional representation of economic, demographic, technical and policy factors as they affect energy use and production at global and regional levels. ERM is amenable to uncertainty analysis in which key model parameters are varied by the model user and the sensitivity of carbon dioxide emission projections to these variations examined.

Key assumptions in the simulation study (outlined in detail in section 4.3) concern the time frame of the analysis, the macroeconomic setting and general technological developments. A long term time horizon to the year 2100 is used since tracing the impact of initial CO_2 emissions to the critical atmospheric concentrations associated with climatic damage involves very long time lags. The macroeconomic setting provides details of regional population growth and of worldwide labour productivity improvements which are needed to simulate regional economic growth and energy requirements. Worldwide technological developments improve the efficiency with which energy is produced and used.

The simulation study (see section 4.4) involves the choice of four environment settings or assumptions to be adopted in a model run. The simulation settings comprise taxation policy, technology convergence, price and income and new technology environments.

The simulations are structured as follows. Simulations are either part of the base case exercise or are uncertainty exercises. Four scenarios involving

I **Overview of the simulation study**



taxation comprise the base case exercise. The first or baseline scenario provides a general reference point from which the effects of variations in assumptions, that is, environment settings can be assessed. In the baseline scenario it is assumed that there is no policy intervention. By contrast, in the other base case scenarios the taxation setting is varied and different degrees of international cooperation in carbon taxation are assumed so as to examine some potential trade-offs between regional income growth and global growth in CO_2 emissions. As an instrument of carbon management policy, carbon taxes are used to change energy prices in favour of less carbon intensive fuels and so encourage energy switching to these fuels.

Three uncertainty exercises are considered, each of which is designed to indicate the sensitivity of the base case results to particular environment settings. Technology transfer scenarios, of which there are twenty-four, repeat the base case exercise for different degrees of technology convergence and taxation settings. Technology convergence refers to the transfer of technical advance, at both macroeconomic and energy sector levels, from leading regions to followers. Technology convergence assumptions thus link technical advances across regions with regional income growth and energy demand requirements. In the eight price and income scenarios, the sensitivity of the base case results to different assumptions regarding the price and income responsiveness of energy demand, with and without an OECD tax, are examined. While changes in relative prices and incomes are uncertain, so too is the responsiveness of energy demand to these changes. An alternative policy instrument to fossil fuel taxation is to subsidise research and development efforts in new technologies which reduce the cost of carbon clean fuels or increase the conversion efficiency of carbon based fuels. In the new technology scenarios two such technologies are added to the baseline scenario and their impact on CO_2 emissions is analysed. Indicator relationships used to analyse the results for CO_2 emissions in all thirty-eight simulations are defined in section 4.4. Results from the simulation study are discussed in the next chapter and key implications and conclusions are outlined in chapter 6.

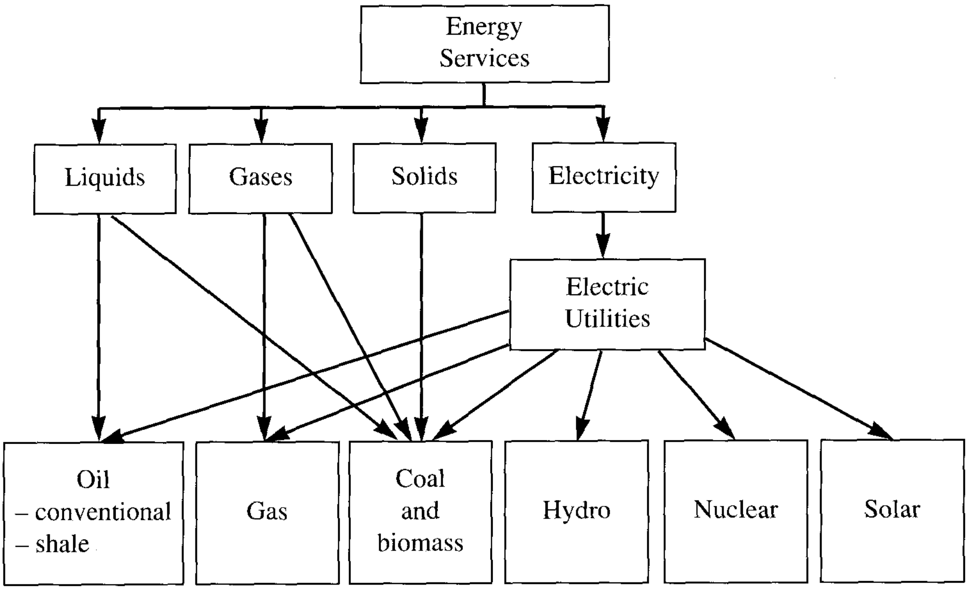
4.2 ERM model outline

The initial version of ERM is documented in Edmonds and Reilly (1983). Most of the subsequent modifications to the model are documented in Edmonds, Reilly, Gardner and Brenkert (1986). Changes made to the model for the simulation study are outlined in appendix A.

Simulation outputs derived from ERM comprise results for energy demands, supplies and prices and net fossil fuel trade and CO_2 emissions. Results are disaggregated by region and fuel type.

In ERM the world is divided into geopolitical regions and energy demands and supplies are modelled for each region. A top-down approach is used to model the derived demands for energy in each region (see figure J). At the top or first level, is demand for energy services. In developed (OECD) regions energy service demand is separated into residential and commercial, industrial and transport sector components. In developing economies energy service demand is modelled in aggregate. In each region the demand for an energy service depends on own price and real per person income, and is usually measured relative to population or real gross national product (GNP). Regional GNP depends on population and labour

J Demands for energy in ERM



Source: Adapted from Edmonds and Reilly (1985)

productivity assumptions and an energy price feedback term.

At the second level is the demand for secondary fuels. The four secondary fuels are liquids, gases, solids and electricity. Each energy service is a composite of services produced from each secondary fuel, subject to fixed conversion efficiencies (the fuel requirement per unit energy service). The share of an energy service supplied by each secondary fuel depends on the relative costs of providing the service using alternative fuels. Secondary fuel demands can be reduced through imposing end-use efficiency improvements.

At the third level is the demand for fuels used in electricity generation. Electricity can be supplied by conversion of oils, gases and solids or directly from hydro, nuclear and solar power. Both non-energy and energy input cost relativities, as well as conversion efficiencies, determine the mix of electricity input demands. In addition, transformation processes are included which convert coal and biomass into synthetic oils and gases as well as solid fuels. The demands for inputs used in synthetic fuel generation are similarly based on the relative costs of production.

At the bottom level of the energy demand hierarchy is the demand for primary fuels. The primary fuels are oil, gas, coal and biomass, and hydro, nuclear and solar energy. Primary energy demands are determined by secondary fuel demands and fuel transformations.

On the supply side of ERM, there are five non-renewable primary energy technologies: conventional and shale oil, natural gas, coal and nuclear. There are three other primary energy forms: hydro and biomass, which are resource constrained renewables; and a backstop technology in the form of solar electricity. The characteristic of a backstop technology is that at a given price, unlimited supply is available. In general, supplies depend on set regional resource bases, associated costs of production and regional prices. Minimum technical costs of production are imposed.

Two main factors govern regional supply response for non-renewable primary fuels — relative resource scarcity and price response. Within each region there is a resource base for each non-renewable fuel which comprises five fixed but continuous resource grades. Low cost grades of a resource are limited in supply and additional grades are more costly to produce. A resource becomes available for production when output price covers the imposed extraction cost. Price rises are needed to induce supply in excess of the rate of economic growth. The nuclear breeder reactor is modelled as an essentially unlimited fuel source available at high cost.

While solar electricity is treated as a backstop technology, over the medium run supply is not perfectly price responsive. The path for global solar electric power costs is imposed. Hydro electricity supply and price are also imposed. Biomass is separated into waste by-products and production from biomass farms. The waste resource base grows with economic activity while the share of the base supplied depends on the price of substitute coal and a base period price of biomass. The resource base from biomass farms is set but the share of the base exploited depends on own and substitute prices.

In ERM only oil, gas and solid fuels are traded internationally on a competitive world market. Net regional trade is measured for each fossil fuel. The market clearing or world price for each fossil fuel is thus determined by equating world energy demand with world energy supply. Tax wedges are used to separate regional consumer prices from producer prices and regional prices can differ from world prices due to taxes and transportation margins. As all other forms of energy are not traded internationally, price is determined by equating domestic demand with domestic supply.

Carbon emissions occur at the point of oxidation of fossil fuels. Hence, to determine a region's carbon emissions requires application of a conversion coefficient (carbon release per unit of energy) at the point of oxidation of each fossil fuel in the energy transformation process. In general, in ERM the amount of a fossil fuel which is combusted equals the quantity directly consumed less indirect non-fuel feedstock use. The carbon release coefficients specified in the model are given in table 9.

The 1989 version of ERM, supplied by Oak Ridge National Laboratories, was used in this study. The model is calibrated to 1975 data and provides projections of energy market developments at 25 year intervals to the year 2100. Nine geopolitical regions are modelled (table 10). The regions comprise the United States (USA); Canada and Western Europe (WEUR); Japan, Australia and New Zealand (JANZ); the Soviet Union and Eastern Europe (EUSSR); China and other centrally planned Asia (CPE); Middle East (MIDE); Africa (AF); Latin America (LA); and South, East and South-East Asia (SEA).

9 Carbon emission coefficients used in ERM model

Source	Coefficient
	Mt/EJ
Oil burnup	19.7
Gas burnup	13.8
Coal burnup	23.9
Coal liquefaction	18.9
Coal gasification	26.9
Shale oil production	27.9
Biomass	0.0
Solar	0.0
Nuclear	0.0
Hydro	0.0

Source: Edmonds and Reilly (1986).

In future ABARE research it is intended to recalibrate the data base to 1985 and disaggregate regions JANZ and SEA.

4.3 Key assumptions

The key assumptions made in the simulation study are outlined in table 11. These parameter values are common to all simulations. An extensive list of model parameters is given in Edmonds and Reilly (1986).

Key assumptions pertain to projections of regional population growth and worldwide trends in labour productivity, energy service efficiency and extraction costs. Edmonds et al. (1986) found that the values adopted for these variables significantly influence CO_2 projections in ERM. The last three variables are essentially technical change terms. As noted earlier, the approach taken in this paper attempts to link technical progress across regions in determining regional incomes and energy use within the model (see below). Hence, general technical change forces are not varied in the simulation exercise. In addition, in this study an energy service price rise stimulates future technical advance within the model, and the associated response parameter needs to be set.

Population growth assumptions correspond to the average values given in Edmonds and Reilly (1986). In this study the growth rate of the regional labour force is assumed to be the same as the growth rate in the regional population. By 2050 it is assumed that the world's population is over 8 billion, more than double the 1975 value. Between 1975 and 2050 world world population growth increases at an annual rate of 1 per cent with the major growth areas being SEA and ROW. While SEA and ROW increase their share in the world's labour resource, CPE experiences a marginal decline. Annual world population growth between 2050 and 2100 is marginally positive at 0.1 per cent and adds 250 million people.

Labour productivity proxies the rate of growth of per person incomes in the

10 Regional definitions in ERM model

Symbol	Region
USA	United States
WEUR	Canada and Western Europe
JANZ	Japan, Australia and New Zealand
EUSSR	Soviet Union and Eastern Europe
CPE	China and other centrally planned Asia
MIDE	Middle East
AF	Africa
LA	Latin America
SEA	South, East and South East Asia

Composite regions

OECDW = USA + WEUR

OECD = OECDW + JANZ

ROW = EUSSR + MIDE + AF + LA

non-OECD Asia = CPE + SEA

11 Key assumptions of the simulation study

Population

Region a	**1975**	**2050**	**2100**
		Population size	
	million	million	million
USA	214	288	292
WEUR	405	553	562
JANZ	128	167	169
CPE	911	1 612	1 647
EUSSR	395	533	541
MIDE	81	232	241
AF	399	1 101	1 150
LA	313	823	849
SEA	1 130	2 888	2 995
World	3 976	8 197	8 446
		Shares of world population	
	%	%	%
OECD	18.8	12.3	12.1
JANZ	3.2	2.0	2.0
CPE	22.9	19.7	19.5
SEA	28.4	35.2	35.5
ROW	29.9	32.8	32.9
		Annual growth b	
	%	%	%
OECD	1.24	0.40	0.03
JANZ	1.14	0.36	0.02
CPE	1.75	0.76	0.04
SEA	2.22	1.26	0.07
ROW	2.06	1.10	0.07
World	1.87	0.97	0.06

Labour productivity growth: average of 1.7 per cent a year in all regions.

End-use technical efficiency growth: average of 1.0 per cent a year in all regions.

Technical change in energy production: average growth of 0.5 per cent a year in all regions.

Energy price elasticity for end-use technical advance: 0.15 in all regions.

Regional annual economic growth rates between 1975 and 2000 (%):

USA a	**WEUR**	**JANZ**	**EUSSR**	**CPE**	**MIDE**	**AF**	**LA**	**SEA**
3.0	2.5	4.0	3.0	7.0	4.0	2.5	3.0	5.5

a Regions are defined in table 10. **b** For 1950–1975, 1975–2050 and 2050–2100.

absence of technology convergence and aggregate energy price changes. End-use technical efficiency represents the rate at which the energy service to GNP ratio improves holding such factors as technology convergence, labour productivity, population and relative prices constant. Technical change in production measures the annual rate of decline in the production costs of all non-renewable fuels, all other factors held constant.

Global improvements in labour productivity and in end-use technical efficiency are assumed to average 1.7 per cent and 1.0 per cent a year respectively between 2000 and 2100. These are the average settings for the OECD regions suggested in Edmonds and Reilly (1986). Worldwide annual production efficiency gains are assumed to average 0.5 per cent per year over the projection period, which also corresponds to the average value in Edmonds and Reilly (1986).

The lagged energy price elasticity for end-use technical advance represents the percentage change in end-use efficiency due to a percentage change in lagged energy service prices, all else constant. This technical elasticity is a new model parameter introduced in this study. The technical elasticity is set at 0.15, which corresponds, in absolute magnitude, to the average value for the energy price feedback elasticity to GNP for the OECD area assumed in Edmonds and Reilly (1986).

The model simulates from 1975 with a first period projection in 2000. However, sixteen years of actual outcomes for regional economic growth rates exist. This information was included in the model by imposing the values for regional economic growth for 1975–2000 given in table 11. Values are based on historical outcomes for the period up to 1990 and ABARE assumptions for the period 1991–2000.

4.4 Simulation settings

In each simulation, data input into ERM is chosen from each of four environments or parameter settings comprising: *taxation*; *technology transfer*; energy demand response; and new technology settings. Key assumptions which are maintained across all simulations were outlined above.

Specific values for each parameter setting are given in table 12. It is stressed that these values are only illustrative and do not necessarily represent any particular forecast. As noted in section 4.1, in the simulation study scenarios are defined as either base case or uncertainty scenarios. Default values shown in table 12 correspond to the baseline scenario. In other base case scenarios carbon taxation is assumed. The uncertainty simulations are named after the main setting which is changed from its default value. With the exception of new technology scenarios uncertainty scenarios are examined with and without carbon taxes.

Taxation policies

The taxation setting comprises a carbon tax free baseline or various degrees of international carbon tax cooperation. A common *ad valorem* carbon tax on primary energy consumption is introduced in: OECD regions alone; or the world excluding China; or globally.

The rate of *ad valorem* tax is 100 per cent for primary energy demand for coal.

12 Scenario parameters for the simulation study

Taxation policies

Carbon tax on primary energy demands: *ad valorem* rate of 100 per cent on coal, 82 per cent on oil and 58 per cent on gas. Tax applies from 2000 to 2100, in either OECD only, world excluding CPEA, or world. The default setting for the taxation environment is carbon tax free.

Technology convergence

Convergence in per person incomes (real gross national product per person, 1975 US$/person) relative to USA, as follows:

		2100		
	2000	nil	moderate (default)	strong
USA	1.00	1.00	1.00	1.00
WEUR	0.57	0.57	0.62	0.67
JANZ	0.81	0.81	0.86	0.91
EUSSR	0.34	0.34	0.39	0.44
CPE	0.11	0.11	0.16	0.21
MIDE	0.20	0.20	0.25	0.30
AF	0.03	0.03	0.08	0.13
LA	0.10	0.10	0.15	0.20
SEA	0.04	0.04	0.09	0.14

Convergence in energy service intensities (energy services per real gross national product, EJ per 1975 US$) relative to JANZ, as follows:

		2100		
	2000	nil	moderate (default)	strong
USA	1.77	1.77	1.72	1.67
WEUR	1.12	1.12	1.07	1.02
JANZ	1.00	1.00	1.00	1.00
EUSSR	2.56	2.31	2.26	2.21
CPE	3.55	2.39	2.34	2.29
MIDE	1.24	1.11	1.06	1.01
AF	1.27	1.25	1.20	1.15
LA	1.43	1.35	1.30	1.25
SEA	1.95	1.54	1.49	1.44

Price and income response

	Range a		
	weak	moderate (default)	strong
Aggregate energy price elasticity	-0.05	-0.70	-1.30
Aggregate income elasticity			
OECD	0.20	1.00	1.40
non-OECD excluding EUSSR	0.50	1.40	2.20
EUSSR	0.20	1.25	1.80

New technology

Final production costs of solar electric power are reduced to 1975 US$7.425/GJ from default value of US$14.85/GJ. Final costs are reached in 2000, rather than (default) 2025.

Conversion efficiency of coal use in electricity generation is increased from default assumption of 0.301 to 0.317 starting in 2000.

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a All values taken from Edmonds et al. (1986).

Reflecting corresponding carbon emission coefficients for oil and gas burnup (see table 9), taxes of 82 per cent and 58 per cent are levied for oil and gas. These tax rates are rather crudely based, since they imply that synthetic fuels and shale oil are undertaxed relative to their carbon intensity. If the tax is imposed it applies over the period from 2000 to 2100.

As an instrument of carbon conservation policy, carbon taxes have been proposed to encourage energy switching and energy conservation. Energy switching, to reduce the carbon intensity of aggregate energy demand, is effected through relative price changes which favour less carbon intensive fossil fuels and carbon clean energy forms. However, to the extent that interfuel substitution options are limited, energy conservation responses are likely.

Since energy is an input in other activities an increase in the relative price of energy services encourages a switch in the input mix from energy to other inputs which tends to reduce the energy intensity of gross national product (GNP). To the extent that interfactor substitution possibilities are limited, an increase in the relative price of energy services tends to reduce GNP and this in turn tends to reduce energy demand. In ERM these features are incorporated through the dependence of energy service demands on the relative price of energy services and GNP and the dependence of GNP on the relative price of energy services. In addition, as modified in this study, an energy price increase also stimulates a lagged increase in energy service efficiency, to proxy the effect of price induced investment in energy saving technologies.

Terms of trade impacts of taxation on energy prices are measured in ERM. However, in ERM carbon tax revenues are implicitly transferred to sectors or regions which, by assumption, have negligible feedback on energy markets. To adequately incorporate revenue feedbacks requires incorporation of a global general equilibrium framework, which links resource flows of goods and services and labour and capital inputs in production, consumption and trade across the globe, and is an intended extension in future research.

Technology convergence

The technology convergence setting involves assumptions regarding technology transfer at the macroeconomic and/or energy sector level.

The projection of long run world economic growth and its regional distribution is characterised by uncertainty. Various theories exist to explain the process of economic development. One hypothesis is that long run world economic development involves technology transfer from leading regions to followers. Technology transfer arises through such factors as international trade. At the macroeconomic level, empirical evidence supports convergence in per person incomes amongst the OECD countries (see Dowrick and Nguyen 1989). It has been argued that technology transfer is the underlying cause of this phenomenon.

However, the potential also exists for significant technology transfer between developed and developing countries. Technology transfer could generate overall improvements in the economic means of aggregate production amongst the developing economies, raising per person living standards and energy demands. Hence, macro level technology transfer is a potential source of world economic growth and carbon dioxide emission growth.

In this study technology transfer at the macroeconomic level is proxied by per person income convergence or technical catchup as in Dowrick and Nguyen (1989). The determination of regional gross national product in ERM was modified to include a convergence parameter which controls the extent to which per person incomes converge across regions over time in the absence of relative price changes (see appendix A).

In addition, technical advance in the energy sector itself could also be transferred from leading regions to followers. Such energy efficiency gains could reduce carbon dioxide emissions. For this reason technology transfer is also analysed at the energy sector specific level. Energy specific technology transfer is proxied by convergence in energy service to GNP ratios. The determination of regional energy service demands in ERM was modified to incorporate convergence or technical catchup in energy service intensities (see appendix A). For example, as modified, a region's demand for an energy service such as industrial boiler heat depends, amongst other things, on the relative efficiency of providing this service in the leading region.

Thus, two forms of technology transfer are juxtaposed in this study, one promoting and the other constraining energy demand and carbon dioxide emission growth. The convergence parameters do not predetermine relative per person income relativities or the aggregate energy intensity of GNP across regions unless all relative price changes and technical advances are held constant.

Three parameter settings are used to control the extent of macroeconomic technology transfer: nil convergence, moderate (default) and strong real per person income technical catchup. Similarly, there is either nil, moderate (default) or strong technology transfer in energy services.

Essentially, the convergence parameters reflect technology transfer forces which might arise in the course of economic development in the absence of aggregate energy price feedbacks, including policy responses to greenhouse concerns. Convergence parameters have both regional and time dimensions. If convergence is assumed it operates between 2000 and 2100.

Relative per person incomes converge to the value one from below, while relative energy service intensities converge to one from above. In either case a convergence ratio close to one indicates strong convergence to the per person income or energy service intensity of the region which is technology leader. For example, average real per person income in JANZ is 81 per cent of that in the leading region in 2000 and, in high convergence scenarios, 91 per cent by 2100 (see table 12). The leading region for per person incomes is assumed to be USA, and for energy service intensities JANZ. Between 2000 and 2100, average real per person incomes in USA are expected to exceed those in other regions, while energy service intensities in the world excluding JANZ are expected to exceed those in JANZ.

Assumptions for moderate and high convergence for per person incomes correspond to nil values arbitrarily marked up by 0.05 point and 0.1 point. Since the energy service output ratio in JANZ is below that elsewhere, assumptions for moderate and high convergence toward JANZ follow by arbitrarily marking down the nil values by 0.05 point and 0.1 point.

Price and income response

Carbon conservation depends on energy switching and energy demand. An uncertain energy demand response environment could influence the timing and scope for carbon management policy and the choice of policy instruments. The responsiveness of energy demand to changes in price and income are examined by varying the price elasticity of demand for energy services or the aggregate income elasticity of demand for energy services. The aggregate energy price elasticity represents the percentage change in the demand for energy services for each percentage change in their price, all else constant. The income elasticity measures the percentage change in energy service demand due to a percentage change in income, all else constant.

The price and income elasticity parameter values are those adopted in the uncertainty analysis of Edmonds et al. (1986). Three values are considered for each elasticity comprising weak, moderate (default) or strong parameter settings. While the same price elasticity is used for all regions, income elasticities vary by region. A unitary income elasticity indicates a constant energy service output ratio in the absence of convergence and relative price changes. In ERM it is assumed that income elasticities in non-OECD regions converge toward unity by 2075. The effect of regional variation in the price responsiveness of energy service demand will be examined in future work. In future it is intended to disaggregate the energy service sector in non-OECD regions and model the derived demands for energy in all regions as originating in agriculture, mining, energy intensive and other manufacturing and service sectors.

New technology

Besides taxing fossil fuel use in an attempt to internalise greenhouse pollution, energy switching may result from stimulating research and development efforts in new technologies which reduce the costs of carbon clean energy forms or increase conversion efficiencies in fossil fuel combustion. The new technology environment comprises a baseline (default) setting of existing technologies and a new technology setting. The new technologies considered either reduce the costs of solar electricity or increase the conversion efficiency of coal in electricity generation. While the effectiveness of these technical advances in reducing carbon emissions is examined in the study it is noted that the costs of investments to achieve these initiatives are not measured in ERM. The assumptions made are meant to be illustrative only.

In the new solar technology scenario it is assumed that the global final production cost of solar electric power is halved from its baseline setting. It is assumed to take 25 years to reach final solar production costs, which is also half of the default value. One may view these assumptions as a subsidy to solar production which starts from zero in 1975 and increases steadily to 100 per cent in 2025. By comparison, all carbon taxes are introduced in 2000 at a rate of 100 per cent. In the new coal technology scenario it is assumed that there is a once off increase of 5 per cent in the conversion efficiency of coal used in electricity generation starting in 2000.

4.5 Indicator relationships

By decomposing carbon dioxide emissions into various intensity measures a set of indicator variables can be derived which help in the characterisation of the greenhouse problem. The algebraic form of the relationships between these measures is:

$$
\begin{aligned}
(1)\ CO2 &= (CO2/GNP)GNP \\
&= (CO2/E)E \\
&= (CO2/E)(E/GNP)GNP \\
&= (CO2/E)(E/GNP) \\
&\quad (GNP/CAP)CAP
\end{aligned}
$$

where

$CO2$ = annual carbon dioxide emissions in gigatonnes ($\mathrm{Gt} = 10^9$ t) of carbon;

$CO2/GNP$ = the carbon intensity of GNP or the inverse of the carbon conservation factor;

GNP = real gross national product in trillions (10^{12}) of 1975 US dollars;

$CO2/E$ = the carbon intensity of energy or the inverse of the energy switching factor;

E = primary energy demand in exajoules ($\mathrm{EJ} = 10^{18}$ J);

E/GNP = the energy intensity of GNP or the inverse of the energy conservation factor;

GNP/CAP = real per person income in thousands of 1975 US dollars per person,

CAP = population in millions of persons.

It is a property of all multiplicative relationships that growth in a variable is approximately equal to the sum of the growth rates of its components. Hence, it follows from equation (1) that growth in CO_2 emissions equals growth in GNP less growth in carbon conservation due to energy switching and energy conservation.

In the model, global economic growth is measured exclusive of global warming feedback effects. That is, only the positive effect of carbon intensive energy use is measured. However, there is some natural limit beyond which greenhouse gases can be regarded as a stock pollutant in the atmosphere. Greenhouse warming damages to economic activity are likely to arise when the pollution stock reaches a critical level of build-up. Consequently, another indicator variable reported in the simulation results is the atmospheric concentration of carbon dioxide (*CUMCO2*). Following Awata, Hattori and Ogawa (1990) cumulative emissions are defined by

$$
(2)\ CUMCO2_t = CUMCO2_{t-1} + abt(CO2_t + CO2_{t-1})/2
$$

where

$CUMCO2$ = the atmospheric concentration of carbon dioxide measured in parts per million (ppm)

$a = 0.5$ = the fraction of carbon dioxide which remains airborne;

$b = 0.471$ = the conversion factor transforming gigatonnes of carbon to parts per million;

$t = 25$ = the time interval between projections in the Edmonds–Reilly model.

Following Edmonds and Reilly (1985) the critical benchmark is chosen to be 600 ppm, approximately double the atmospheric concentration of carbon dioxide in 1975.

In using equation (2) this paper concentrates solely on the contribution of fossil fuel combustion to the atmospheric concentration of carbon dioxide. It is assumed that future emissions from other sources remain constant. Effects of other greenhouse gases in contributing to global warming potential are also implicitly held constant in the analysis. Further, in equation (2) it is assumed that the fraction of carbon dioxide emissions which remain airborne is independent of the level of emissions. Considerable uncertainty surrounds the rate of removal of airborne carbon dioxide into the ocean or other sinks (World Resources Institute 1990), and it may be that as emissions rise the airborne fraction decreases.

CHAPTER 5

Simulation results

In this chapter the results from the simulation analysis are reported. Results for the baseline scenario are presented first since they provide a general reference point for the simulation study. This scenario is then contrasted with other base case scenarios in which different degrees of global cooperation in carbon taxation are assumed. The sensitivity of the results to technology transfer, price and income response and new technology assumptions is then considered. The main qualifications to the simulation study and directions for further research are noted in the final section. In appendix B a simplified algebraic model is used to provide insights into the global results of the simulation study. Further details from the technology convergence scenarios are given in appendix C.

5.1 The baseline scenario

The baseline scenario reflects the evolution of world energy markets and CO_2 emissions for the period 1975–2100 in the absence of policy responses to greenhouse concerns, using moderate assumptions for convergence in per person incomes and convergence in energy service intensities.

Indicator relationships

Compared with 339 ppm in 1975, the atmospheric concentration of carbon dioxide in the baseline scenario reaches 473 ppm by 2050 and at 612 ppm in 2100 exceeds the warming benchmark of 600 ppm. Between 1975 and 2100 the long run annual growth rate of global carbon dioxide emissions averages 1.0 per cent per year while the growth rate in the atmospheric concentration of carbon dioxide averages 0.5 per cent per year. Indicator results for the baseline scenario are given in table 13. Between 1975 and 2050 emission growth is far stronger in both non-OECD Asian regions than in the ROW and OECD regions. Between 2050 and 2100 emission growth slows markedly in CPE but speeds up in ROW. By 2100 combined emissions in non-OECD Asia are 50 per cent of the OECD value, compared with 27 per cent in 1975. By contrast, relative emissions in the ROW rise marginally by 2100.

Emission growth depends on economic growth, as measured by real gross national product (GNP), and growth in the carbon intensity of GNP. Global economic growth averages 2.7 per cent between 1975 and 2050 and then moderates to 2.0 per cent per year between 2050 and 2100. Overall, economic growth is strongest in non-OECD Asia, where it exceeds 4 per cent per year over the first period before moderating. Regional economic growth rates largely reflect the per person income convergence and population growth rate assumptions.

13 Baseline indicator results

		Region a					
Variable b	**Period**	**World**	**OECD**	**JANZ**	**CPE**	**SEA**	**ROW**
Absolute trends (Annual growth rates)							
		%	%	%	%	%	%
CO2	1975–2050	0.9	0.9	1.3	2.0	2.2	0.5
	2050–2100	1.1	1.0	1.1	0.2	0.9	1.7
CO2/GNP	1975–2000	–1.7	–1.4	–1.3	–1.9	–1.8	–1.8
	2050–2100	–0.9	–0.7	–0.6	–1.8	–1.6	–0.3
GNP	1975–2050	2.7	2.3	2.6	4.0	4.1	2.7
	2050–2100	2.0	1.8	1.8	2.0	2.6	2.0
CAP	1975–2050	1.0	0.4	0.4	0.8	1.3	1.1
	2050–2100	0.1	0.0	0.0	0.0	0.1	0.1
GNP/CAP	1975–2050	1.7	1.9	2.2	3.2	2.8	1.5
	2050–2100	1.9	1.7	1.7	2.0	2.5	2.0
E/GNP	1975–2050	–1.3	–1.3	–1.1	–1.2	–1.2	–1.7
	2050–2100	–1.1	–1.1	–0.7	–1.3	–1.0	–1.0
CO2/E	1975–2050	–0.4	–0.1	–0.2	–0.6	–0.7	–0.4
	2050–2100	0.2	0.4	0.1	–0.5	–0.6	0.7
Relativities		index	index	ratio c	ratio c	ratio c	ratio c
CO2	1975	100	100	0.12	0.19	0.08	0.66
	2050	194	194	0.16	0.44	0.21	0.50
	2100	331	323	0.17	0.30	0.20	0.70
CO2/GNP	1975	100	100	0.80	2.35	1.36	1.64
	2050	27	35	0.88	1.60	0.96	0.95
	2100	17	24	0.92	0.94	0.61	1.17
GNP	1975	100	100	0.15	0.08	0.06	0.40
	2050	718	551	0.19	0.27	0.22	0.52
	2100	1 908	1 317	0.19	0.32	0.32	0.60
GNP/CAP	1975	100	100	0.87	0.07	0.04	0.25
	2050	348	408	1.12	0.17	0.08	0.20
	2100	898	962	1.13	0.20	0.11	0.22
E/GNP	1975	100	100	0.78	1.65	1.14	1.38
	2050	38	38	0.88	1.68	1.23	1.00
	2100	22	22	1.04	1.49	1.25	1.05
CO2/E	1975	100	100	1.03	1.42	1.19	1.19
	2050	72	92	1.00	0.95	0.79	0.96
	2100	79	110	0.88	0.63	0.49	1.12

a Regions were defined in table 10. **b** Variables were defined in section 4.5. **c** Relative to OECD average.

Between 1975 and 2100, about a ninefold rise in average real per person incomes in the OECD is projected in the baseline scenario. Over this period, per person incomes in CPE and SEA converge to the OECD average by 13 and 7 percentage points respectively. The average per person income in ROW diverges from the OECD average between 1975 and 2050. This deterioration primarily reflects actual events between 1975 and 1990. However, between 2050 and 2100 there is some per person income convergence in ROW. While the relative per person income of JANZ exceeds the OECD average throughout the forecast period, it remains below the USA average.

Global growth in CO_2 emissions is weaker than global growth in gross national product over the projection period due to carbon conservation. As projected, the global carbon intensity of GNP falls by 1.7 per cent a year between 1975 and 2050 and by 0.9 a year between 2050 and 2100. Growth in carbon conservation is strongest in non-OECD Asia. Energy conservation provides the main control on emission growth in the baseline scenario. The global energy intensity of GNP falls by 1.3 per cent a year between 1975 and 2050 and by 1.1 per cent a year between 2050 and 2100. Energy conservation in turn reflects technical advance in energy service delivery, comprising technology transfer from JANZ and a moderate assumed world-wide technical stimulus of 1 per cent per year. The rate of energy efficiency improvement exceeds that in JANZ for all regions in both periods since all regions other than JANZ benefit additionally from technology transfer from JANZ. Overall, growth in energy conservation is stronger than the OECD in CPE and ROW, and weaker in SEA and JANZ. In the baseline scenario in 2100 the OECD, JANZ and ROW have approximately equal energy intensities, and the SEA region is less energy intensive than CPE.

Globally, energy switching contributes to carbon conservation between 1975 and 2050 but promotes carbon intensive energy and emission growth between 2050 and 2100. As projected, the carbon intensity of energy falls by 0.4 per cent a year between 1975 and 2050 but rises by 0.2 per cent a year between 2050 and 2100. This global pattern reflects developments in the OECD and ROW regions. By contrast, in non-OECD Asia the pace of energy switching toward carbon clean fuels (comprising hydro, nuclear and solar), while slowing is not reversed in the second period. By 2100 in the baseline scenario all regions have less carbon intensive energy demands than the OECD with the exception of ROW.

Energy demand mix

In the baseline scenario global primary energy demand grows at an average annual rate of 1.1 per cent between 1975 and 2100. At the global level, growth in demand for clean fuels, used in electricity generation, is strongest and, of the fossil fuels, growth in coal demand is strongest. Baseline results for the primary energy demand mix are shown in table 14. World coal demand growth exceeds that for clean fuels between 2050 and 2100. World gas demand expands more rapidly than oil demand between 1975 and 2050. However, gas demand contracts dramatically between 2050 and 2100, while there is a modest decline in oil demand.

14 Baseline energy demand mix

Variable a	Period	Region					
		World	OECD	JANZ	CPE	SEA	ROW
		%	%	%	%	%	%
Annual growth rates							
E	1975–2000	1.3	1.0	1.4	2.7	2.9	0.9
	2050–2100	0.9	0.7	1.0	0.7	1.5	1.0
OIL	1975–2050	0.6	0.3	0.3	2.8	1.2	0.3
	2050–2100	–0.4	–0.5	–0.5	–0.1	0.3	–0.6
GAS	1975–2050	1.1	0.7	1.5	6.9	3.5	1.0
	2050–2100	–5.9	–6.8	–7.1	–5.9	–6.3	–4.8
COAL	1975–2050	1.6	2.0	2.5	1.7	3.2	0.5
	2050–2100	2.2	2.3	2.4	1.7	2.4	2.5
CF	1975–2050	2.7	2.0	2.5	5.1	4.5	2.9
	2050–2100	1.3	1.2	1.4	0.7	1.1	1.9
Fuel shares		share	share	share	share	share	share
OIL/E	1975	0.4	0.4	0.5	0.2	0.5	0.3
	2050	0.2	0.3	0.2	0.2	0.1	0.2
	2100	0.1	0.1	0.1	0.1	0.1	0.1
GAS/E	1975	0.3	0.3	0.2	0.0	0.1	0.3
	2050	0.2	0.3	0.2	0.2	0.1	0.3
	2100	0.0	0.0	0.0	0.0	0.0	0.0
COAL/E	1975	0.2	0.1	0.1	0.8	0.3	0.3
	2050	0.3	0.2	0.3	0.4	0.4	0.2
	2100	0.6	0.6	0.6	0.7	0.7	0.5
CF/E	1975	0.1	0.1	0.1	0.0	0.1	0.1
	2050	0.2	0.2	0.2	0.2	0.3	0.3
	2100	0.3	0.3	0.3	0.2	0.2	0.4

a E denotes primary energy demand; *OIL* denotes conventional and shale oil; *GAS* denotes conventional gas; *COAL* denotes coal plus biomass; and *CF* denotes clean fuels hydro, nuclear and solar.

The changes in energy demand are stimulated by real income and relative price changes and depend both on the substitutability between the various fuels and on relative resource constraints. Low cost conventional oil and gas reserves are assumed to be relatively scarce but low cost coal is available in plentiful supply. Coal can be used directly as a fuel, converted to electricity, or processed into synthetic liquids and gases. However, while backstop supply costs of clean fuels are assumed to decline over the projection period due to technical progress, the availability of low cost clean fuel alternatives to coal are limited. Over the next century, a rise in relative prices for fossil fuels is assumed in the baseline scenario. This reflects increasing mining and exploration costs as low cost fossil fuel resources are depleted. By 2050 gas and oil prices rise sufficiently to stimulate market penetration of synthetic fuel supplies from coal.

In the baseline scenario, the share of clean fuels in the energy demand mix rises fairly steadily between 1975 and 2050 across all regions but never exceeds 30 per cent. Over this period, the market penetration of clean fuels is at the expense of oil in the OECD and SEA, at coal's expense in CPE, and at the expense of oil and coal fuels in the ROW. By 2100 clean fuel market penetration is no more than 40 per cent. In all regions coal is dominant with a minimum share of 50 per cent while clean fuels have a minimum share of 20 per cent. By 2100 coal's share is 60 per cent in OECD regions, 70 per cent in CPE and SEA, and 50 per cent in ROW. These changes are all at the expense of combined oil and gas, for which market share is severely eroded.

Net energy trade

Baseline results for regional net trade in fossil fuels are given in table 15. As modelled in the baseline scenario, the dominant net coal exporting regions by 2050 are EUSSR and USA. Major net coal importing regions are CPE, SEA and WEUR by 2050. In 2050 net imports into non-OECD Asia are 73 per cent of world net coal trade, and 63 per cent in 2100. At the level of regional disaggregation given in the Edmonds–Reilly model region JANZ is a small net coal importer. However, this masks developments within JANZ with respect to the net coal export potential of Australia and the import requirements of Japan.

Regional developments in net gas trade are volatile over the long term projection period. In the baseline scenario, by 2050 the dominant gas exporter is MIDE and both the OECD and non-OECD Asia are major net gas importers. By 2100 the major source of net gas export supply is EUSSR, and USA becomes a net exporter.

As expected, the major net exporter of oil is the MIDE throughout the projection period. In general, the other regions comprising ROW are also net oil exporters. Major oil importers are the OECD and non-OECD Asia. In aggregate, in the baseline scenario the main net energy importers over the long term are the OECD and non-OECD Asia, while ROW is the main net energy exporting bloc.

5.2 Carbon tax cooperation scenarios

The greenhouse policy response examined in this study is the introduction of a carbon tax on primary energy demand. These scenarios are developed based on different degrees of global cooperation in carbon taxation. It is assumed that the tax is introduced in the OECD only, or in the world excluding CPE, or globally. In all cases the tax is a 100 per cent *ad valorem* carbon tax which is assumed to be introduced in

15 **Baseline results for regional net trade** [a]

Region [b]	*COAL* 2050	*COAL* 2100	*GAS* 2050	*GAS* 2100
	EJ	EJ	EJ	EJ
USA	-30.95	-55.07	11.04	-16.13
WEUR	17.89	38.55	20.72	26.47
JANZ	2.46	5.62	10.42	0.56
EUSSR	-56.61	-102.96	-2.41	-39.53
CPE	42.93	56.07	22.46	17.05
MIDE	0.80	2.31	-53.65	1.54
AF	2.39	6.75	-9.98	3.35
LA	-1.08	5.32	-6.81	1.26
SEA	22.22	43.73	8.20	5.58
Total [c]	88.64	158.03	72.86	55.65

	OIL		*TOTAL* [d]	
	EJ	EJ	EJ	EJ
USA	45.99	32.38	26.08	-38.82
WEUR	15.68	32.84	54.29	97.86
JANZ	10.75	9.70	23.63	15.88
EUSSR	-14.74	-25.94	-73.76	-168.43
CPE	14.98	28.88	80.37	102.00
MIDE	-45.02	-74.67	-97.87	-70.82
AF	-21.96	-20.96	-29.55	-10.86
LA	-14.97	11.39	-22.86	17.97
SEA	9.38	6.46	39.80	55.77
Total [c]	96.69	121.56	258.19	335.24

a Net trade in commodity is positive for net imports and negative for net exports. **b** Regions were defined in table 10. **c** Global net trade in commodity equals sum of net imports or negative sum of net exports. **d** Regional and total entries denote horizontal sums of net trade entries for *OIL*, *GAS* and *COAL*.

2000. The level of the carbon tax adopted here is simply illustrative of possible impacts on emissions and energy market prospects. The level of the tax and the extent to which emissions may need to be reduced to avoid significant warming damage is uncertain and as a consequence the actual rate of tax required is unknown. Key sources of uncertainty include the estimation of carbon dioxide absorption by sinks, emissions from other activities and the atmospheric concentration of other greenhouse gases.

Global indicator relationships

Global indicator results for each of the base case scenarios are shown in table 16. Compared with baseline, carbon dioxide emission growth is reduced under each of the three tax scenarios, and the reductions increase as more regions join the tax club. In 2100, an OECD tax reduces emissions by 24 per cent in that year, a global tax excluding China reduces emissions by 47 per cent, and under a global tax emissions decline by 63 per cent relative to baseline.

16 Base case global indicator results a

		CO2	*CO2/E*	*E/GNP*	*CO2/GNP*	*GNP*	*CUMCO2*
Scenario	**Year**	index	index	index	index	index	ppm
Actual	1975	100	100	100	100	100	339
Baseline	2050	194	72	38	27	718	473
OECD tax	2050	163	64	36	23	714	457
Global tax exc. CPE	2050	129	55	33	18	704	440
Global tax	2050	109	49	32	16	697	427
Baseline	2100	331	79	22	17	1 908	612
OECD tax	2100	252	66	20	13	1 892	567
Global tax exc. CPE	2100	175	49	19	9	1 870	521
Global tax	2100	124	37	18	7	1 845	492
Annual growth rates 1975–2050							
		%	%	%	%	%	%
Baseline		0.89	–0.44	–1.29	–1.73	2.66	0.45
OECD tax		0.66	–0.59	–1.36	–1.95	2.66	0.40
Global tax exc. CPE		0.34	–0.80	–1.45	–2.24	2.64	0.35
Global tax		0.12	–0.94	–1.52	–2.44	2.62	0.31
Annual growth rates 2050–2100							
Baseline		1.07	0.20	–1.08	–0.89	1.97	0.52
OECD tax		0.87	0.05	–1.13	–1.08	1.97	0.43
Global tax exc. CPE		0.61	–0.21	–1.13	–1.33	1.97	0.34
Global tax		0.25	–0.56	–1.13	–1.63	1.97	0.28

a Variable definitions were given in section 4.5. In 1975 *CO2* = 4.697 Gt of carbon, *E* = 251 exajoules and *GNP* = 6.056 trillion 1975 US dollars.

Carbon dioxide concentrations in the atmosphere are reduced by far smaller amounts, however. By 2100 cumulative emissions are minimally 7 per cent below baseline under an OECD tax and maximally 20 per cent below baseline under a global tax.

The global tax scenario is obviously the most effective tax scenario when considering the reduction in cumulative emissions alone.

Carbon taxes create relative price wedges favouring clean fuels and less carbon intensive fuels. Their effectiveness in promoting energy switching depends on the strength of interfuel substitution possibilities. Carbon taxes also typically promote energy conservation by raising the relative price of energy compared with other inputs, so encouraging input switching away from energy. As modelled, when the price of energy services rises this also tends to reduce GNP. In addition, when the price of composite energy input rises this promotes investment in and development of energy efficient technologies. Further, the imposition of a carbon tax in OECD regions promotes energy service transfer from JANZ.

Taking snapshots at 2050 and 2100, the level of world GNP is only marginally reduced from baseline under all of the tax scenarios (see table 16). World GNP falls because real energy service prices rise on average across the globe with global carbon taxation. The reductions in GNP from baseline increase as more regions cooperate in carbon taxation. In undiscounted 1975 dollars, the cost of a global tax is US$1.26 trillion ($10^{12}$) in 2050 and US$1.03 trillion in 2100. In 2100 real GNP is, minimally, 1 per cent below baseline under an OECD tax, and, maximally, 3 per cent below baseline under global cooperation. This result is discussed further below.

In all tax scenarios the global carbon intensity of GNP falls compared with baseline. The decline in the carbon intensity of GNP reflects the rise in carbon conservation. As more regions cooperate the rate of decline in the global carbon intensity of GNP accelerates. The carbon intensity of GNP comprises the carbon intensity of energy and the energy intensity of GNP. Minimally, under an OECD tax the global carbon intensity of energy and the energy intensity of GNP are 16 per cent and 9 per cent, respectively, below baseline in 2100. The fall in the carbon intensity of energy indicates the rise in energy switching, that is, the energy mix moves towards less carbon intensive fuels. The fall in the energy intensity of GNP indicates the rise in energy conservation. Maximally, under a global tax global energy switching and energy conservation are 53 per cent and 18 per cent higher than baseline in 2100.

Compared with the baseline, between 1975 and 2050 all carbon taxes reduce the global carbon intensity of energy, and so accelerate global energy switching towards less carbon intensive fuels. However, carbon intensity is not always reduced over the period 2050–2100, reflecting different interfuel substitution possibilities between regions in that period. Compared with the baseline, between 2050 and 2100 the OECD tax only slows the rate of growth in the global carbon intensity of energy and so only slows the rate of global penetration of carbon-based energy. This reflects weak substitution prospects in the OECD over this period. By contrast, between 2050 and 2100 the addition of ROW and SEA to the tax agreement reduces the global carbon intensity of energy from its baseline value. Since the energy service sector is modelled in aggregate in non-OECD regions fuel substitution prospects are implicitly stronger in these regions compared with the OECD. Furthermore, the addition of China to the tax agreement means a further decline in global carbon intensity of greater size than that resulting from the addition of ROW and SEA.

Compared with baseline, over both subperiods all carbon taxes reduce the global energy intensity of GNP and so accelerate global energy conservation. Between 1975 and 2050 the rate of global energy conservation increases as more regions cooperate in carbon taxation. Between 2050 and 2100 it is largely only the OECD, and its tax policy, which affect the global rate of energy conservation. In the baseline scenario regional and global economic growth rates are stronger between 1975 and 2050 than between 2050 and 2100, and this pattern is reflected in growth in energy demand. Hence, the impact of carbon taxation on energy service price is a relatively weaker channel for energy conservation over the second period such that energy service transfer from JANZ becomes the dominant channel by which carbon taxation promotes energy conservation relative to baseline.

Energy demand mix

Base case results for the energy demand mix are shown in table 17. Relative to baseline, under each tax scenario global primary energy demand declines due to increased energy conservation and the extent of the decline grows as more regions join the tax club. However, it is the composition of the energy demand mix rather than energy demand itself which is the more responsive to carbon taxation.

Even under a global tax, when energy conservation is strongest, world energy demand increases by 1.1 per cent a year between 1975 and 2050, and averages 0.8 per cent growth per year between 2050 and 2100. In this case contractions in world energy demand from baseline average 0.3 and 0.1 per cent a year over the first and second periods. By comparison, in the same instance, carbon dioxide emissions decline by 0.8 per cent a year relative to baseline over both periods.

The primary energy switching effect of taxation is from coal to clean fuels. This result follows since the combined world energy market share of oil and gas is relatively insensitive to the carbon taxes modelled. The rate of tax applied to coal is set at a higher rate than for oil and gas since coal combustion has a higher carbon release per unit of energy. Hence, the tax rate setting is designed to encourage a stronger shift in the energy mix away from coal to clean fuels than from conventional oil and gas to clean fuels. However, as noted in section 4.4, as modelled the carbon tax is imperfect as all coal is taxed at one rate, whereas synthetic liquids and gases produced from coal have higher carbon emission release coefficients, and a similar imperfection arises for shale oil.

A further reason for the primary switching effect being from coal to clean fuels is that potential interfuel substitution possibilities between oil and gas and clean fuels are generally weaker than for conventional coal and clean fuels. While clean fuels can be readily substituted for conventional coal in electricity generation, liquid fuel substitution possibilities are limited. As less low cost conventional oil and gas reserves are available in the period 2050–2100, use of those fuels is increasingly concentrated in applications where few alternatives are available. Coal is the main resource used in the baseline in 2100 as low cost reserves of oil and gas are by then depleted.

Under a global tax the share of clean fuels in world energy demand is projected to be 50 per cent in 2100 and of coal 40 per cent, up and down 20 percentage points respectively from the baseline scenario. While the global rate of coal market penetration declines relative to baseline, world coal demand growth remains strong under all tax scenarios. Minimally, under a global tax, the average annual rate of expansion in world coal demand is 0.8 per cent over the years 1975–2050 and 2.0 per cent

17 Base case results for energy demand mix [a]

		COAL/E						CF/E					
Scenario	**Year**	**World**	**OECD**	**JANZ**	**CPE**	**SEA**	**ROW**	**World**	**OECD**	**JANZ**	**CPE**	**SEA**	**ROW**
		share	share	share	share	share	share	share	share	share	share	share	share
Actual	1975	0.2	0.1	0.1	0.8	0.3	0.3	0.1	0.1	0.1	0.0	0.10	0.10
Baseline	2050	0.3	0.2	0.3	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.3	0.3
OECD tax	2050	0.3	0.2	0.2	0.4	0.4	0.2	0.3	0.4	0.4	0.2	0.3	0.2
Global tax exc. CPE	2050	0.2	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.4	0.2	0.4	0.3
Global tax	2050	0.2	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.4	0.3	0.4	0.3
Baseline	2100	0.6	0.6	0.6	0.7	0.7	0.5	0.6	0.3	0.3	0.2	0.2	0.4
OECD tax	2100	0.5	0.4	0.4	0.6	0.6	0.4	0.5	0.5	0.5	0.2	0.2	0.4
Global tax exc. CPE	2100	0.4	0.3	0.4	0.6	0.5	0.3	0.4	0.5	0.4	0.2	0.5	0.5
Global tax	2100	0.4	0.3	0.4	0.4	0.5	0.3	0.4	0.5	0.5	0.4	0.5	0.5
		OIL/E + GAS/E						E					
		share	share	share	share	share	share	index	index	index	index	index	index
Actual	1975	0.7	0.8	0.7	0.2	0.6	0.6	100	100	100	100	100	100
Baseline	2050	0.4	0.5	0.5	0.4	0.3	0.5	271	211	294	717	827	199
OECD tax	2050	0.4	0.5	0.4	0.4	0.3	0.6	255	182	254	709	829	205
Global tax exc. CPE	2050	0.4	0.5	0.4	0.5	0.3	0.5	235	186	257	708	645	159
Global tax	2050	0.4	0.5	0.4	0.4	0.3	0.5	222	187	257	516	649	159
Baseline	2100	0.1	0.2	0.1	0.1	0.1	0.1	417	293	488	1013	1726	333
OECD tax	2100	0.1	0.1	0.1	0.2	0.1	0.1	384	246	395	988	1646	328
Global tax exc. CPE	2100	0.2	0.2	0.2	0.2	0.1	0.2	355	259	410	967	1191	274
Global tax	2100	0.2	0.2	0.1	0.2	0.1	0.1	331	260	407	694	1180	266

[a] Variables were defined in table 14.

over the years 2050–2100. As in the baseline scenario, world coal demand growth remains very strong in the second period due to the economic depletion of low cost conventional oil and gas reserves.

In general, compared with baseline regional market penetration of clean fuels rises when a region joins the tax club. By 2100, in OECD regions, market penetration is largest under an OECD tax. For SEA and ROW penetration is 30 percentage points above baseline by 2100 when these regions join, irrespective of participation by CPE. When China joins its clean fuel share of domestic primary energy demand rises by 20 percentage points by 2100.

World fossil fuel prices

Base case results for world fossil fuel price movements are given in table 18. When a carbon tax is imposed, relative prices for fossil fuels fall relative to baseline because of lower demand. Across the tax scenarios, world price declines from baseline are largest for oil, followed by gas and then coal. This pattern of results is consistent with an assumption that, relative to demand, the price responsiveness of world coal supply is much stronger than that for oil and gas. In general, if more regions join the tax club world fossil fuel prices decline further from baseline, but the world coal price remains the least sensitive to taxation.

18 Base case world fossil fuel price movements

Scenario	Prices [a]	Units	1975	2050	2100
Baseline	*OIL*	index	100	233	297
	GAS	index	100	368	706
	COAL	index	100	153	200
	OIL/COAL	ratio	3.61	5.50	5.35
	GAS/COAL	ratio	1.24	2.97	4.36
OECD tax	*OIL*	% of baseline		–9.79	–7.14
	GAS	% of baseline		–6.90	–3.82
	COAL	% of baseline		0.00	–2.94
	OIL/COAL	% of baseline		–9.79	–4.33
	GAS/COAL	% of baseline		–6.90	–0.91
Global tax exc. CPE	*OIL*	% of baseline		–16.55	–20.15
	GAS	% of baseline		–11.21	–3.82
	COAL	% of baseline		0.00	–2.94
	OIL/COAL	% of baseline		–16.55	–17.73
	GAS/COAL	% of baseline		–11.21	–0.91
Global tax	*OIL*	% of baseline		–18.41	–16.85
	GAS	% of baseline		–13.36	–5.17
	COAL	% of baseline		–1.28	–6.86
	OIL/COAL	% of baseline		–17.36	–10.72
	GAS/COAL	% of baseline		–12.24	1.81

[a] As calibrated in ERM, in 1975 the world price of oil in 1975 dollars was US$1.84/GJ, the world price of gas was US$0.63/GJ and the world price of coal was US$0.51/GJ.

Compared with baseline, in 2050 and 2100 an OECD tax increases the world price of coal relative to both oil and gas. In 2050 this trend strengthens with greater tax cooperation. In 2100 if SEA and ROW are included in the tax club only the relative price of coal to oil increases further relative to baseline. In 2100 the addition of CPE reduces the relative price of coal to gas and increases the relative price of coal to oil compared with the baseline.

Regional indicator relationships

Base case regional indicator results are shown in table 19. The primary effect of an OECD tax is to reduce emissions in the OECD via energy switching and energy conservation. Under an OECD tax, CO2 emissions in the OECD drop by 45 per cent relative to baseline by 2100, or by about 0.5 percentage point a year over the projection period. JANZ, as a member of the OECD, experiences similar emission contractions.

As modelled, GNP in OECD regions declines if the real price of energy services rises. The declines in OECD real incomes due to OECD taxation are marginal and effects on average annual economic growth rates are almost negligible. In 2100 real GNP in the

19 **Base case regional indicator results, 1975–2100 a**

Scenario	OECD	JANZ	CPE	SEA	ROW
	%	%	%	%	%
			CO2		
OECD tax	–0.48	–0.51	0.04	0.08	–0.14
Global tax exc. CPE	–0.50	–0.56	0.16	–0.84	–1.05
Global tax	–0.61	–0.59	–0.57	–1.03	–1.25
			GNP/CAP b		
OECD tax	–0.02	–0.02	0.00	0.00	0.00
Global tax exc. CPE	–0.01	–0.01	0.01	–0.03	–0.03
Global tax	–0.01	–0.01	–0.05	–0.04	–0.03
			E/GNP		
OECD tax	–0.12	–0.15	–0.02	–0.04	–0.01
Global tax exc. CPE	–0.09	–0.13	–0.05	–0.26	–0.13
Global tax	–0.08	–0.13	–0.25	–0.26	–0.15
			CO2/E		
OECD tax	–0.34	–0.34	0.06	0.11	–0.12
Global tax exc. CPE	–0.40	–0.42	0.19	–0.53	–0.88
Global tax	–0.51	–0.44	–0.26	–0.70	–1.06

a Annual percentage point deviations from baseline. Variables were defined in section 4.5. **b** Per person income changes also equal GNP changes.

OECD is only 2 per cent below baseline. Interfuel substitution dampens the effect of the tax on the price of energy services, as does energy conservation. In addition, since the OECD is generally a large net energy importer in the baseline scenario, its reduced demand for fossil fuels depresses world fossil fuel prices.

As modelled, regions are linked through trade in fossil fuels and through per person income and energy service technology convergence. Compared with the baseline, it might be expected that the decline in world fossil fuel prices due to OECD taxation would increase carbon-based energy demand in other large consuming regions due to favourable price and income effects. Between 1975 and 2100, under an OECD tax, the carbon intensities of energy demand in non-OECD Asia rise on average by around 0.1 percentage point a year relative to baseline. Energy demand declines marginally relative to baseline in non-OECD Asia.

As modelled, technology transfer at the macroeconomic level from the OECD to other regions is proxied by per person income convergence. For major energy consuming regions an increase in energy service price reduces GNP, all else constant. If GNP falls in the OECD and/or if GNP in non-OECD Asia rises this tends to depress per person income convergence to preserve baseline relativities. Hence, an OECD tax slows down the rate of aggregate technology transfer from the OECD to other major energy importing regions. The converse argument applies to energy service technology transfer. That is, an OECD tax speeds up energy service technology transfer from JANZ to other regions. As a result of these technology transfer adjustments income growth in non-OECD regions is largely unchanged from baseline and energy service convergence tends to preserve baseline energy intensities. In fact the energy intensities of GNP in non-OECD Asia fall marginally relative to baseline.

Under an OECD tax, average emission growth in ROW contracts by 0.1 percentage point a year relative to baseline. When OECD demand declines, major fossil fuel production regions search for other export markets in non-OECD regions. To the extent that these opportunities are limited, fossil fuel prices tend to decline. Energy consumption in producing regions does not accelerate due to energy service transfer adjustment. For major energy producing regions an increase in energy service price increases GNP, all else constant. Hence, in ROW per person income convergence speeds up to preserve baseline relativities under an OECD tax. Carbon intensities of GNP and of energy tend to decline where export opportunities are limited.

If the ROW and SEA enter the tax club, that is, under a global tax which excludes only CPE, annual growth in emissions drop by about 1 per cent a year for ROW and SEA relative to baseline and emission growth in CPE rises by 0.2 per cent a year relative to baseline. With the exception of EUSSR, the imposition of the carbon tax in ROW tends to stimulate net exports from this bloc and reduce world prices. Since CPE is the only untaxed source for exports this tends to limit further world price falls.

If CPE enters the tax club, that is, under a global tax, average emission growth in this region declines by 0.6 per cent a year relative to baseline due to energy conservation and energy switching. Since all regions are subject to similar taxation, global carbon emission growth declines most in this simulation. As trade leakages of carbon intensive energy are most limited, the carbon intensities of energy are lowest in all regions in this scenario.

Overall, free rider incentives across the tax scenarios appear limited. As modelled, changes in the growth rates of per person income and relative per person incomes are fairly insensitive to the degree of global cooperation in carbon taxation. The level of real incomes declines only marginally when regions join the tax club and there is marginal acceleration in emission growth when some regions refrain.

Relative to baseline, energy conservation typically expands under each tax scenario although conservation intensifies when regions cooperate. Also, as expected, energy switching forces intensify when regions join the tax club and weaken if they do not, that is, the relative price of carbon based energy becomes more expensive or cheaper than baseline.

Net energy trade

Base case results for regional net trade in 2100 are shown in table 20. As expected, compared with baseline carbon taxation reduces net energy trade in fossil fuels and, as simulated in 2100, trade declines as cooperation in carbon taxation increases. The trade reduction in 2100 from an OECD tax is a 22 per cent fall from baseline, and the additional tax scenarios each reduce net energy trade by about half this amount.

The dominant impact of the OECD tax in 2100 is to reduce net energy imports into WEUR from EUSSR. If SEA and ROW enter the tax club net energy imports into SEA decline but rise in the OECD region. Net energy exports drop further in EUSSR but rise in the Middle East, Africa and Latin America. The addition of China, which completes the global tax club, reduces net energy imports into CPE and reduces previous tax induced gains in net energy exports from the Middle East. By adding China to the tax club energy imports increase in the OECD and net energy exports rise from EUSSR.

Only net coal trade consistently declines in 2100 under all tax club scenarios. The largest absolute reduction in net coal trade in 2100 arises when SEA and ROW join the tax club. In 2100, under an OECD tax net coal exports from EUSSR to the OECD fall. If the ROW and SEA join the tax club net coal import demand declines in both SEA and CPE and there are corresponding declines in net coal exports from EUSSR. The least developed African and Latin American regions in the ROW bloc become minor net coal exporters and export supply declines symmetrically in the USA. The addition of CPE, which completes the global tax club, has a marginal effect on net coal trade in 2100 since reduced net demand in CPE tends to be offset by increased demand in the OECD. Irrespective of the tax club scenario, in 2100 the major net coal exporter and major net coal importer are expected to be EUSSR and CPE. However, coal trade potential in SEA and the USA is strongly influenced by carbon taxation.

The impacts of carbon taxation on gas trade are similar to those for coal. An OECD tax results in lower imports

20 Base case results for regional net trade in 2100

	COAL				*GAS*			
Region	Scenario				Scenario			
	Baseline	OECD tax	Global tax exc. CPE	Global tax	Baseline	OECD tax	Global tax exc. CPE	Global tax
	EJ	EJ	EJ	EJ	EJ	EJ	EJ	EJ
USA	–55.07	–58.42	–23.58	–3.08	–16.13	–17.12	–3.54	2.89
WEUR	38.55	16.29	7.53	16.48	26.47	9.55	5.72	8.62
JANZ	5.62	0.14	9.33	7.70	0.56	–1.19	2.17	1.62
EUSSR	–102.96	–71.28	–25.17	–32.94	–39.53	–19.86	–4.54	–7.84
CPE	56.07	57.02	41.43	22.50	17.05	18.20	10.71	6.10
MIDE	2.31	2.27	0.55	0.49	1.54	1.64	0.65	0.62
AF	6.75	6.73	–9.54	–9.51	3.35	3.72	–2.03	–2.14
LA	5.32	5.24	–8.03	–11.94	1.26	-0.40	–6.44	–7.83
SEA	43.73	42.03	7.61	10.32	5.58	5.47	–2.66	–2.04
Total	158.03	129.7	66.32	57.48	55.65	38.58	19.21	19.84

	OIL				*TOTAL*			
Region	Scenario				Scenario			
	Baseline	OECD tax	Global tax exc. CPE	Global tax	Baseline	OECD tax	Global tax exc. CPE	Global tax
	EJ	EJ	EJ	EJ	EJ	EJ	EJ	EJ
USA	32.38	28.74	48.59	48.85	–38.82	–46.80	21.47	48.65
WEUR	32.84	6.70	17.60	17.25	97.86	32.54	30.85	42.35
JANZ	9.70	4.85	10.33	9.38	15.88	3.79	21.83	18.70
EUSSR	–25.94	7.86	12.50	0.94	–168.43	–83.28	–17.21	–39.83
CPE	28.88	29.29	39.17	19.39	102.00	104.51	91.30	47.99
MIDE	–74.67	–84.25	–117.85	–89.73	–70.82	–80.35	–116.65	–88.62
AF	–20.96	–9.43	–10.95	–9.48	–10.86	1.01	–22.52	–21.12
LA	11.39	6.46	–3.15	0.40	17.97	11.30	–17.62	–19.37
SEA	6.46	9.78	4.34	3.01	55.77	57.28	9.29	11.28
Total	121.56	93.69	131.96	99.21	335.24	261.96	217.49	176.53

from EUSSR into Western Europe but little change elsewhere. Adding ROW and SEA to the tax club results in CPE and WEUR imports as well as USA and EUSSR exports declining, while Africa, Latin America and SEA become exporters.

As expected, even in 2100 the major impacts of carbon taxation on oil trade are dominated by developments in the Middle East. Admittedly, as for other internationally traded fuels, an OECD tax reduces OECD net imports of oil at the expense of EUSSR which becomes a net oil importer. However, when a tax is imposed in the Middle East export supply rises sufficiently in this region such that net oil trade exceeds the tax free baseline volume in 2100. However, when CPE completes the tax club export supply in the Middle East falls back toward the value projected under an OECD tax.

5.3 Uncertainty analysis

Reference scenarios from which to assess the effectiveness of potential greenhouse policies are characterised by uncertainty which in turn may impact on policy outcomes. In this section the sensitivity of results to uncertain technology convergence, energy demand response and new technology environments is considered.

Technology convergence scenarios

Two forms of technology transfer, or technology convergence, are juxtaposed in the study. Per person income convergence is used to proxy macroeconomic level technology transfer from USA to other regions, which increases world economic growth and carbon dioxide emissions, other factors held constant. Energy service intensity convergence is used to proxy energy specific technology transfer from JANZ to other regions, which decreases carbon dioxide emissions other factors held constant.

Five technology convergence scenarios are considered in both the absence and presence of carbon taxation. The first three scenarios combine nil, moderate and strong per person income convergence assumptions with corresponding energy convergence assumptions. These scenarios are referred to as nil, moderate and strong convergence scenarios. Note that moderate convergence refers to the baseline or a carbon tax base case scenario. Two additional scenarios pertain to asymmetric convergence assumptions. That is, nil per person income convergence is paired with strong energy service convergence or strong per person income convergence is coupled with nil energy service convergence. These two scenarios are referred to as strong energy service convergence and strong per person income convergence scenarios. Scenario settings were given in table 12.

Selected global results from the technology convergence scenarios are shown in table 21. Detailed results are given in appendix C.

In the absence of carbon taxation, under nil convergence, growth in world GNP is projected to average around 2.2 per cent a year between 1975 and 2100. Cumulative carbon dioxide emission growth is 0.45 per cent a year and annual carbon emission growth averages 0.9 per cent a year. Under nil convergence cumulative emissions approximate the global warming benchmark of 600 ppm by 2100.

Comparing nil convergence with the moderate baseline assumption, on average nil convergence reduces world GNP growth by 0.2 percentage point a year while annual carbon dioxide emissions and cumulative emissions fall by 0.1 and 0.02 percentage point a year respectively. In this case in 2100 world GNP is 22 per cent lower, annual carbon dioxide emissions are 11 per cent lower and cumulative emissions are 3 per cent

21 Global highlights from the technology convergence scenarios

	CUMCO2			CO2		GNP	
Scenario	ppm [a]	index [b]	% [c]	index [b]	% [c]	index [b]	% [c]
Description							
(i) *No tax policy*							
nil convergence	597	176	0.45	295	0.87	1 483	2.18
moderate [d]	612	181	0.47	331	0.96	1 908	2.39
strong	643	190	0.51	405	1.13	2 325	2.55
strong energy service	571	168	0.42	242	0.71	1 488	2.18
strong income	688	203	0.57	508	1.31	2 320	2.55
(ii) *OECD carbon tax*							
nil convergence	555	164	0.40	223	0.65	1 471	2.17
moderate [d]	567	167	0.41	252	0.74	1 892	2.38
strong	594	175	0.45	313	0.92	2 304	2.54
strong energy service	532	157	0.36	181	0.47	1 478	2.18
strong income	635	187	0.50	402	1.12	2 296	2.54
(iii) *Global carbon tax exc. CPE*							
nil convergence	516	152	0.34	162	0.38	1 451	2.16
moderate [d]	521	154	0.34	175	0.45	1 870	2.37
strong	537	158	0.37	203	0.57	2 273	2.53
strong energy service	497	147	0.31	125	0.18	1 453	2.16
strong income	567	167	0.41	261	0.77	2 295	2.54
(iv) *Global carbon tax*							
nil convergence	489	144	0.29	123	0.16	1 437	2.16
moderate [d]	492	145	0.30	124	0.17	1 845	2.36
strong	505	149	0.32	152	0.34	2 256	2.52
strong energy service	476	140	0.27	101	0.01	1 444	2.16
strong income	529	156	0.36	201	0.56	2 250	2.52

a Measured at 2100. **b** Measured at 2100. Index base 1975=100. **c** Annual average percentage change between 1975 and 2100. **d** 'Moderate convergence': baseline or corresponding base case scenario.

lower if nil rather than moderate convergence is assumed.

Comparing strong convergence with baseline, on average world GNP expands by 0.2 percentage points a year while annual emissions and cumulative emissions increase by 0.2 and 0.04 percentage point a year respectively. In this case in 2100 world GNP is 22 per cent higher, annual carbon dioxide emissions are also 22 per cent higher and cumulative emissions are 5 per cent higher due to strong rather than baseline convergence. In 2100 cumulative emissions are 31 ppm in excess of baseline under strong convergence.

On the basis of the last two comparisons, the effect of technology transfer on economic growth is an important determinant of CO_2 emissions. Further, the rate of emission growth rises with greater convergence.

To highlight the sole role of the energy service technical convergence assumption the results from strong energy service convergence may be compared with nil convergence. For a common growth rate in world GNP of

2.2 per cent a year, strong energy service convergence reduces annual and cumulative carbon dioxide emission growth by 0.2 and 0.03 percentage point a year respectively. In this case in 2100 cumulative emissions are 4 per cent lower and annual carbon emissions 18 per cent lower due to strong energy service convergence given a nil per person income convergence assumption. In 2100 cumulative emissions are 26 ppm lower due to strong rather than nil energy service convergence.

To highlight the sole role of the per person income convergence assumption the results from strong per person income convergence may be compared with nil convergence. For a 0.4 percentage point improvement in world GNP growth, cumulative emission growth expands by 0.12 percentage point a year and carbon emissions expand by 0.4 percentage point a year. In this case in 2100 cumulative emissions are 15 per cent higher and annual emissions are 72 per cent higher due to per person income convergence given a nil energy service convergence assumption. In 2100 cumulative emissions are 91 ppm higher due to strong rather than nil per person income convergence. However, if strong energy service convergence is added to strong per person income convergence this increase is halved.

Hence, while economic growth due to per person income convergence increases fossil fuel demand and so adds to emission growth, strong energy service convergence, which increases energy efficiency, appears to act as a useful brake. However, equal incremental improvements in the convergence forces are far from offsetting influences on cumulative emissions.

As simulated, it is apparent that even marginally inaccurate estimates of long run world economic growth will be strongly magnified in terms of the long run outcome for the absolute level of cumulative emissions. It is also clear from the results that as per person income convergence increases, energy service efficiency transfer gains must rise much more sharply to keep the absolute level of cumulative emissions from expanding markedly. That is, if energy conservation is the main source of carbon dioxide emission control, with economic growth off a higher base energy conservation growth must intensify to meet a set target.

For any given convergence assumption, an OECD tax reduces cumulative carbon dioxide emission growth by about 0.1 percentage point a year relative to the no tax outcome. In addition, as more regions cooperate cumulative emission reductions increase. As modelled, the maximum reduction in cumulative emissions over the corresponding no tax baseline in 2100 is around 20 per cent, which is realised under a global tax. Real world GNP growth is only marginally reduced by this level of carbon tax. That is, partial equilibrium feedbacks from the energy sector to global economic growth are fairly insensitive to the convergence assumptions for the given tax rate. Hence, as modelled, the effectiveness of the carbon tax policies in reducing cumulative emission growth does not appear to hinge on reducing world economic growth but rather on carbon conservation.

However, it is also clear that uncertainty in estimating the critical benchmark has significant consequences for setting the tax rate. The tax rate used will depend on the emission target and the absolute level of cumulative emissions in the long run is strongly sensitive to per person income convergence. For any given convergence assumption, each of the global taxes modelled achieves a cumulative emission outcome in 2100 below 600 ppm and achieves a roughly equal percentage reduction in cumulative emissions relative to the corresponding no tax outcome. However, a common percentage change implies a larger absolute reduction from a series with a higher base. That is, the losses to global GNP are obviously greater when there is stronger per person income convergence, and emission reductions are also larger. Stronger than expected convergence will result in an under-estimate of cumulative emissions and world economic activity. Symmetrically, low convergence will result in an overestimate of the actual outcomes for cumulative emissions and world GNP.

Hence, setting an appropriate carbon tax rate depends critically on estimating accurately the level of world GNP and the degree of convergence in per person incomes. It also follows that achieving a particular emission target from a stronger emission base will require an increase in the tax rate and a stronger percentage contraction in GNP. Further, as modelled, policies which promote energy service convergence will reduce the actual tax rate setting required to achieve a particular emission target.

Price and income response scenarios

One of the problems of achieving a particular greenhouse carbon dioxide concentration target by using economic measures such as carbon taxes is uncertainty regarding price and income response parameters in aggregate energy service demand. The effect of variations in these parameters is now examined.

The price response scenarios are considered in both the absence and presence of an OECD tax. In these scenarios the aggregate price elasticity of demand for energy services is varied. As noted in section 4.4, the price elasticity measures the percentage reduction in energy service demand due to a 1 per cent increase in price, all else constant. From table 12, the settings for the price elasticity are: –0.05 (weak), –0.7 (moderate) or –1.30 (strong). Similarly, three income response scenarios are considered in both the absence and presence of an OECD tax. In these scenarios the income elasticity of demand for energy services is varied. The income elasticity measures the percentage increase in energy service demand due to a 1 percentage point increase in real income, all else constant. From table 12, in OECD regions the settings for the income elasticity are: 0.2 (weak), 1.0 (default) or 1.4 (strong). In EUSSR the income settings are: 0.2 (weak), 1.25 (default) or 1.8 (strong). In all other regions the income settings are: 0.5 (weak), 1.4 (default) and 2.2 (strong). Note that moderate settings for price and income response parameters refer to the baseline or an OECD tax base case scenario.

Global indicator results from these scenarios are given in table 22. As expected, in the absence of tax, and given price responsive energy supply, energy demand and cumulative emissions rise with stronger income

22 **Global results from the price and income response scenarios**

Description	Actual scenario	Reference scenario		Annual percentage point deviations from reference scenario, 1975–2100						
			CUMCO2	CUMCO2	CO2	GNP	CO2/ GNP	E	E/GNP	CO2 /E
			ppm **a**	%	%	%	%	%	%	%
(a) No tax policy										
(i) Price response **b**										
	strong	moderate	546	–0.09	–0.35	0.01	–0.36	–0.24	–0.24	–0.12
	weak	moderate	761	0.17	0.49	0.00	0.49	0.36	0.36	0.13
(ii) Income response **b**										
	strong	moderate	1104	0.47	1.09	–0.01	1.11	0.98	0.99	0.11
	weak	moderate	412	–0.32	–2.04	0.04	–2.07	–1.67	–1.70	–0.37
(b) OECD carbon tax										
(i) Price response										
(1) given certainty **c**										
	strong	strong	505	–0.06	–0.26	–0.01	–0.25	–0.09	–0.09	–0.16
	moderate	moderate	567	–0.06	–0.22	–0.01	–0.21	–0.07	–0.06	–0.15
	weak	weak	711	–0.05	–0.15	–0.01	–0.14	–0.02	–0.01	–0.13
(2) given uncertainty **d**										
	strong	moderate	505	–0.09	–1.95	0.04	–1.99	–1.31	–1.35	–0.13
	weak	moderate	711	0.18	0.56	0.00	0.57	0.41	0.41	–0.15
(ii) Income response										
(1) given certainty **c**										
	strong	strong	1014	–0.07	–0.10	–0.01	–0.09	–0.04	–0.03	–0.06
	weak	weak	403	–0.02	–0.11	0.00	–0.11	0.02	0.03	–0.14
(2) given uncertainty **e**										
	strong	moderate	1014	0.47	1.21	–0.01	1.23	1.01	1.02	–0.12
	weak	moderate	403	–0.27	–1.93	0.04	–1.97	–1.57	–1.62	–0.07

a Refers to absolute value for actual scenario measured at 2100. **b** Comparison is with scenario in which response is moderate: namely, the baseline scenario (see tables 16–20). **c** Comparisons are with corresponding no-tax scenarios. **d** Comparisons are with the same tax policy but with moderate price response. **e** Comparisons are with the same tax policy with moderate income response.

responsiveness or weaker price responsiveness of demand for energy services. Indeed, if income response parameters are strong, cumulative emissions rise by 0.47 percentage point a year relative to a baseline in which moderate income responsiveness of energy demand is assumed. In this case, by 2100 cumulative emissions are about 500 ppm in excess of the global warming benchmark if income elasticities are strong rather than moderate.

As modelled, income response parameters have a critical influence on cumulative emission growth. The results for cumulative emissions would be even larger than 1100 ppm if the moderate convergence baseline assumption was replaced by strong development pressures in non-OECD regions. If in the course of development the income responsiveness of energy demand in non-OECD regions is strong, major improvements in regional energy efficiency and associated technology transfer could be needed to curtail strong emission growth.

Compared with a tax free baseline, a decrease in price elasticity only marginally weakens the annual rate of decline in cumulative emissions under an OECD tax. Besides the direct price effect, a carbon tax may also curb cumulative emission growth by reducing individual real purchasing power. As modelled this income effect is relatively weak such that an increase in income elasticity only marginally retards cumulative emission growth. However, in both cases the tax free baseline has strong cumulative emission growth.

Uncertainty in estimating the income and price responsiveness of energy demand critically influences the effectiveness of a carbon tax in achieving a particular greenhouse cumulative emission target. For example, if an OECD tax is put in place and income responsiveness is thought to be moderate when in fact it is strong, carbon conservation will be sharply retarded relative to expectations. In this case, instead of a projected outcome for cumulative emissions of 567 ppm in 2100, cumulative emissions would be 1014 ppm according to the model.

As modelled, the rate of carbon tax required to achieve a particular cumulative emission target rises sharply with income elasticity and falls with the price elasticity of demand for energy services. The downside risk to economic growth exclusive of greenhouse damage is that the tax rate is overestimated due to overestimation of the income elasticities, which will be compounded by overestimation of per person income convergence in the developing regions. Conversely, the downside risk to economic growth due to greenhouse damage is that the tax rate is underestimated.

New technology scenarios

Besides taxing fossil fuels other possible policy responses to greenhouse pollution suggested in the literature include reducing the costs of carbon clean energy and increasing the fuel efficiency of carbon-based energy. The results of two new technology scenarios are shown in table 23 and table 24.

Given moderate convergence, in the first new technology scenario it is assumed that a major breakthrough is made in solar energy production which halves its cost of production relative to baseline and advances the time of introduction of this backstop technology. A comparison of the results from this scenario with baseline serves solely to illustrate the effectiveness of solar energy advances in curbing future CO2 emissions. As such, the change in the solar cost profile does not represent a forecast of actual solar technology costs.

Cumulative emissions do not decline markedly as a result of sharply reduced solar energy costs. By assumption a stronger cost advantage to solar energy is given in the nearer term. The technical advance sharply reduces the cost of solar relative to coal electricity in 2000. Compared with baseline, this competitive cost wedge is largest in 2000 and then levels off to around 50 per cent from 2050 onwards. If interfuel substitution possibilities between clean and carbon-based electric energy are constant, this kick-start advance would be expected to result in a strong jump in solar penetration of the electricity market in

23 Global results — reduced costs of solar energy

	Scenario: Baseline					Scenario: reduced costs of solar			
Variable a	**Units**	**1975**	**2000**	**2050**	**2100**	**Units**	**2000**	**2050**	**2100**
CUMCO2	ppm	339	376	473	612	ppm	375	467	585
CUMCO2	index	100	111	139	180	% baseline	–0.16	–1.31	–4.33
E	index	100	187	271	417	% baseline	0.42	6.63	4.26
ELEC	index	100	227	445	826	% baseline	0.98	18.50	15.13
ELEC/E	share	0.29	0.35	0.48	0.58	% baseline	0.55	11.13	10.43
CF/ELEC	share	0.29	0.38	0.49	0.51	% baseline	16.63	29.46	31.07
CIF/ELEC	share	0.71	0.62	0.51	0.49	% baseline	–10.07	–28.70	–32.55
SOLAR/CF	share	0.00	0.00	0.12	0.17	**b**	0.18	0.27	0.32
PSOLAR	1975US$/GJ	200.60	54.58	14.85	14.85	1975US$/GJ **c**	7.425	7.425	7.425
PSOLAR/COALEL	index	100	26	7	7	% baseline	–83.99	–45.20	–44.00
PELEC	index	100	113	139	154	% baseline	–0.53	–9.36	–14.97
CO2/E	index	100	88	72	79	% baseline	–2.99	–9.38	–17.57
E/GNP	index	100	81	38	22	% baseline	0.40	6.38	3.71
CO2	index	100	164	194	331	% baseline	–2.58	–9.38	–17.57

a *CUMCO2* denotes atmospheric concentration of carbon dioxide. *E* denotes primary energy demand. *ELEC* denotes electricity demand. *CF* denotes clean fuel electric energy demand. *CIF* denotes carbon intensive electric energy demand. *SOLAR* denotes solar electric energy demand. *PSOLAR* denotes primary energy price of solar in USA. *PSOLAR/COALEL* denotes relative generation costs of solar electricity compared with coal in USA. *PELEC* denotes secondary energy price of electricity in USA. **b** Absolute differences in shares. **c** Actual values in scenario.

2000, which would then level off to a higher plateau over the baseline thereafter. However, in the model interfuel substitution responses between different forms of electricity are much smaller in the nearer term due to adjustment lags. This latter effect dominates the results and is particularly apparent in the deviation from baseline of the relative price path of coal to total electricity.

In 1975 solar electricity's share of the electricity market and, hence, of the global primary energy demand market, was negligible. It remains negligible in the baseline scenario in 2000 but is 8 per cent with the solar technical advance. In the baseline, solar penetration of the electricity market is 6 per cent in 2050 and and 9 per cent in 2100. Under the solar advance, by 2050 market penetration has picked up markedly to satisfy 25 per cent of electricity demand, and by 2100, 33 per cent.

As expected, the solar advance fosters interfuel substitution within clean forms of electricity and interfuel substitution away from carbon-based electricity generation. However, interfuel substitution away from carbon-based fuels is far stronger from 2050 onwards. The real price of electricity falls only marginally in 2000. By contrast, from 2050 onwards the feedback from technical advance to the real price of electricity is strong. Overall, this makes carbon intensive electricity much less competitive and stimulates stronger interfuel substitution toward clean fuels and particularly solar.

24 Global results – increased coal conversion efficiency

	Scenario: Baseline					Scenario: Increased coal conversion efficiency			
Variable a	**Units**	**1975**	**2000**	**2050**	**2100**	**Units**	**2000**	**2050**	**2100**
CUMCO2	ppm	339	376	473	612	ppm	376	482	646
	index	100	111	139	180	%baseline	0.13	1.92	5.64
E	index	100	187	271	417	%baseline	–1.34	1.19	–0.41
ELEC	index	100	227	445	826	%baseline	–2.73	3.60	–4.06
ELEC/E	share	0.29	0.35	0.48	0.58	share	0.35	0.49	0.56
						%baseline	–1.40	2.39	–3.66
CF/ELEC	share	0.29	0.38	0.49	0.51	share	0.27	0.36	0.32
						%baseline	–29.17	–26.70	–37.35
CIF/ELEC	share	0.71	0.62	0.51	0.49	share	0.73	0.64	0.68
						%baseline	17.66	26.02	39.13
COAL/ELEC	share	0.32	0.40	0.27	0.33	share	0.47	0.35	0.46
						%baseline	18.89	28.55	39.48
(OIL+GAS)/ELEC	share	0.39	0.23	0.23	0.16	share	0.26	0.29	0.22
						%baseline	15.54	23.05	38.40
PCOAL/OILEL	index	100	94	82	77	%baseline	–1.75	–2.47	–2.01
PCOAL/SOLAREL	index	100	382	1425	1529	%baseline	–1.50	–1.74	–1.37
PELEC	index	100	113	139	154	%baseline	–1.07	–0.26	1.25
CO2/E	index	100	88	72	79	%baseline	5.10	10.20	20.08
E/GNP	index	100	81	38	22	%baseline	–1.32	1.25	–0.32
CO2	index	100	164	194	331	%baseline	3.69	11.50	19.58

a *CUMCO2* denotes atmospheric concentration of carbon dioxide. *E* denotes primary energy demand. *ELEC* denotes electricity demand. *CF* denotes clean fuel electric energy demand. *CIF* denotes carbon intensive electric energy demand. *COAL* denotes coal electric energy demand. *OIL+GAS* denotes oil plus gas electric energy demand. *PCOAL/OILEL* denotes relative generation costs of coal electricity compared with oil in USA. *PCOAL/SOLAREL* denotes relative generation costs of coal electricity compared with solar in USA. *PELEC* denotes secondary energy price of electricity *PELEC* denotes secondary energy price of electricity in USA. C02 denotes carbon dioxide emissions. *GNP* denotes world gross national product in 1975 US$.

Furthermore, with cheaper relative prices for electricity there is also strong interfuel substitution toward electric energy, which raises the electricity to primary energy demand ratio and increases the aggregate clean fuel and, particularly, solar shares of primary energy demand over baseline. The decline in the carbon intensity of energy over baseline is much larger from 2050 onwards on account of greater clean fuel market penetration. However, the decline in the real price of electricity does boost the energy intensity of gross national product somewhat.

On balance, as modelled the delayed nature and extent of the electricity demand response to the assumed solar electric cost reduction means that cumulative emissions are only marginally down on the baseline results. If the adjustment lag to a solar advance amounts to decades then other policy responses would need to be instigated to curtail the buildup in emissions during the adjustment period.

The second new technology option considers the effect on emissions of a 5 per cent increase in the conversion efficiency of coal used in electricity generation instituted in 2000. Clearly, increased efficiency reduces CO_2 emissions from coal conversion in electricity generation for a given level of throughput. However, increased efficiency amounts to an effective price reduction in coal electricity. In theory the price reduction may encourage interfuel substitution toward the cheaper coal source increasing coal throughput. The net effect on emissions would be positive if substitution possibilities are large.

As simulated, an improvement in coal conversion efficiency increases cumulative emissions of CO_2. Compared with baseline, the electric power generation costs of coal fall and there is interfuel substitution away from clean fuels and toward coal and oil and gas. Substitution away from clean fuels is readily explained as the relative cost of clean electricity rises.

However, substitution toward oil and gas is surprising. This result implies that carbon-based and non-carbon-based energy forms in the model are effectively composite alternatives in electricity generation. The efficiency advance reduces the composite price of carbon-based energy input and results in substitution toward the carbon composite. All carbon-based energy sources gain but since the efficiency advance was instituted in coal its market share expands relative to oil and gas.

While increased efficiency reduces carbon dioxide emissions for a given level of coal throughput, coal throughput and cumulative emissions rise. That is, the real price of coal is effectively lower as a result of the technical breakthrough. Given these results, technical advances in carbon-based conversion efficiency may need to be accompanied by carbon taxation in order to curtail substitution away from clean fuels and keep the level of coal throughput from rising.

5.4 Qualifications

The main qualifications to the simulation study stem from the use of a partial equilibrium modelling framework of analysis. In the study, greenhouse policy is confined to the energy sector and the implications of a range of carbon taxation alternatives and energy efficiency measures on the atmospheric concentration of carbon dioxide are considered.

In the Edmonds–Reilly model, adopted in the simulation study, only the energy sectors of the world's economies are linked through trade. However, greenhouse policy in the energy sector could alter the sectoral composition of trade, production and consumption in energy intensive and other goods and services as firms and households adjust to changes in relative energy prices. Feedbacks on energy sectors from these adjustments are implicitly assumed to be offsetting in the simulation study.

Feedback effects from climatic change associated with the enhanced greenhouse effect, although highly uncertain, could generate changes in the regional composition of energy requirements. The benefits to the energy sector from potential net damages avoided in other sectors by greenhouse management are also implicitly held fixed in the simulation study.

A cost-effective solution to greenhouse management requires consideration of trade-offs between a broad range of activities that affect the atmospheric mix of greenhouse gases. Trade-offs between activities generating CO_2 emissions outside the energy sector and of the levels of other greenhouse gases are also implicitly held constant in the simulation study.

For the above reasons a priority for future research is to expand the Edmonds-Reilly modelling framework to incorporate intersectoral linkages over space and time between the main human and natural activities which affect the potential for greenhouse warming.

Further, the results of the simulation study illustrate that the effectiveness of carbon taxation in reducing the atmospheric concentration of carbon dioxide depends on accurately projecting macroeconomic and energy specific developments over the long term. By implication, the stronger are uncontrolled emission pressures the higher is the carbon tax rate required to reduce emissions and the larger are adjustment costs to economies from emission abatement.

The downside risk to economic growth exclusive of greenhouse damages is that development pressures are weaker than expected and that abatement costs are excessive. The downside risk to economic growth from greenhouse damages is that development pressures are stronger than expected and that damage costs are excessive. Given these potential risks a combined system of transferable emission permits and carbon taxes might be used to reduce the costs of uncertainty associated with greenhouse management.

To reduce the potential risk of excessive damage a permit system might be imposed for emissions in excess of some threshold. The demand for permits would determine the permit price and, hence, the cost of abatement in this circumstance. To reduce the potential risk of excessive control costs, below the given threshold a carbon tax could be used to limit the incremental costs of emission abatement. Such a combined system to reduce the potential costs imposed by uncertainty associated with the enhanced greenhouse effect also warrants further research.

In assessing the overall contribution of this study it needs to be recognised that taxation has been the major policy instrument considered. Investment in research and development into ways of reducing emissions in relation to major fuels may also have a high effective payoff to reducing any damage that might arise from the enhanced greenhouse effect. Assessment of this alternative is left for future work.

CHAPTER 6

Conclusions

The consequences of the enhanced greenhouse effect are surrounded by uncertainty. The current state of scientific knowledge is such that many estimates of the values of important greenhouse parameters are best expressed as ranges. There is little doubt, however, that carbon dioxide is the major contributor to the enhanced greenhouse effect, and that the major source of increased carbon dioxide emissions to the atmosphere is the burning of fossil fuels. Despite the uncertainty, the potential consequences of global warming due to the enhanced greenhouse effect are such that considerable attention is being paid to the design of a policy regime which may be needed to reduce greenhouse gas emissions.

Uncertainty creates significant problems in the design of such a policy regime. The extent to which greenhouse gas emissions must be reduced to minimise potential damage costs from global warming is not known. The scale and scope of any instruments needed to achieve a given level of reductions is also not known. Finally, the effects of these instruments cannot be predicted with precision. What is clear is that international cooperation will be required for effective reductions in emissions to be achieved. Even then, however, the extent of international cooperation needed, and the impact of different levels of international cooperation, are uncertain.

One possible policy instrument to reduce carbon dioxide emissions is a carbon tax. The analysis in this paper suggests that the effectiveness of such a tax increases considerably the greater the degree of international cooperation in its imposition. The effect of a carbon tax on the atmospheric concentration of carbon dioxide will be much smaller than its effect on the level of carbon dioxide emissions, however. This result is of primary importance, since global warming depends on atmospheric concentrations of greenhouse gases, not their level of emissions at any point in time. Levels of emissions are only one part of the equation determining concentrations. Greenhouse gas sinks, of which much less is known, are of equal importance from a policy viewpoint.

Changes in the growth rates of per person incomes, and income relativities between regions, seem fairly insensitive to the degree of global cooperation in carbon taxation. Income growth and income relativities are, however, very important determinants of the growth in carbon dioxide emissions and thus of the size of carbon taxes needed to avert global warming. Technology transfer from high income and more energy efficient regions to lower income or less energy efficient regions is also of considerable importance. The greater the rate at which per person incomes converge, the faster carbon dioxide emissions grow. Transfer of energy efficient technologies can slow this rate of emissions growth, but the results of this study indicate that the rate of energy efficiency transfers must rise much more sharply than the rate of income convergence to prevent the level of cumulative emissions from rising markedly. As a result pressure for economic development in the future will tend to lead to rising carbon dioxide emission levels.

The effect of carbon taxes would seem to be not so much to reduce energy consumption or economic growth, as to encourage switching out of fossil fuels, particularly coal, to renewable and nuclear technologies with low or no carbon dioxide emissions. While overall energy consumption levels may be little affected, the regional pattern of energy trade is likely to be greatly affected under a carbon taxation regime. This change in trade may in turn have significant economic consequences not directly examined in this study.

The study results also indicate that significant reductions in the cost of energy technologies may not lead to quick reductions in atmospheric concentrations of greenhouse gases, and in some cases may even lead to an increase in greenhouse gas emissions. The conclusion to be drawn from this result is that the consequences of research and development efforts on, or calls to subsidise, certain technologies on the grounds that they could lead to reduced greenhouse gas emissions need to be examined carefully. The full implications over time of such policy measures need to be measured against all alternatives.

It is apparent that even marginally inaccurate estimates of long run world economic growth will be strongly magnified in terms of the long run outcome for the absolute level of cumulative emissions, and thus of the potential for global warming. Setting an appropriate carbon tax rate in an attempt to reduce greenhouse gas emissions depends critically on estimating accurately the level of world economic activity and the degree of convergence in per person incomes between regions. The difficulty in such accurate estimation means that any carbon tax regime would have to be administered flexibly over time, to allow for changes in economic and other circumstances.

The degree to which energy consumption is responsive to changes in economic activity and to changes in energy prices is also important in setting tax rates. The rate of carbon tax required to achieve a particular emission target rises sharply with income elasticity and falls with the price elasticity of demand for energy services. The way in which these responses will change over time as countries develop is a major area of uncertainty in greenhouse policy analysis.

Changes to ERM model

Three changes were made to the ERM model which pertain to the determination of GNP, energy service demand and technical advance in energy services. These changes are outlined below.

A.1 Determination of GNP

Standard form

The standard specification for real gross national product in region q and period t, GNP_{tq}, in ERM is given by

$$\text{(A1)} \quad GNP_{tq} = GNP_{tq}^{*} PS_{tq}^{-\delta_q}$$

where GNP_{tq}^{*} denotes desired real income, PS_{tq} is a real energy service price index, with unit base in 1975, and δ_q is the energy service feedback elasticity in region q.

Desired income in region q and period t is given by

$$\text{(A2)} \quad GNP_{tq}^{*} = LPG_{tq} LFG_{tq} GNP_{t-1q}$$

where LPG_{tq} denotes exogenously specified labour productivity growth and LFG_{tq} denotes labour force growth which is proxied by exogenous past population growth, $POPG_{t-1q}$, given by

$$\text{(A3)} \quad LFG_{tq} = POPG_{t-1q}$$

Convergence form

The convergence form for real gross national product in region q and period t is given by

$$\text{(A4)} \quad GNP_{tq} = GNP_{tq}^{**} PS_{tq}^{-\delta_q}$$

where new desired income GNP_{tq}^{**} is similar to the standard form adjusted for per person income convergence in region q toward region 1, represented by the ratio of lagged per person income in region q to lagged per person income in region 1, and is given by

$$\text{(A5)} \quad GNP_{tq}^{**} = GNP_{tq}^{*} \left(\frac{GNP_{t-1q}^{*} \,/\, POP_{t-1q}}{GNP_{t-11}^{*} \,/\, POP_{t-11}} \right)^{-\lambda_q}$$

where $0 \le \lambda_q \le 1$ and

$$\text{(A6)} \quad GNP_{tq}^{*} \,/\, POP_{tq} = LPG_{tq} GNP_{t-1q} \,/\, POP_{t-1q}$$

where $POPG_{tq}$ denotes actual population and λ_q is an exogenously specified parameter determining the degree of per person income convergence for region q.

In general, the closer λ_q is to 1 the stronger is per person income convergence. Finally, note that for the year 2000, in the convergence form, GNP_{tq}^{**} is exogenously specified in order to use the most recent historical data and medium term projections.

A.2 Determination of demand for energy services

Standard form

In ERM, energy service demand in OECD regions, indexed $q = 1,..,3$, is separated into residential and commercial, industrial and transport sector demands, indexed $k = 1,2,3$. In non-OECD regions, indexed $q = 4,...,9$, only aggregate energy service demand is modelled, indexed $k = 1$. In particular, the standard demand for energy services of type k in region q and year t, E^*_{kqt}, is given by

$$\text{(A7)} \quad E^*_{kqt} = \alpha_{kq} P_{kqt}^{-\beta_{kq}} \left(GNP_{kqt} / POP_{kqt} \right)^{\delta_{kq}} GNP_{kqt}$$

for $k = 1$, $q = 1,...,9$

$$= \alpha_{kq} P_{kqt}^{-\beta_{kq}} GNP_{kqt}^{\delta_{kq}}$$

for $k = 2$, $q = 1,2,3$

$$= \alpha_{kq} P_{kqt}^{-\beta_{kq}} \left(GNP_{kqt} / POP_{kqt} \right)^{\delta_{kq}} POP_{kqt}$$

for $k = 3$, $q = 1,2,3$

where Greek letters denote parameters and P_{kqt} is the real price of the energy service.

Convergence form

The convergence form for energy service demand of type k in region q and year t comprises the standard specification modified for aggregate energy service intensity convergence in region q toward region 3, represented by the ratio of lagged energy service demand relative to GNP in region 3 to lagged energy demand relative to GNP in region q, and is given by

$$\text{(A8)} \quad E_{kqt} = E^*_{kqt} \left(\frac{\sum_k E_{k3t-1} / GNP_{3t-1}}{\sum_k E_{kqt-1} / GNP_{qt-1}} \right)^{\mu_q}$$

where $0 \le \mu_q \le 1$ and μ_q is an exogenously specified convergence parameter.

A.3 Determination of energy service technical advance

In the case of energy service technical advance the only change was to include a price feedback elasticity, that is,

$$\text{(A9)} \quad TECH_{tq} = TECH_{tq} PS_{t-1q}^{\beta q}$$

where $\beta \ge 0$, $TECH_{tq}$ is the standard exogenously specified technical advance and β_q is the feedback elasticity.

APPENDIX B

Simplified global modelling framework

In this appendix theoretical insights into the global results of the simulation study are developed using a comparative statics model, which is presented in percentage change form. The global model is a skeletal version of the ERM model in which underlying theoretical principles are emphasised. The global model is used to highlight the global impact of fossil fuel taxation, labour force growth and various forms of technical progress on energy demand, CO_2 emissions and world GNP. The sensitivity of taxation impacts to changes in key parameters are considered.

The equations of the global model are derived from a two level nested optimisation problem with CES production structures. At the first level energy and labour inputs are used to produce GNP. Decreasing returns to scale is assumed for the level 1 CES technology to represent the ERM model assumption. The first level optimisation problem is to maximise profits from GNP allowing for technical change in labour and energy inputs (see Woodland 1982; Dixon, Parmenter, Sutton and Vincent 1982). At the second level energy is produced from a fossil fuel and a clean fuel, and the technology exhibits constant returns to scale. The second level optimisation problem is to minimise the cost of energy production allowing for technical change in fossil and clean fuel inputs. For simplicity the model abstracts from the fact that there is more than one fossil fuel and more than one clean fuel.

B.1 Equations of the global model

The model equations are expressed in linear percentage change form (see Dixon et al. 1982). For example, rather than writing:

$$y = f(x_1, x_2)$$

where y is output and x_1 and x_2 are inputs, the linear percentage change form is used:

$$\mathrm{d}y/y = (\delta f/\delta x_1).(x_1/y).(\mathrm{d}x_1/x_1)$$

$$+ (\delta f/\delta x_2).(x_2/y).(\mathrm{d}x_2/x_2)$$

which simplifies to:

$$Y = HX_1.X_1 + HX_2.X_2$$

where $Y = \mathrm{d}\ \ln y$, $X_1 = \mathrm{d}\ \ln x_1$, $x_2 = \mathrm{d}\ \ln x_2$

and HX_1 and HX_2 are elasticities which may sometimes simplify to base period shares.

The model equations are as follows.

APPENDIX B

Level 1

The GNP function

$$(B1)\quad Y = HE.E + (R-HE)L + HE.TE + (R-HE)TL$$

where $HE = pe.e/(py.y)$
and $0<R<1$ and $0<HE<R$

The price of GNP

$$(B2)\quad PY = \{HE.PE + (R-HE)PL + (1-R)Y\}/R$$

The demand for aggregate energy

$$(B3)\quad E-Y = -SY(PE-PY) + (1/R-1)(1-SY)Y - [1-SY(1-HE/R)]TE - SY(1-HE/R)TL$$

where $SY>0$

Level 2

The price of aggregate energy

$$(B4)\quad PE = HEF.PEF + (1-HEF).PEC$$

where $HEF = pef.ef/(pe.e)$
and $0<HEF<1$

The demand for fossil fuel

$$(B5)\quad EF-E = -SE(PEF-PE) - (1-SE(1-HEF))TEF - SE(1-HEF)TEC$$

and $SE>0$

The demand for clean fuel

$$(B6)\quad EC-E = -SE(PEC-PE) - (1-SE.HEF))TEC - SE.HEF.TEF$$

The price of fossil fuel

$$(B7)\quad PEF = PF + TAX$$

Equation (B1) is a log linear version of the CES production function for GNP, denoted by Y, with inputs aggregate energy E and labour L. HE denotes the value share of aggregate energy input in the production of GNP in the base year prior to any exogenous shocks to the model. The GNP function is homogeneous of degree R in E and L. Hence, a 1 per cent increase in E and L equals an R per cent increase in Y, other factors constant. In equation (B1) $R = 1$ corresponds to the special case of constant returns to scale. However, in general decreasing returns to scale ($R<1$) is assumed. Exogenous labour productivity TL and energy productivity TE also influence GNP. If $TL = TE = 1$ then technical change is neutral such that a 1 per cent increase in GNP is achieved for a given level of inputs. Note that a prefix P in front of a quantity variable denotes the corresponding price for the variable.

Equation (B2) is the 'price equals marginal cost' condition required for profit maximisation of GNP.

The demand for aggregate energy in equation (B3) follows from Shephard's lemma. The left hand side of (B3) represents the percentage change in the share of aggregate energy inputs in the production of GNP, that is, the energy intensity of GNP. A 1 per cent fall in energy intensity equals a 1 per cent rise in energy conservation. The energy intensity of GNP comprises substitution, returns to scale and technical change terms. SY denotes the interfactor substitution elasticity between energy and labour inputs. A 1 per cent increase in the price of energy relative to the price of GNP equals an *SY* per cent fall in the share of aggregate energy in GNP, other factors constant. If $R<1$ and $SY<1$ then an increase in GNP increases the energy intensity of GNP, other factors constant. If $R<1$ and $SY>1$ then the converse holds. If $R<1$ and $SY=1$ then GNP has no direct impact on the energy intensity of GNP as is the case if $R=1$.

The price of aggregate energy in (B4) is symmetric with (B2) given constant returns to scale. The new variables introduced are the demands for fossil *EF* and clean fuels *EC* and their corresponding prices. *HEF* denotes the base period value share of fossil fuels in total energy input.

The demand for fossil fuel in (B5) has some aspects which are symmetric with (B3).The left hand side of (B5) represents the percentage change in the share of fossil fuel in energy demand. *SE* denotes the interfuel substitution elasticity between fossil and clean fuels. A 1 per cent rise in the relative price of fossil fuel to total energy equals an *SE* per cent fall in the share of fossil fuel in the energy demand mix, other factors constant. *TEF* denotes technical change in fossil fuel and *TEC* denotes technical change in clean fuel. If $TEC = TEF = 1$ then technical change is neutral and a 1 per cent advance reduces the demand for fossil fuel by 1 per cent, other factors constant. An improvement in energy efficiency reduces the energy intensity of GNP if $SY< R/(R-HE)$ but increases energy intensity in the converse situation, other factors constant. That is, a technical advance in energy induces an effective energy price fall which may outweigh the pure conservation effect when *SY* is large. An improvement in labour productivity reduces the energy intensity of GNP, other factors constant. Note that since there is only one fossil fuel and the carbon release coefficient is assumed to be constant the left hand side of (B5) denotes the percentage change in the carbon intensity of energy. A 1 per cent fall in the carbon intensity of energy equals a 1 per cent rise in energy switching.

The demand for clean fuels in (B6) is symmetric with (B5) and directly measures energy switching.

To incorporate a carbon tax on fossil fuel a wedge is introduced between the producer price of energy *PF* and the consumer price *PEF*. A 1 per cent increase in *TAX* causes a 1 per cent increase in the consumer price of fossil fuel, other factors constant.

The seven equations comprise the full model system. The exogenous variables are the labour force *L*, the technical change terms *TE*, *TEL*, *TEF* and *TEC* and the carbon tax *TAX*, the price of clean fuel *PEC* and the producer price of fossil fuel *PF*. Since only relative prices matter in this system the price of GNP is chosen as numeraire. The model is log linear in variables but non-linear in the *H* and *S* terms (value shares and substitution elasticities).

Since the model is log linear in variables the impact of each exogenous shock on the results may be derived separately and the results aggregated to derive impacts from combination shocks. The exogenous shocks of interest pertain to the carbon tax, labour force growth and technical change. Some simplifications can be made to analyse the impact of each of these shocks. Since $PY = 0$ equation (B2) can be dropped as this is used to determine the real wage to labour which is not of particular interest in this specific analysis. Since the producer price of fossil fuel and the price of clean fuel are assumed exogenous these variables have no impact on the effect of the exogenous shocks of interest and so can be set to zero percentage change, that is, $PF = PEC = 0$. Given these assumptions the equation system simplifies as follows.

Simplified equations of the global model

$$\text{(B7)}\quad \begin{aligned} Y &= HE.E + (R-HE)L \\ &\quad + HE.TE + (R-HE)TL \end{aligned}$$

$$\text{(B8)}\quad \begin{aligned} E &= -SY.PE + Z(R,SY)Y \\ &\quad - [1-SY(1-HE/R)]TE \\ &\quad - SY(1-HE/R)TL \end{aligned}$$

where $Z(R,SY) = 1 + (1/R-1)(1-SY)$

$$\text{(B9)}\quad PE = HEF.PEF$$

$$\text{(B10)}\quad \begin{aligned} EF - E &= -SE(PEF-PE) \\ &\quad - (1 - SE(1-HEF))\,TEF \\ &\quad - SE(1-HEF)TEC \end{aligned}$$

$$\text{(B11)}\quad \begin{aligned} EC - E &= SE.PE \\ &\quad - (1 - SE.HEF))TEC \\ &\quad - SE.HEF.TEF \end{aligned}$$

$$\text{(B12)}\quad PEF = TAX$$

Note that an intermediate elasticity Z has been introduced into the system for analytical ease. From the simplified model it is apparent that equations (B9)–(B12) are a subsystem in the fuel shares in aggregate energy demand. Given PE, derived from (B12) and (B9), equations (B7) and (B8) comprise a subsystem in Y and E. Adding the solution for E to (B10) and (B11) gives the solutions for EF, which corresponds to the percentage change in CO_2 emissions, and EC. Hence, the model has a block recursive structure.

B.2 Tax impact

The solution for the simplified model under a carbon tax shock is as follows.

$$\text{(B13)}\quad PEF = TAX > 0$$

$$\text{(B14)}\quad PE = HEF.PEF = HEF.TAX > 0$$

$$\text{(B15)}\quad \begin{aligned} EF - E &= -SE(PEF-PE) \\ &= -SE(1-HEF)TAX < 0 \end{aligned}$$

$$\text{(B16)}\quad \begin{aligned} EC - E &= SE.PE \\ &= SE.HEF.TAX > 0 \end{aligned}$$

$$\text{(B17)}\quad E = -SY.PE/(1-Z.HE)$$

where $Z.HE < 1$

$$\text{(B18)}\quad Y = HE.E < 0$$

The impacts of the tax are as follows. All price changes are expressed relative to the price of GNP. A carbon tax increases the relative price of fossil fuel paid by users and this increases the price of aggregate energy. The carbon intensity of energy falls so that energy switching increases. The demand for energy falls, GNP is reduced and energy conservation rises. The demand for fossil fuel and CO_2 emissions fall due to energy switching and energy conservation. The demand for clean fuel increases if energy switching is stronger than energy conservation, that is, if $SE > SY(1-Z.HE)$, but falls in the converse situation.

Holding the share parameters constant, for a given carbon tax an increase in the interfuel substitution elasticity SE, strengthens energy switching toward clean fuel and reduces fossil fuel demand and CO_2 emissions. As linearised, an increase in SE has no impact on PE. However, PE falls as HEF falls. As second order impacts, an increase in SE dampens the rise in energy conservation and the falls in energy demand and GNP due to the carbon tax.

Holding HE constant, an increase in the interfactor substitution elasticity SY weakens the energy intensity of GNP and reduces aggregate energy demand. As a second order impact an increase in SY dampens the fall in GNP due to the carbon tax.

In summary, for a given carbon tax, fossil fuel demand and CO_2 emissions weaken with stronger interfuel substitution due to energy switching, and with stronger interfactor substitution due to energy conservation. Each of these effects tends to reduce the negative impact of a carbon tax on GNP. These effects are consistent with the global carbon tax scenario in the simulation study.

Assuming decreasing returns to scale, the direct effect of increasing the returns to scale parameter R is to reduce the negative effect of the carbon tax on energy demand if $SY < 1$ and to strengthen the negative impact if $SY > 1$.

B.3 Labour force impact

In the global model, labour force growth affects aggregate energy demand, energy conservation and GNP but does not influence the energy demand mix. The model solution for the labour force shock is as follows.

(B19) $Y = [(R-HE)/(1-Z.HE)]L > 0$

(B20) $E = ZY > 0$

An increase in L increases GNP and aggregate energy demand. If $R < 1$ then labour force growth increases the energy intensity of GNP if $SY < 1$ and decreases the energy intensity of GNP if $SY > 1$. Under constant returns to scale the energy intensity of GNP is unaffected by labour force growth. If $R < 1$ then an increase in Z alone increases the positive labour force impact on energy demand and increases the energy intensity of GNP.

An increase in SY reduces Z, other factors constant.

B.4 Combined tax and labour force impacts

The aggregate energy demand equation and GNP equations for the tax and labour force impacts may be combined as follows. Note that the energy demand mix pertains to the carbon tax results.

(B21) $E = [-SY.PE + Z(R-HE)L]/(1-Z.HE)$

where $PE = HEF.TAX$

(B22) $Y = HE.E + (R-HE)L$

In ERM, Z denotes the income elasticity of aggregate energy demand and SY denotes the price elasticity of aggregate energy demand, and these parameters are modelled separately. An increase in SY alone increases the effectiveness of the carbon tax in reducing energy demand and hence fossil fuel demand, irrespective of labour force growth. This result is consistent with the price response scenarios in the simulation study. An increase in Z reduces energy demand due to carbon taxation, other factors constant. However, an increase in Z increases energy demand due to labour force growth, other factors constant. In the income response scenarios the carbon tax impact on energy demand is more than offset by the positive impact from combining a larger income elasticity with labour force growth.

B.5 Technical change impacts

The model solution for the technical change impacts is as follows.

$$\text{(B23)}\quad EC - E = -(1 - SE.HEF))\,TEC - SE.HEF.TEF$$

$$\text{(B24)}\quad EF - E = -(1 - SE(1-HEF))TEF - SE(1 - HEF)TEC$$

$$\text{(B25)}\quad Y = HE.TE + (R-HE)TL$$

$$\text{(B26)}\quad E - Y = -[1 - SY(1-HE/R)]TE - SY(1-HE/R)TL$$

For simplicity in examining the impact effects it is assumed that the share parameters are fixed, which approximates the solution for small technical changes. Given the global model's block recursive structure, advances in fossil and clean fuel impact solely on the energy demand mix leaving aggregate energy demand unchanged. Hence, changes in the energy demand mix induced by changes in fossil and clean fuel technologies are equivalent to changes in fossil and clean fuel demands. In the global model a neutral advance in clean and fossil fuel technologies equally reduces the growth in demand for each of these fuels and leaves aggregate energy demand unchanged.

A sole technical advance in clean fuel technology increases the clean fuel share in energy demand if the price induced reduction in the technology exceeds the pure conservation effect, that is, if $SE.HEF > 1$. This impact is apparent in the new solar technology scenario. Conversely, a clean fuel advance reduces the clean fuel share in the energy demand mix if $SE.HEF < 1$. An advance in clean fuel technology has a negative impact on fossil fuel demand as clean fuel is made effectively cheaper. Symmetrically, a sole technical advance in fossil fuel technology increases the fossil fuel share in the energy demand mix if the price cutting effect dominates the pure conservation impact, that is, if $SE(1-HEF) > 1$, and reduces the fossil fuel share conversely. In the new coal technology scenario the price cutting effect dominates the conservation impact. A fossil fuel advance has a negative impact on clean fuel demand in the global model.

The impacts on energy conservation of technical advance are symmetric to the energy demand mix impacts. A sole improvement in energy efficiency reduces the energy intensity of GNP if $SY(1-HE/R) < 1$ but reduces energy conservation if the price effect dominates. A sole improvement in labour productivity stimulates energy conservation. In the global model a neutral technical change in energy and labour efficiency has no impact on energy demand as output expansion and energy and labour conservation impacts are offsetting. Energy demand falls with improved energy efficiency alone if $SY < (1-HE)R/(R-HE)$.

Detailed results from the technology convergence scenarios

In this appendix the sensitivities of the base case scenarios to the technology convergence assumptions are examined in detail. Per person income convergence toward USA is used to proxy technology transfer of the aggregate means of production. Convergence in energy service intensities toward JANZ proxies technology transfer in the tertiary or end-use energy sector. The convergence assumptions determine these relativities in the absence of relative price changes and other productivity changes. Analogous to the single baseline scenario there are four new convergence scenarios which assume no tax policy response to greenhouse warming concerns. Correspondingly, twelve new tax scenarios are also introduced to cover the triplet of base case tax scenarios for each given new convergence scenario.

Two symmetric and two asymmetric convergence scenarios are included. Compared with the moderate convergence baseline, nil convergence combines nil technical catchup in per person incomes with nil technical transfer in energy services. Strong convergence combines strong technical catchup in per person incomes with strong energy service transfer. The two asymmetric scenarios pair moderate per person income technical catchup with nil or strong energy service transfer.

The convergence assumptions were outlined in table 12. Nil technology transfer or convergence values correspond to the degree of convergence between 2000 and 2100 implicit in the model in the absence of explicit technology transfer convergence controls. That is, the convergence control parameters are set to zero. The assumptions used to set the moderate and high convergence control parameters involved .05 and .1 percentage point incremental adjustments across all regions of the nil convergence assumptions for relative per person incomes and energy service intensities in the year 2100.

C.1 Global results

The sensitivity of the level of cumulative emissions and of the global indicator results to the convergence assumptions, by 2100, are shown in tables 25 and 26. Results in the absence of greenhouse tax policy are discussed first.

As expected, with no tax policy in place, the effect on cumulative emissions of convergence in per person incomes is strongly positive (table 25). Across the no tax scenarios, only if there is nil per person income convergence is the global warming benchmark not exceeded. Hence, with greater convergence the sooner the global warming indicator of 600 ppm is reached. Over the projection period, a moderate increment in per person income convergence increases world economic growth by 0.2 percentage point a year. Carbon conservation cannot keep a pace with

25 Atmospheric concentration of carbon dioxide by 2100 – technology convergence scenarios a

Convergence scenario b	No tax policy	OECD tax	Global tax exc. CPE	Global tax
	ppm	ppm	ppm	ppm
Nil convergence	597	555	516	489
Moderate income + nil energy	642	594	541	508
Moderate	612	567	521	492
Moderate income + strong energy	606	563	517	489
Strong	643	594	537	505

a Values of *CUMCO2*. **b** Moderate convergence refers to baseline reference scenario.

this additional growth and, consequently, CO2 emissions rise. Baseline cumulative emissions in 2100 are about 7 per cent higher than otherwise due to moderate rather than nil convergence in per person incomes.

As shown in table 26, six comparisons are made to facilitate analysis of convergence impacts on the indicator results in the absence of tax. As modelled, convergence in energy service intensities reduces the world energy-to-output ratio and has little effect on world economic activity. However, a moderate incremental advance in energy service intensity convergence does not stop cumulative emission growth when there is a moderate improvement in per person income convergence. Further, as modelled, if there is greater than moderate convergence in per person incomes, a symmetric improvement in energy service convergence is of greatly diminished value in curbing emissions. Technology transfer in energy services can offset emission growth from per person income convergence when income convergence is moderate and energy service improvements are stronger. Overall, given greenhouse concerns, the need for energy technological advance and technology transfer greatly intensifies with economic development as modelled here.

Considerable uncertainty pervades the estimation of carbon dioxide emissions and critical atmospheric buildup. Long range projections of world economic growth are one major source of this uncertainty. As shown in table 26, the global indicator results from the various tax policies are relatively insensitive to the degree of per person income technology transfer or technical catchup and, hence, one major source of uncertainty in world economic growth estimates. For any given tax scenario, compared with the relevant baseline in 2100, percentage changes in cumulative emissions or in world GNP are fairly similar across the convergence scenarios. As modelled, nil technology transfer has the lowest world economic growth rate of all the scenarios. All other scenarios involve higher economic growth paths due to per person income technical catchup. Hence, as modelled, the negative effects on global economic growth of the various carbon tax policies are not intensified under high growth

26 Global indicator comparisons – technology convergence scenarios: percentage changes from reference scenario in 2100 a

Actual convergence scenario b	**Reference convergence scenario**	***CUMCO2***	***CO2***	***GNP***	***CO2/ GNP***	***E***	***E/GNP***	***CO2/E***
		%	%	%	%	%	%	%
No tax policy								
Moderate income and nil energy	Nil convergence	7.43	35.28	28.33	5.42	30.64	1.81	3.55
Moderate	Moderate income and nil energy	–4.71	–16.96	0.25	–17.16	–12.60	–12.82	–4.98
Moderate	Nil convergence	2.38	12.34	28.65	–12.68	14.18	–11.25	–1.61
Strong	Moderate income and strong energy	6.13	27.27	21.79	4.50	21.12	–0.55	5.08
Moderate income and strong energy	Moderate	–0.98	–3.84	0.08	–3.92	–2.77	–2.85	–1.10
Strong	Moderate	5.09	22.39	21.89	0.40	17.77	–3.39	3.93
Carbon tax policies, compared with reference scenario								
Nil convergence in incomes and energy								
OECD tax		–7.13	–24.15	–0.83	–23.51	–8.72	–7.96	–16.89
Global tax exc. CPE		–13.59	–45.11	–2.13	–43.91	–15.38	–13.53	–35.14
Global tax		–18.11	–58.37	–3.09	–57.05	–20.83	–18.31	–47.42
Moderate income and nil energy convergence								
OECD tax		–7.51	–22.75	–0.87	–22.07	–7.60	–6.79	–16.40
Global tax exc. CPE		–15.72	–47.72	–2.33	–46.47	–15.61	–13.60	–38.04
Global tax		–20.82	–60.51	–3.10	–59.25	–20.87	–18.34	–50.10
Moderate convergence in incomes and energy								
OECD tax		–7.28	–23.81	–0.80	–23.19	–8.02	–7.28	–17.16
Global tax exc. CPE		–14.82	–47.19	–1.97	–46.13	–15.00	–13.28	–37.88
Global tax		–19.54	–62.61	–3.26	–61.34	–20.53	–17.85	–52.94
Moderate income and strong energy convergence								
OECD tax		–7.07	–20.77	–0.79	–20.14	–7.86	–7.12	–14.01
Global tax exc. CPE		–14.55	–47.16	–2.03	–46.06	–14.93	–13.17	–37.8
Global tax		–19.22	–62.67	–3.26	–61.41	–20.33	–17.65	–53.14
Strong convergence in incomes and energy								
OECD tax		–7.52	–22.60	–0.90	–21.90	–7.38	–6.54	–16.44
Global tax exc. CPE		–16.43	–49.78	–2.24	–48.62	–15.73	–13.80	–40.40
Global tax		–21.44	–62.46	–2.99	–61.31	–20.28	–17.82	–52.92

a *CUMCO2* denotes atmospheric concentration of carbon dioide, *CO2* denotes carbon emissions, *GNP* denotes real gross national product, *CO2/GNP* denotes carbon intensity of GNP, *E* denotes primary energy demand, *E/GNP* denotes energy intensity of GNP, *CO2/E* denotes carbon intensity of energy. **b** Moderate convergence refers to baseline reference scenario.

scenarios which involve per person income technical catchup. An OECD tax is least effective in curbing emissions while a global tax is more effective. As regions join the tax club world GNP contracts marginally.

C.2 Regional results

Regional results are discussed first for the reference scenarios in which no carbon tax policy is assumed. Convergence impacts are then analysed under carbon taxation.

Reference scenarios

Convergence comparisons for regional indicator variables under no tax policy are shown in table 27.

Per person income convergence

As modelled, in all regions, relative per person income depends inversely on past relative per person income compared with USA. This dependence proxies technology transfer of the aggregate means of production from this economy to other regions. For a given convergence control parameter, the higher is past relative per person income the weaker is convergence, other things equal. In this situation, raising the convergence control parameter increases convergence. Relative per person income is also negatively related to the real price of energy services and is positively related to labour productivity assumptions. Labour productivity assumptions are unchanged across the scenarios. Hence, effects on relative per person incomes can only deviate from the technical transfer assumptions if technology transfer forces are weaker than energy price feedback effects.

As shown in table 27, trends in per person income relativities, per person income relative to the OECD, largely reflect the dominance of aggregate technology transfer forces and thereby the underlying aggregate technology transfer assumptions. This means that offsetting energy service price feedback effects to real output are relatively weak in these scenarios.

Each of the non-OECD regions is assumed to be at a different stage of development prior to technology transfer. Over the long term, under nil technology transfer relative per person income in CPE is expected to rise, in SEA remain largely unchanged and in ROW contract. By 2100, in non-OECD regions, the move from nil to moderate to strong technology transfer from the OECD of the aggregate means of production, increases per person income relativities by increments of around 5 percentage points across all regions. The results for per person income relativities are insensitive to energy service convergence.

Energy service convergence

Across all convergence scenarios there is an assumed uniform improvement in end use technical efficiency of 1 per cent a year. Overall, annual reductions in the average growth rates of the energy intensity of GNP centre around 1 per cent a year. Under nil convergence, growth in energy conservation is stronger in ROW and the OECD due to energy price feedbacks.

Differences in the rate of energy conservation across the convergence scenarios broadly reflect the dominance of energy service transfer forces and therefore the underlying assumptions regarding technology transfer of energy

27 Regional indicator relativities – reference technology convergence scenarios

		Region				
Convergence scenario [a]	**Year**	**OECD**	**JANZ**	**ROW**	**CPE**	**SEA**
		Annual growth rates				
		%	%	%	%	%
Variable [b]: *CO2*						
Nil convergence	1975–2100	0.92	1.17	0.84	1.32	1.01
Moderate income + nil energy	1975–2100	1.01	1.30	1.15	1.61	1.89
Moderate	1975–2100	0.94	1.23	0.99	1.28	1.66
Moderate income + strong energy	1975–2100	0.91	1.22	0.95	1.27	1.63
Strong	1975–2100	0.99	1.32	1.22	1.49	2.03
Variable: *GNP/CAP*						
Nil convergence	1975–2100	1.79	1.99	1.45	2.41	1.94
Moderate income + nil energy	1975–2100	1.83	2.04	1.72	2.69	2.66
Moderate	1975–2100	1.83	2.04	1.72	2.70	2.66
Moderate income + strong energy	1975–2100	1.83	2.04	1.72	2.70	2.66
Strong	1975–2100	1.86	2.08	1.92	2.92	3.03
Variable: *E/GNP*						
Nil convergence	1975–2100	–1.13	–0.94	–1.38	–0.97	–0.96
Moderate income + nil energy	1975–2100	–1.20	–0.99	–1.34	–1.00	–0.92
Moderate	1975–2100	–1.19	–0.97	–1.41	–1.27	–1.12
Moderate income + strong energy	1975–2100	–1.22	–0.96	–1.44	–1.29	–1.15
Strong	1975–2100	–1.27	–0.99	–1.43	–1.31	–1.14
Variable: *CO2/E*						
Nil convergence	1975–2100	0.03	–0.09	0.11	–0.57	–0.73
Moderate income + nil energy	1975–2100	0.15	0.05	0.11	–0.54	–0.60
Moderate	1975–2100	0.08	–0.05	0.02	–0.57	–0.63
Moderate income + strong energy	1975–2100	0.07	–0.06	0.01	–0.57	–0.63
Strong	1975–2100	0.16	0.03	0.07	–0.55	–0.61
		Relative to OECD average				
		ratio	ratio	ratio	ratio	ratio
Variable: *CO2*						
Actual	1975	1.00	0.12	0.66	0.19	0.08
Nil convergence	2100	1.00	0.16	0.60	0.32	0.09
Moderate income + nil energy	2100	1.00	0.17	0.78	0.40	0.24
Moderate	2100	1.00	0.17	0.70	0.30	0.20
Moderate income + strong energy	2100	1.00	0.18	0.69	0.30	0.20
Strong	2100	1.00	0.18	0.88	0.36	0.29
Variable: *GNP/CAP*						
Actual	1975	1.00	0.87	0.25	0.07	0.04
Nil convergence	2100	1.00	1.12	0.17	0.14	0.05
Moderate income + nil energy	2100	1.00	1.13	0.22	0.20	0.11
Moderate	2100	1.00	1.13	0.22	0.20	0.11
Moderate income + strong energy	2100	1.00	1.13	0.22	0.20	0.11
Strong	2100	1.00	1.14	0.27	0.25	0.16

27 Continued

		Relative to OECD average				
		ratio	ratio	ratio	ratio	ratio
Variable: *E/GNP*						
Actual	1975	1.00	0.78	1.38	1.65	1.14
Nil convergence	2100	1.00	1.00	1.00	2.03	1.40
Moderate income + nil energy	2100	1.00	1.02	1.16	2.14	1.61
Moderate	2100	1.00	1.04	1.05	1.49	1.25
Moderate income + strong energy	2100	1.00	1.07	1.04	1.50	1.24
Strong	2100	1.00	1.10	1.12	1.56	1.34
Variable: *CO2/E*						
Actual	1975	1.00	1.03	1.19	1.42	1.19
Nil convergence	2100	1.00	0.89	1.32	0.67	0.46
Moderate income + nil energy	2100	1.00	0.91	1.13	0.60	0.46
Moderate	2100	1.00	0.88	1.12	0.63	0.49
Moderate income + strong energy	2100	1.00	0.88	1.11	0.64	0.50
Strong	2100	1.00	0.87	1.06	0.58	0.46

a Moderate convergence refers to baseline reference scenario. **b** Variables were defined in table 26 except for *GNP/CAP* which denotes real per person income.

services from JANZ. In theory, as energy transfer rises the energy intensity of GNP tends to fall, all other factors held constant. From table 27 given moderate per person income convergence, moderate energy service technology transfer promotes energy conservation in non-OECD regions and the effects are largest in CPE.

The rate of energy conservation accelerates more sharply between nil and moderate than between moderate and strong energy service transfer. With moderate per person income convergence, the move from nil to moderate energy service transfer results in a strong drop in relative energy intensity in all non-OECD regions. However, the move from moderate to strong convergence in energy service intensities has negligible effect on relative primary energy intensities suggesting that energy price feedback effects are present.

In theory, as per person income rises so does the energy intensity of GNP, all other factors held constant. The results show that, given strong energy service transfer, per person income convergence promotes stronger energy conservation in CPE but weaker conservation in SEA and ROW. As modelled, endogenous technical advance is also stimulated by increases in the real price of energy services. This suggests that negative energy price feedback effects to energy demand are stronger in CPE, and sufficient to offset a positive income effect on primary energy intensity. However, in terms of relative energy intensities, given strong energy service transfer, per person income convergence raises comparative energy intensities in all regions.

With nil convergence, relative to the OECD, energy intensities are expected to rise in CPE and SEA and fall in ROW. For CPE and ROW, under all imposed energy service technical catchup scenarios relative energy conservation is stronger than the 1975 outcome. For SEA, all scenarios have worse relative conservation outcomes than 1975. That is, compared with energy services, per person income technical catchup is relatively stronger in SEA.

Energy switching

Energy conservation is by far the primary source of carbon conservation over the projection period across all scenarios. By contrast, in the absence of a carbon tax, energy switching is virtually negligible outside of non-OECD Asia. In CPE and SEA the carbon intensity of energy declines by about 0.6 per cent a year. In 1975 the carbon intensity of energy exceeded the OECD average in CPE by 42 per cent and in SEA by 19 per cent. For CPE this reflected the predominant use of coal as an energy source, and in SEA was due to a larger share of coal per unit of primary energy than in the OECD.

In the Edmonds–Reilly model demand for energy services is modelled in aggregate for non-OECD regions but is decomposed by residential and commercial, industrial and transport end use sectors in the OECD regions. Interfuel substitution prospects for a region could be more constrained when end–use demand is decomposed, as some fuels are concentrated by modal use. To the extent that end use energy sectors are less well developed in non OECD–Asia there could, however, be more scope for future interfuel substitution as reflected here.

Emissions

In the absence of technology transfer, between 1975 and 2100, $C0_2$ emission growth is projected in all regions to average about 1 per cent a year. None of the technology transfer scenarios halt emission growth. In general, in the absence of tax, per person income technical catchup accelerates CO_2 emission growth while energy service convergence acts as a break.

Under nil convergence, each of the three non-OECD regions is at a different stage in the emission cycle by 2100. Relative emissions are above the 1975 outcome for CPE, approximately unchanged for SEA and below the 1975 outcome for ROW. The results for CO_2 emission growth across the convergence scenarios broadly reflect the process of technology transfer associated with economic development that is modelled here through per person income catchup and energy service catchup.

By 2100 under nil technology transfer $C0_2$ emissions in the OECD are 300 per cent of their 1975 outcome, which represents an average annual growth rate of 0.9 per cent. At their peak OECD CO_2 emissions are 350 per cent under moderate income growth with nil energy service catchup to JANZ. Across all scenarios average annual emission growth is stronger in all non-OECD regions and also in JANZ.

Even with nil per person income technical catchup, relative emissions in CPE are expected to rise markedly over the long term. For CPE emission growth and relative emissions are highest under moderate per person income catchup and nil energy service catchup but lowest when energy service catchup is added. As simulated, this suggests that energy service transfer could provide a major constraint on emission growth in CPE.

For SEA with nil convergence relative emissions in 2100 are approximately as per 1975. However, with per person income technical catchup emission relativities increase markedly. Relative emissions are maximum with strong per person income convergence and minimum with moderate energy service transfer. Emission growth is strongest in SEA than in all other regions under strong convergence.

The 1 per cent emission growth path for SEA with negligible per person income catchup appears highly implausible. In all other scenarios emission growth is strongest in SEA than in all other regions. To the extent that long term growth prospects are bullish in SEA, energy service transfer could need to intensify more than shown here if, for example, a uniform emission growth standard were imposed.

ROW emissions are closest to the OECD in 1975 due to the dominance of EUSSR in the ROW aggregate. Across all scenarios, the ROW remains the second largest CO_2 emitter next to the OECD aggregate, which itself is dominated by USA. For the ROW aggregate, emission relativities are expected to rise markedly with per person income convergence for a given energy service transfer assumption.

Across all scenarios the lowest relative emissions are registered in JANZ despite the fact that emission growth rises in this region. By 2100, under strong convergence, emissions in non-OECD Asia are maximally 65 per cent of the OECD value and 88 per cent in ROW, compared with values in 1975 of 27 and 66 per cent.

Carbon tax policy scenarios

Convergence comparisons for regional indicator variables by each tax policy are shown in tables 28–30. All measurements are annual percentage point deviations in the results of the convergence scenarios from their corresponding values in the baseline scenarios.

Clearly, emission growth potential depends on the convergence assumptions. As modelled, energy service transfer can target relatively energy inefficient regions and regions where GNP growth is strong with some success. However, in the baseline results this force does not prevent global warming by 2100, except under nil per person income technical catchup. By contrast, as shown in the global results, carbon taxes could achieve this goal.

OECD tax policy

As modelled, as per person income and energy service convergence takes place technical transfer forces adjust to inhibit free rider incentives under an OECD tax. Consequently, the OECD tax falls largely on OECD emissions which decline by about 0.5 percentage point a year relative to baseline (table 28). The OECD's share of world fossil fuel emissions averages around 0.45 across scenarios, so world emission growth decelerates by 0.2 percentage point a year. The tendency for free riding emission growth by non-OECD regions never exceeds 0.1 percentage point a year relative to baseline, and this tendency also occurs under nil convergence.

Per person income changes from baseline are marginal. As expected, under nil convergence there is a decline in per person income growth in the OECD regions due to energy price rises, and a rise in non-OECD regions due to world

28 Regional indicator results – technology convergence comparisons, with OECD tax: annual percentage point deviations from reference scenarios, 1975–2100 [a]

OECD tax scenario	Region				
	OECD	JANZ	ROW	CPE	SEA
	%	%	%	%	%
Variable: *CO2*					
Nil convergence	–0.44	–0.48	–0.14	0.05	0.10
Moderate income + nil energy	–0.50	–0.55	–0.15	0.03	0.06
Moderate	–0.48	–0.51	–0.14	0.04	0.08
Moderate income + strong energy	–0.47	–0.51	–0.13	0.04	0.08
Strong	–0.51	–0.54	–0.14	0.02	0.06
Variable: *GNP/CAP*					
Nil convergence	–0.02	–0.02	0.00	0.01	0.01
Moderate income + nil energy	–0.02	–0.02	0.00	0.00	0.00
Moderate	–0.02	–0.02	0.00	0.00	0.00
Moderate income + strong energy	–0.02	–0.02	0.00	0.00	0.00
Strong	–0.02	–0.02	0.00	0.00	0.00
Variable: *E/GNP*					
Nil convergence	–0.14	–0.16	0.03	–0.04	–0.05
Moderate income + nil energy	–0.13	–0.16	–0.02	–0.01	–0.04
Moderate	–0.12	–0.15	–0.01	–0.02	–0.04
Moderate income + strong energy	–0.12	–0.15	–0.01	–0.02	–0.04
Strong	–0.12	–0.15	–0.02	–0.01	–0.04
Variable: *CO2/E*					
Nil convergence	–0.29	–0.29	–0.17	0.09	0.14
Moderate income + nil energy	–0.34	–0.37	–0.13	0.04	0.10
Moderate	–0.34	–0.34	–0.12	0.06	0.11
Moderate income + strong energy	–0.33	–0.33	–0.12	0.06	0.11
Strong	–0.36	–0.36	–0.11	0.03	0.09

a Reference scenario is the corresponding no-tax convergence scenario. Moderate convergence refers to baseline reference scenario.

fossil fuel price falls, but the annual changes in magnitudes are small. In the absence of tax, sizeable growth in per person income in non-OECD regions was predicted with per person income convergence. Growth in emissions in these regions might be expected to accelerate markedly under an OECD tax as real world fossil fuel prices drop. This follows since income and price effects on energy demand are themselves positive.

However, given the assumptions for energy demand responses, carbon intensive energy demand does not accelerate markedly outside of the OECD as a whole as technology transfer at the aggregate and energy sector levels adjust to inhibit this tendency. Other things equal, a drop in OECD relative per person income slows the rate of aggregate technical catchup. That is, technical transfer forces tend to preserve the per person income relativities which

29 Regional indicator results – technology convergence comparisons, with global tax excluding CPE: annual percentage point deviations from reference scenarios, 1975–2100 a

Global tax exc. CPE scenario	Region				
	OECD	JANZ	ROW	CPE	SEA
	%	%	%	%	%
Variable: *CO2*					
Nil convergence	–0.48	–0.55	–1.02	0.12	–1.38
Moderate income + nil energy	–0.55	–0.66	–1.14	0.14	–0.78
Moderate	–0.50	–0.56	–1.05	0.16	–0.84
Moderate income + strong energy	–0.50	–0.56	–1.06	0.15	–0.87
Strong	–0.56	–0.64	–1.38	0.17	–0.76
Variable: *GNP/CAP*					
Nil convergence	–0.01	–0.01	–0.03	0.01	–0.04
Moderate income + nil energy	–0.02	–0.01	–0.03	0.01	–0.04
Moderate	–0.01	–0.01	–0.03	0.01	–0.03
Moderate income + strong energy	–0.01	–0.01	–0.03	0.01	–0.03
Strong	–0.01	–0.01	–0.03	0.01	–0.04
Variable: *E/GNP*					
Nil convergence	–0.12	–0.15	–0.11	–0.07	–0.27
Moderate income + nil energy	–0.08	–0.12	–0.15	–0.04	–0.28
Moderate	–0.09	–0.13	–0.13	–0.05	–0.26
Moderate income + strong energy	–0.09	–0.13	–0.12	–0.05	–0.25
Strong	–0.06	–0.11	–0.17	–0.03	–0.26
Variable: *CO2/E*					
Nil convergence	–0.34	–0.38	–0.87	0.17	–1.04
Moderate income + nil energy	–0.45	–0.52	–0.94	0.17	–0.45
Moderate	–0.40	–0.42	–0.88	0.19	–0.53
Moderate income + strong energy	–0.39	–0.41	–0.90	0.19	–0.56
Strong	–0.48	–0.51	–1.17	0.18	–0.45

a Reference scenario is the corresponding no-tax convergence scenario. Moderate convergence refers to baseline reference scenario.

underly the no tax policy growth process. Other things equal, a drop in OECD energy intensity speeds up energy service transfer.

In the OECD both energy conservation and energy switching are stimulated by the OECD tax. The percentage point decline in the carbon intensity of energy exceeds that in energy conservation.

Outside the OECD there are small rises in the carbon intensity of energy in non-OECD Asia due to favourable world fossil fuel prices. By contrast, in ROW the carbon intensity of energy declines as in the OECD. Since ROW is a net energy supplier to the OECD, carbon emissions associated with energy production would contract, and less carbon intensive fuel production and trade would be needed to preserve economic growth.

Percentage deviations from baseline of the energy intensity of GNP are also

30 Regional indicator results – technology convergence comparisons, with global tax: annual percentage point deviations from reference scenarios, 1975–2100 [a]

Global tax scenario	Region OECD	 JANZ	 ROW	 CPE	 SEA
	%	%	%	%	%
Variable: *CO2*					
Nil convergence	–0.56	–0.55	–1.07	–0.53	–1.55
Moderate income + nil energy	–0.63	–0.64	–1.17	–0.47	–0.81
Moderate	–0.61	–0.59	–1.25	–0.57	–1.03
Moderate income + strong energy	–0.60	–0.58	–1.25	–0.58	–1.05
Strong	–0.64	–0.63	–1.19	–0.50	–0.83
Variable: *GNP/CAP*					
Nil convergence	–0.01	–0.01	–0.03	–0.06	–0.04
Moderate income + nil energy	–0.01	–0.01	–0.03	–0.05	–0.04
Moderate	–0.01	–0.01	–0.03	–0.05	–0.04
Moderate income + strong energy	–0.01	–0.01	–0.03	–0.05	–0.04
Strong	–0.01	–0.01	–0.03	–0.04	–0.03
Variable: *E/GNP*					
Nil convergence	–0.11	–0.16	–0.12	–0.27	–0.26
Moderate income + nil energy	–0.06	–0.11	–0.15	–0.25	–0.27
Moderate	–0.08	–0.13	–0.15	–0.25	–0.26
Moderate income + strong energy	–0.08	–0.13	–0.14	–0.25	–0.25
Strong	–0.05	–0.11	–0.16	–0.23	–0.26
Variable: *CO2/E*					
Nil convergence	–0.43	–0.37	–0.92	–0.19	–1.22
Moderate income + nil energy	–0.55	–0.51	–0.98	–0.17	–0.48
Moderate	–0.51	–0.44	–1.06	–0.26	–0.70
Moderate income + strong energy	–0.50	–0.43	–1.07	–0.27	–0.73
Strong	–0.58	–0.50	–0.98	–0.22	–0.52

[a] Reference scenario is the corresponding no-tax convergence scenario. Moderate convergence refers to baseline reference scenario.

small. Across all technical transfer scenarios energy conservation is marginally promoted by an OECD tax. It might be expected that with world fossil fuel price declines that energy conservation would drop in non-OECD regions, particularly given high per person income growth. However, under all technical transfer scenarios in non-OECD regions this tendency is offset by energy service transfer adjustment.

Global tax policy excluding CPE

In these scenarios ROW and SEA join the tax club while CPE remains outside. Across all scenarios emissions in ROW contract by around 1 percentage point a year relative to baseline. Under the OECD tax, emissions contract by 0.2 percentage point a year relative to baseline. When ROW and SEA join the tax club emissions are reduced by a further 0.3 percentage points. The contribution of ROW is more significant as this region is a major emitter in the reference scenarios. Negative effects on per person income growth in SEA and ROW and positive effects in CPE are marginal. Adjustments in aggregate technology transfer ensure that these effects are virtually the same as under nil convergence. Energy conservation and energy switching contribute to the emission contractions in SEA and ROW. Given income convergence, adjustments in energy service transfer keep the energy intensity of GNP in CPE from rising relative to baseline.

Global tax

Under a global tax, world emission growth contracts by around 0.8 percentage point across the scenarios. That is, when CPE joins the tax club this adds a further 0.3 percentage point more to emission reductions than a global tax which excludes CPE. Again, the effects on per person income growth are minimal.

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