7 Projecting the Growth of Greenhouse-Gas Emissions

Key Messages

Greenhouse-gas concentrations in the atmosphere now stand at around 430ppm CO_2 equivalent, compared with only 280ppm before the Industrial Revolution. The stock is rising, driven by increasing emissions from human activities, including energy generation and land-use change.

Emissions have been driven by economic development. CO_2 emissions per head have been strongly correlated with GDP per head across time and countries. North America and Europe have produced around 70% of CO_2 emissions from energy production since 1850, while developing countries – non-Annex 1 parties under the Kyoto Protocol – account for less than one quarter of cumulative emissions.

Annual emissions are still rising. Emissions of carbon dioxide, which accounts for the largest share of greenhouse gases, grew at an average annual rate of around 2½% between 1950 and 2000. In 2000, emissions of all greenhouse gases were around 42GtCO_2e, increasing concentrations at a rate of about 2.7ppm CO_2e per year.

Without action to combat climate change, atmospheric concentrations of greenhouse gases will continue to rise. In a plausible 'business as usual' scenario, they will reach 550ppm CO_2e by 2035, then increasing at 4½ppm per year and still accelerating.

Most future emissions growth will come from today's developing countries, because of more rapid population and GDP growth than developed countries, and an increasing share of energy-intensive industries. The non-Annex 1 parties are likely to account for over three quarters of the increase in energy-related CO_2 emissions between 2004 and 2030, according to the International Energy Agency, with China alone accounting for over one third of the increase.

Total emissions are likely to increase more rapidly than emissions per head, as global population growth is likely to remain positive at least to 2050.

The relationship between economic growth and development and CO_2 emissions growth is not immutable. There are examples where changes in energy technologies, the structure of economies and the pattern of demand have reduced the responsiveness of emissions to income growth, particularly in the richest countries. Strong, deliberate policy choices will be needed, however, to decarbonise both developed and developing countries on the scale required for climate stabilisation.

Increasing scarcity of fossil fuels alone will not stop emissions growth in time. The stocks of hydrocarbons that are profitable to extract (under current policies) are more than enough to take the world to levels of CO_2 concentrations well beyond 750ppm, with very dangerous consequences for climate-change impacts. Indeed, with business as usual, energy users are likely to switch towards more carbon-intensive coal, oil shales and synfuels, tending to *increase* rates of emissions growth. It is important to redirect energy-sector research, development and investment away from these sources towards low-carbon technologies.

Extensive carbon capture and storage would allow some continued use of fossil fuels, and help guard against the risk of fossil fuel prices falling in response to global climate-change policy, undermining its effectiveness.

7.1 Introduction

Part II showed that continuing climate change will produce harmful and ultimately dangerous impacts on the environment, the global economy and society. This chapter shows that, in the absence of deliberate policy to combat climate change, global greenhouse-gas emissions will continue to increase at a rapid rate.

Even if annual greenhouse-gas (GHG) emissions remained at the current level of 42 $GtCO_2$ equivalent[1] each year[2], the world would experience major climate change. That rate of emissions would be sufficient to take greenhouse-gas concentrations to over 650ppm CO_2 equivalent (CO_2e) by the end of this century, likely to result eventually in a rise in the global mean temperature of at least 3°C from its pre-industrial level[3].

But annual emissions are not standing still – they are rising, at a rapid rate. If they continue to do so, then the outlook is even worse.

This chapter reviews some of the projections of emissions growth in Section 7.2, noting that, despite the uncertainties about the precise pace of increases, there is powerful evidence, robust to plausible variations in the detail of forecasts, that with 'business as usual' emissions will reach levels at which the impacts of climate change are likely to be very dangerous. Sections 7.3 to 7.5 then look behind the headline projections to consider the main drivers of energy-related emissions growth: economic growth, technological choices affecting carbon intensity of energy use and energy intensity of output, and population growth. This is helpful not only in understanding what underlies the projections but also in identifying the channels through which climate-change policy can work. Finally, in Section 7.6, the chapter argues that fossil fuels' increasing scarcity is not going to rein in emissions growth by itself. To the contrary, there will be a problem for climate-change policies if they induce significant falls in fossil-fuel prices. That is one reason why carbon capture and storage technology is so important.

7.2 Past greenhouse-gas emissions and current trends

57% of emissions are from burning fossil fuels in power, transport, buildings and industry; agriculture and changes in land use (particularly deforestation) produce 41% of emissions.

Total greenhouse-gas emissions were 42 $GtCO_2e$[4] in 2000[5], of which 77% were CO_2, 14% methane, 8% nitrous oxide and 1% so-called F-gases such as perfluorocarbon and sulphur hexafluoride. Sources of greenhouse-gas emissions comprise:

- Fossil-fuel combustion for energy purposes in the power, transport, buildings and industry sectors amounted to 26.1 $GtCO_2$ in 2004[6]. Combustion of coal, oil and gas in electricity and heat plants accounted for most of these emissions, followed by transport (of which three quarters is road transport), manufacturing and construction and buildings.
- Land-use change such as deforestation releases stores of CO_2 into the atmosphere.
- Methane, nitrous oxide and F-gases are produced by agriculture, waste and industrial processes. Industrial processes such as the production of cement and chemicals involve a chemical reaction that releases CO_2 and non-CO_2 emissions. Also, the process of

[1] Greenhouse gases are converted to a common unit, CO_2 equivalent, which measures the amount of carbon dioxide that would produce the same global warming potential (GWP) over a given period as the total amount of the greenhouse gas in question. In 2000, 77% of the 100-year GWP of *new emissions* was from CO_2. See Table 8.1 for conversion factors for different gases. Figures for the *stock* of greenhouse gases are usually reported in terms of the amount of CO_2 that would have the equivalent effect on current radiative forcing, i.e. they focus on the GWP over one year.

[2] GHG emissions in 2000 were 42 $GtCO_2e$, WRI (2006). This does not include some emissions for which data are unavailable. For example: CO_2 emissions from soil; additional global warming effect of aviation, including the uncertain contrail effect (see Box 15.6); CFCs (for example from refrigerants in developing countries); and aerosols (for example, from the burning of biomass).

[3] Chapter 8 examines the relationship between stabilisation levels, temperatures and emissions trajectories.

[4] WRI (2006).

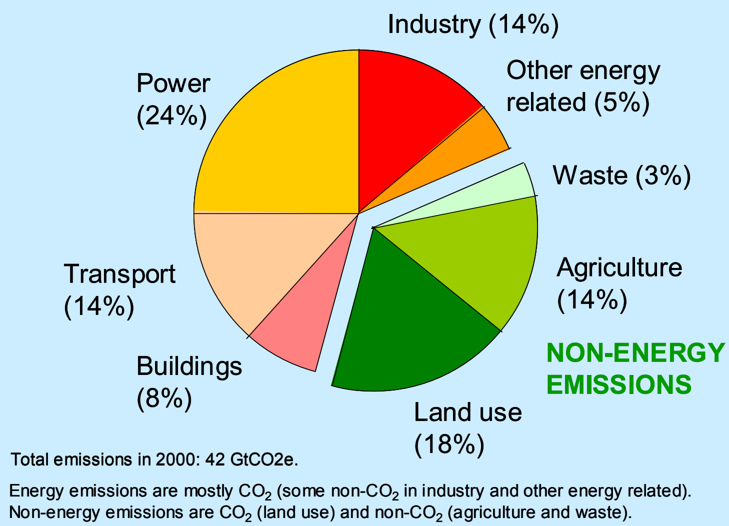
[5] WRI (2006). Historical emission figures are drawn from the WRI's Climate Analysis Indicators Database (CAIT) http://cait.wri.org. Emission estimates exclude: CO_2 emissions from soil; additional global warming effect of aviation, including the uncertain cirrus cloud effect (see Box 15.6); CFCs (for example from refrigerants in developing countries); and aerosols (for example, from the burning of biomass).

[6] IEA (in press).

extracting fossil fuels and making them ready for use generates CO_2 and non-CO_2 emissions (so-called fugitive emissions).

The shares are summarised in Figure 7.1 below, and emissions sources are analysed further by sector in Box 7.1 and Annexes 7.B to 7.G[7].

Figure 7.1 GHG emissions in 2000, by source[8]



Source: WRI (2006)

Box 7.1 Current and projected emissions sources by sector

Power

A quarter of all global greenhouse-gas emissions come from the generation of power and heat, which is mostly used in domestic and commercial buildings, and by industry. This was the fastest growing source of emissions worldwide between 1990 and 2002, growing at a rate of 2.2% per year; developing-country emissions grew most rapidly, with emissions from Asia (including China and India), the Middle East and the transition economies doubling between 1990 and 2000.

This sector also includes emissions arising from petroleum refineries, gas works and coal mines in the transformation of fossil fuel into a form that can be used in transport, industry and buildings. Emissions from this source are likely to increase over four-fold between now and 2050 because of increased synfuel production from gas and coal, according to the IEA. Total power-sector emissions are likely to rise more than three-fold over this period. For more detail on power emissions, see Annex 7.B.

Land use

Changes in land use account for 18% of global emissions. This is driven almost entirely by emissions from deforestation. Deforestation is highly concentrated in a few countries. Currently around 30% of land-use emissions are from Indonesia and a further 20% from Brazil.

Land-use emissions are projected to fall by 2050, because it is assumed that countries stop deforestation after 85% of forest has been cleared. For more detail, see Annex 7.F.

---

[7] For Annexes 7B to 7G, see www.sternreview.org.uk

[8] Emissions are presented according to the sector from which they are directly emitted, i.e. emissions are by source, as opposed to end user/activity; the difference between these classifications is discussed below.

Agriculture
Non-CO_2 emissions from agriculture amount to 14% of total GHG emissions. Of this, fertiliser use and livestock each account for one third of emissions; other sources include rice and manure management. Over half of these emissions are from developing countries. Agricultural practices such as the manner of tillage are also responsible for releasing stores of CO_2 from the soil, although there are no global estimates of this effect. Agriculture is also indirectly responsible for emissions from land-use change (agriculture is a key driver of deforestation), industry (in the production of fertiliser), and transport (in the movement of goods). Increasing demand for agricultural products, due to rising population and incomes per head, is expected to lead to continued rises in emissions from this source. For more detail on trends in agriculture emissions, see Annex 7.G.

Total non-CO_2 emissions are expected to double in the period to 2050[9].

Transport
Transport accounts for 14% of global greenhouse-gas emissions, making it the third largest source of emissions jointly with agriculture and industry. Three-quarters of these emissions are from road transport, while aviation accounts for around one eighth and rail and shipping make up the remainder. The efficiency of transport varies widely between countries, with average efficiency in the USA being around two thirds that in Europe and half that in Japan[10]. Total CO_2 emissions from transport are expected to more than double in the period to 2050, making it the second-fastest growing sector after power.

CO_2 emissions from aviation are expected to grow by over three-fold in the period to 2050, making it among the fastest growing sectors. After taking account of the additional global warming effects of aviation emissions (discussed in Box 15.8), aviation is expected to account for 5% of the total warming effect (radiative forcing) in 2050[11]. For more detail on trends in transport emissions, see annex 7.C.

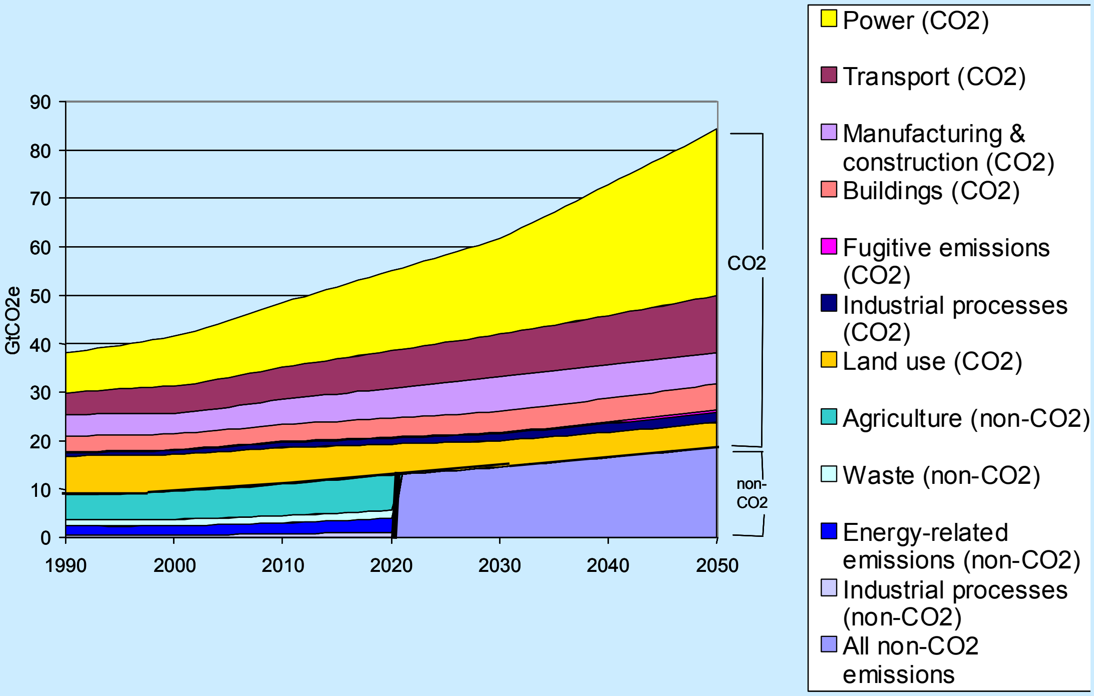
Industry
Industry accounts for 14% of total direct emissions of GHG (of which 10% are CO_2 emissions from combustion of fossil fuels in manufacturing and construction and 3% are CO_2 and non-CO_2 emissions from industrial processes such as production of cement and chemicals).

Buildings
A further 8% of emissions are accounted for by direct combustion of fossil fuels and biomass in commercial and residential buildings, mostly for heating and cooking.

The contribution of the buildings and industry sectors to climate change are greater than these figures suggest, because they are also consumers of the electricity and heat produced by the power sector (as shown in Figure B below). Direct emissions from both industry and buildings are both expected to increase by around two thirds between 2000 and 2050 under BAU conditions. For more detail on industry and buildings emissions, see Annex 7.D and 7.E respectively.

[9] There are no projections available splitting non-CO_2 emission estimates into individual sector sources after 2020.
[10] An and Sauer (2004).
[11] For explanation of how these percentages are calculated, see Box 15.6. The transport emissions presented in Figure A and B include CO_2 emissions from aviation, but exclude the additional global warming effect of these emissions at altitude because there is no internationally agreed consensus on how to include these effects.
[12] Note that the estimates of energy-related CO_2 emissions in the early 1990s include approximate estimates of emissions from transition economies, which are sometimes excluded from data tables from the WRI (2006).

Figure A Historical and projected GHG emissions by sector (by source)



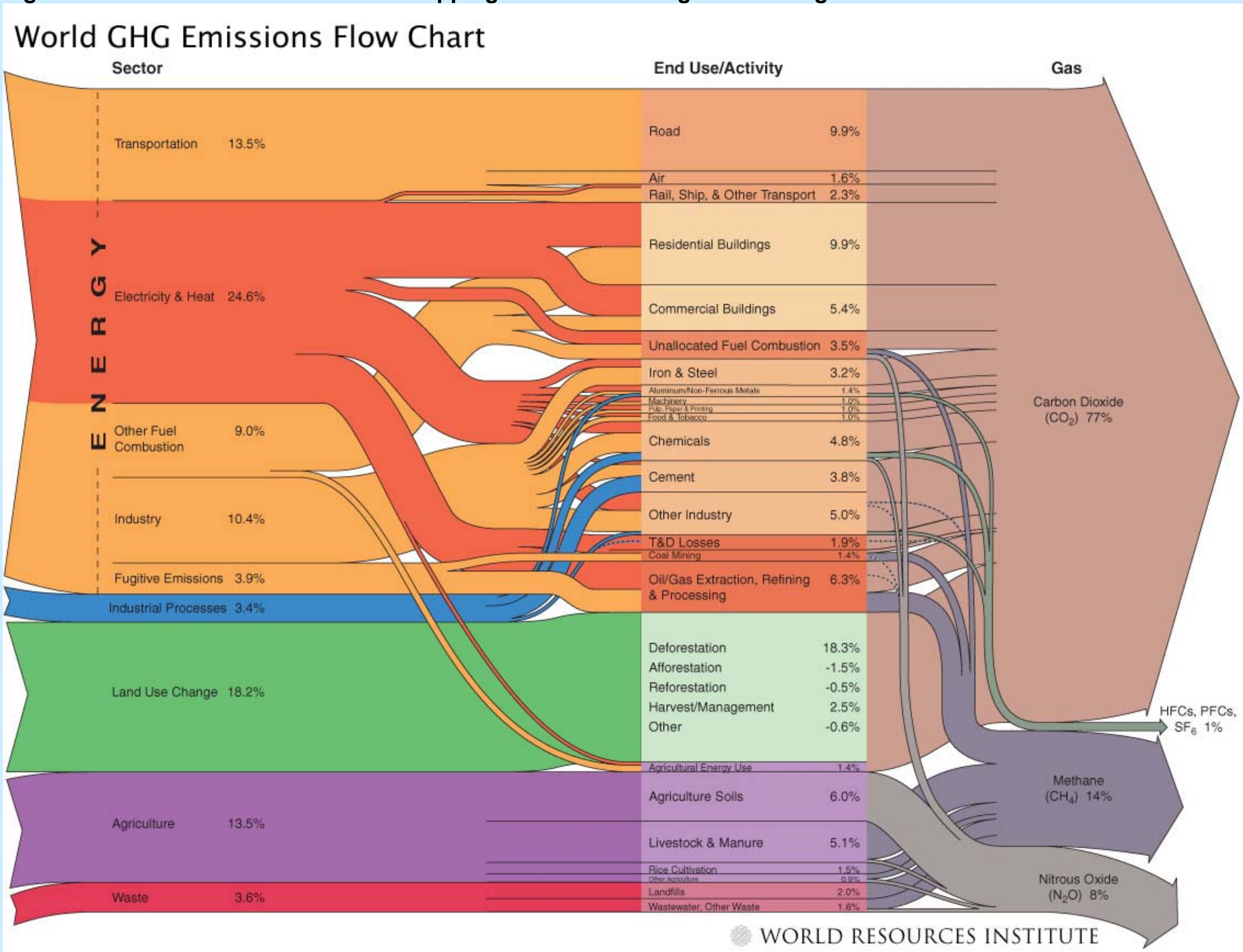
Source: WRI (2006), IEA (in press), IEA (2006), EPA (forthcoming), Houghton (2005).

GHG emissions can also be classified according to the activity associated with them. Figure B below shows the relationship between the physical source of emissions and the end use/activity associated with their production. For example, at the left-hand side of the diagram it can be seen that electricity generation leads to production of emissions at the coal, gas or oil plant; the electricity produced is then consumed by residential and commercial buildings and in a range of industries such as chemicals and aluminium.

This analysis is useful for building a detailed understanding of the drivers behind emissions growth and how emissions can be cut. For example, emissions from the power sector can be cut either by improving the efficiency and technology of the power plant, or by reducing the end-use demand for electricity.

<u>Data sources for historical and projected GHG emissions used in this box and throughout the report:</u>
Historical data on all GHG emissions (1990-2002) from WRI (2006)[12].
Fossil-fuel emissions projections (i.e. power, transport, buildings and industry CO_2 emissions) from IEA. Data for 2030 taken from IEA (in press) and data for 2050 from IEA (2006). Intermediate years calculated by extrapolation.
Land-use emission projections were taken from Houghton (2005).
Non-CO_2 emission projections to 2020 from EPA (forthcoming). Figures extrapolated to 2050 using IPCC SRES scenarios A1F1 and A2.
CO_2 industrial-process and CO_2 fugitive emissions projections extrapolated at 1.8% pa (the growth rate in fossil fuel emissions anticipated by the IEA).

Figure B World Resources Institute mapping from sectors to greenhouse-gas emissions



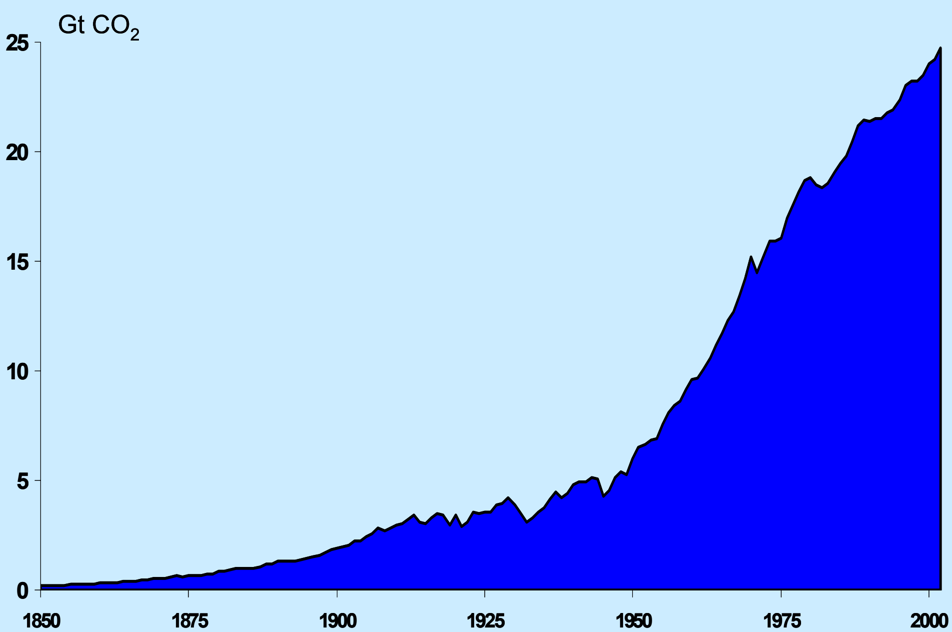
Annual global greenhouse-gas emissions have been growing.

Figure 7.2 illustrates the long-run trend of energy-related CO_2 emissions[13], for which reasonable historical data exist. Between 1950 and 2002, emissions rose at an average annual rate of over 3%. Emissions from burning fossil fuels for the power and transport sectors have been increasing since the mid-nineteenth century, with a substantial acceleration in the 1950s.

The rate fell back somewhat in the three decades after 1970, but was still 1.7% on average between 1971 and 2002 (compared with an average rate of increase in energy demand of 2.0% per year). The slowdown appears to have been associated with the temporary real increases in the price of oil in the 1970s and 1980s, the sharp reduction in emissions in Eastern Europe and the former Soviet Union due to the abrupt changes in economic systems in the 1990s, and increases in energy efficiency in China following economic reforms.

The majority of emissions have come from rich countries in the past. North America and Europe have produced around 70% of the CO_2 from energy production since 1850, while developing countries – non-Annex 1 parties under the Kyoto Protocol – account for less than one quarter of cumulative emissions.

Figure 7.2 Global CO_2 emissions from fossil-fuel burning and cement over the long term



Source: Climate Analysis Indicators Tool (CAIT) Version 3.0. (Washington, DC: World Resources Institute, 2006)

Less is known about historical trends in emissions from agriculture and changes in land use, but emissions due to land-use changes and deforestation are thought to have risen on average by around 1.5% annually between 1950 and 2000, according to the World Resources Institute.

In total, between 1990 and 2000 (the period for which comprehensive data are available), the average annual rate of growth of non-CO_2 greenhouse gases, in CO_2-equivalent terms, was 0.5% and of all GHGs together 1.2%.

[13] Including emissions from international aviation and shipping and CO_2 emissions from the industrial process of making cement.

Global emissions are projected to continue to rise in the absence of climate-change policies; 'business as usual' will entail continuing increases in global temperatures well beyond levels previously experienced by humankind.

Some simple arithmetic can illustrate this. The concentration of greenhouse gases in the atmosphere is currently at around 430ppm CO_2e, adding 2-3ppm a year. Emissions are rising. But suppose they continue to add to GHG concentrations by only 3ppm a year. That will be sufficient to take the world to 550ppm in 40 years and well over 700ppm by the end of the century. Yet a stable global climate requires that the stock of greenhouse gases is constant and therefore that emissions are brought down to the level that the Earth system can naturally absorb from the atmosphere annually in the long run.

Formal projections suggest that the situation in the absence of climate-change policies is worse than in this simple example. The reference scenario[14] in the International Energy Agency (IEA)'s 2006 World Energy Outlook projects an increase of over 50% in annual global fossil fuel CO_2 emissions between 2004 and 2030, from 26 $GtCO_2$ to 40 $GtCO_2$, an annual average rate of increase of 1.7%. The reference scenario for the IEA's Energy Technology Perspectives envisages emissions of 58 $GtCO_2$ by 2050.

Developing countries will account for over three-quarters of the increase in fossil-fuel emissions to 2030, according to the World Energy Outlook, thanks to rapid economic growth rates and their growing share of many energy-intensive industries. China may account for over one third of the increase by itself, with Chinese emissions likely to overtake those of the United States by the end of this decade, driven partly by heavy use of coal.

The fastest growing sectors are driven by growth in demand for transport. The second fastest source of emissions is expected to be aviation, expected to rise about three-fold over the same period. Fugitive emissions are expected to increase over four-fold in the period to 2050, because of an increase in production of synfuels from gas and coal, mostly for use in the transport sector.

Other 'business as usual' (BAU) projections show similar patterns. The US Energy Information Administration is currently projecting an increase from 25 $GtCO_2$ in 2003 to 43.7 $GtCO_2$ by 2030, at an annual average rate of increase of 2.1%[15], as does the POLES model[16]. The factors responsible for the rise in energy-related missions are considered further in the sections below.

Projections of future emissions from land-use changes remain uncertain. At the current rate of deforestation, most of the top ten deforesting nations would clear their forests before 2100. Based on rates of deforestation over the past two decades, and assuming that countries stop deforestation when 85% of the forests they had in 2000 have been cut down, annual emissions will remain at around 7.5 $GtCO_2$/yr until 2012, falling to 5 $GtCO_2$/yr by 2050 and 2 $GtCO_2$/yr by 2100[17].

The US Environmental Protection Agency (EPA) projects an increase in agricultural emissions from 5.7 to 7.3 $GtCO_2e$ between 2000 and 2020 with business as usual. The key drivers behind agricultural emissions growth are population and income growth. While the share of emissions from the OECD and transition economies is expected to fall, the share from developing countries is expected to increase, especially in Africa and Latin America. The income elasticity of demand for meat is often high in developing countries, which will tend to raise emissions from livestock. Increases in emissions from other sources, including waste and industrial processes, are also expected.

[14] The reference scenario assumes no major changes to existing policies.
[15] Different modellers may use slightly different definitions of emissions, depending on their treatment of international marine and aviation fuel bunkers and gas flaring.
[16] According to WRI (2006).
[17] Houghton (2005)

Looking at emissions from all sources together, the IPCC Special Report on Emissions Scenarios, published in 2000, considered a wide range of possible future scenarios. Although they differ considerably, all entail substantial increases in emissions for at least the next 25 years and increases in greenhouse-gas concentrations at least until the end of the century. All but one SRES storyline envisage a concentration level well in excess of 650ppm CO_2e by then. Academic studies also envisage steady increases. The MIT EPPA model reference projection, for example, envisages an average annual increase in CO_2 emissions of 1.26% between 1997 and 2100 (faster in the earlier years). In the rest of this review, for the purposes of illustrating the size of the emission abatement required to achieve various CO_2e concentration levels, a BAU trajectory based on IEA, EPA, IPCC and Houghton projections has been used[18]. This is broadly representative of BAU projections in the literature and results in emissions reaching 84 $GtCO_2e$ per year, and a greenhouse-gas level of around 630ppm CO_2e, by 2050.

Despite the differences across the emissions scenarios in the literature and the unavoidable uncertainty in making long-run projections, any plausible BAU scenario entails continuing increases in global temperatures, well beyond levels previously experienced by humankind, with the profound physical, social and economic consequences described in Part II of the Review. If, for instance, the average annual increase in greenhouse-gas emissions is 1.5%[19], concentrations will reach 550ppm CO_2e by around 2035, by when they will be increasing at 4½ppm per year and still accelerating.

The rest of this chapter takes a more detailed look at the drivers that lie behind these headline projections.

7.3 The determinants of energy-related CO_2 emissions

The drivers of emissions growth can be broken down into different components.

The reasons why annual emissions are projected to increase under 'business as usual' can be better understood by focusing on energy-related CO_2 emissions from the combustion of fossil fuel, which have been more thoroughly investigated than emissions from land use, agriculture and waste[20].

The so-called Kaya identity expresses total CO_2 emissions in terms of the components of an accounting identity: the level of output (which can be further split into population growth and GDP per head); the energy intensity of that output; and the carbon intensity of energy[21]:

$$CO_2 \text{ emissions from energy} \equiv \text{Population} \times (\text{GDP per head}) \times (\text{energy use/GDP}) \times (CO_2 \text{ emissions/energy use})$$

Trends in each of these components can then be considered in turn. In particular, it can immediately be seen that increases in world GDP will tend to increase global emissions, unless income growth stimulates an offsetting reduction in the carbon intensity of energy use or the energy intensity of GDP.

Table 7.1 abstracts from the impact of population size and focuses on emissions per head, which are equal to the product of income per head, carbon intensity of energy and energy intensity. These are reported for the world and various countries and groupings within it. The table

---

[18] Fossil fuel projections to 2050 are taken from IEA (2006). Non-CO_2 emission projections to 2020 are taken from EPA (forthcoming) and extrapolated forward to 2050 in a manner to be consistent with non-CO_2 emissions reached by SRES scenarios A1F1 and A2. Land use emissions to 2050 are taken from Houghton (2005). Actual estimates of CO_2 emissions from industrial processes and CO_2 fugitive emissions were taken from CAIT until 2002; henceforth, they are extrapolated at 1.8% pa (the average growth rate for fossil fuel emissions projected by IEA).

[19] This assumes that total emissions of greenhouse gases grow more slowly than emissions of CO_2. Their annual growth rate was about 0.5 percentage points lower during 1990 to 2000.

[20] Econometric studies of past data have tended to focus on energy-related CO_2 emissions, although modellers are increasingly including non-CO_2 GHGs in their projections. See, for example, Paltsev et al. (2005).

[21] Kaya (1990)

illustrates the wide variation in emissions per head across countries and regions, and how this variation is driven primarily by variations in income per head and, to a lesser extent, by variations in energy intensity. It also illustrates the similarity in the carbon intensity of energy across countries and regions.

Table 7.1 Key ratios for energy-related[22] CO_2 emissions in 2002

Country/grouping	CO_2 per head (tCO_2)	GDP per head ($ppp2000)	CO_2 emissions/energy use (tCO_2/toe)	Energy use/GDP (toe/$ppp2000 x 10^6)
USA	20.4	34430	2.52	230.8
EU	9.4	23577	2.30	158.0
UK	9.6	27176	2.39	140.6
Japan	9.8	26021	2.35	155.7
China	3.0	4379	3.08	219.1
India	1.1	2555	2.05	201.3
OECD	11.7	24351	2.41	193.0
Economies in transition	7.7	7123	2.57	421.2
Non-Annex 1 parties	2.2	3870	2.48	217.8
World	4.0	7649	2.43	219.5
Source: WRI (2006).				

Some of the factors determining these ratios change only very slowly over time. Geographers have drawn attention to the empirical importance of a country's endowments of fossil fuels and availability of renewable energy sources[23], which appear to affect both the carbon intensity of energy use and energy use itself. Qatar, a Gulf oil-producing state, for example, has the highest energy use per head and the highest CO_2 emissions per head[24]. China, which uses a greater proportion of coal in its energy mix than the EU, has a relatively high figure for carbon intensity. A country's typical winter climate and population density are also important influences on the energy intensity of GDP.

But some factors are subject to change. Economists have stressed, for example, the role of the prices of different types of energy, the pace and direction of technological progress, and the structure of production in different countries in influencing carbon intensity and energy intensity[25].

Falls in the carbon intensity of energy and energy intensity of output have slowed the growth in global emissions, but total emissions have still risen, because of income and population increases.

In Table 7.2, the Kaya identity is used to break down the total growth rates of energy-related CO_2 emissions for various countries and regions over the period 1992 to 2002 into the contributions – in an accounting sense – from population growth, changes in the carbon intensity of energy use, changes in the energy intensity of GDP, and growth of GDP per head. It shows that, in the recent past, income growth per head has tended to raise global emissions (by 1.9% per year) whereas reductions in global carbon and energy intensity have tended to reduce them (by the same amount). Because world population has grown (by 1.4% per year), emissions have gone up.

[22] Energy-related emissions include all fossil-fuel emissions plus CO_2 emissions from industrial processes.
[23] E.g. Neumayer (2004)
[24] Generous endowments of raw materials are not necessarily reflected in domestic consumption (e.g. South Africa and diamonds), but in the case of energy there does seem to be a significant correlation, perhaps because of the broad-based demand for energy and the tendency for local energy prices to be relatively low in energy-rich countries.
[25] E.g. Huntington (2005) and McKibbin and Stegman (2005)

Table 7.2 Annual growth rates in energy-related[26] CO_2 emissions and their components, 1992-2002 (%)					
Country/grouping	CO_2 emissions ($GtCO_2$)	GDP per head	Carbon intensity	Energy intensity	Population
USA	1.4	1.8	0.0	-1.5	1.2
EU	0.2	1.8	-0.7	-1.2	0.3
UK	-0.4	2.4	-1.0	-2.3	0.2
Japan	0.7	0.7	-0.5	0.2	0.3
China	3.7	8.5	0.5	-6.4	0.9
India	4.3	3.9	1.1	-2.5	1.7
OECD	1.2	1.8	-0.3	-1.1	0.7
Economies in transition	-3.0	0.4	-0.6	-2.7	-0.1
Non-Annex 1 parties	3.3	3.5	0.2	-2.0	1.6
World	**1.4**	**1.9**	**-0.1**	**-1.7**	**1.4**
Source: WRI (2006).					

There has been a variety of experience across countries. The EU and the economies in transition were able to reduce carbon intensity considerably during the period, but there was a significant increase in India, from a very low base. Population growth, as well as increases in GDP per head, was particularly important in developing countries. The reductions in the energy intensity of output in China, India and the economies in transition are striking. If energy intensity had fallen in China only at the speed it fell in the OECD, global emissions in 2002 would have been over 10% higher. But Table 7.1 shows that, at least in China and India, energy intensity is now below that of the United States. Economic reforms helped to reduce wasteful use of energy in many countries in the 1990s, but many of the improvements are likely to have reflected catching up with best practice, boosting the level of energy efficiency but not necessarily bringing reductions in its long-run growth rate.

7.4 The role of growth in incomes and population in driving emissions

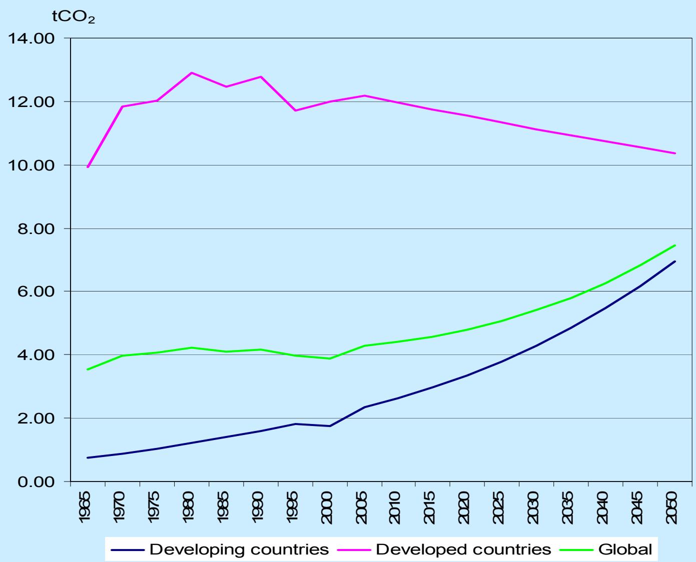
In the absence of policies to combat climate change, CO_2 emissions are likely to rise as the global economy grows.

Historically, economic development has been associated with increased energy consumption and hence energy-related CO_2 emissions per head. Across 163 countries, from 1960 to 1999, the correlation between CO_2 emissions per head and GDP per head (expressed as natural logarithms) was nearly 0.9[27]. Similarly, one study for the United States estimated that, over the long term, a 1% rise in GDP per head leads to a 0.9% increase in emissions per head, holding other explanatory factors constant[28].

Consistent with this, emissions per head are highest in developed countries and much lower in developing countries – although developing countries are likely to be closing the gap, because of their more rapid collective growth and their increasing share of more energy-intensive industries, as shown in the example of the projection in Figure 7.3[29].

[26] Energy-related emissions include all fossil-fuel emissions plus CO_2 emissions from industrial processes.
[27] See Neumayer, (2004)
[28] See Huntington (2005). GDP per head is itself a function of many other variables, and emissions projections should in principle be based upon explicit modelling of the sources of growth; for example, the consequences for emissions will be different if growth is driven by innovations in energy technology rather than capital accumulation.
[29] Holtsmark, B (2006). McKitrick and Strazicich (2005) have pointed out that global emissions per head have behaved as a stationary series subject to structural breaks. But this does not preclude increases in global emissions per head in future, either because of structural changes within economies, or changes in the distribution of emissions across fast- and slow-growing economies, leading to further structural breaks.

Figure 7.3 Global emissions per head: history and extrapolations

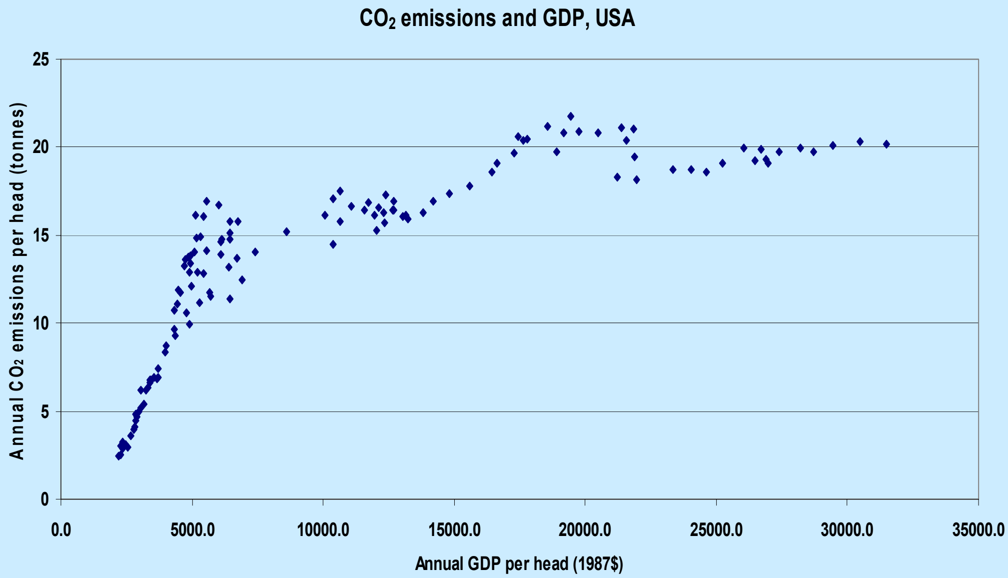


Source: Holtsmark (2006)

Structural shifts in economies may change the relationship between income and emissions.

Structural changes in economies will have a significant impact on their emissions. In some rich countries, the shift towards a service-based economy has helped to slow down, or even reverse, the growth in national emissions. Indeed, emissions per head have fallen in some countries over some periods (e.g. they peaked in the United Kingdom in 1973 and fell around 20% between then and 1984). Holtsmark's extrapolation in Figure 7.3 envisages a decline in emissions per head for the developed world as a whole. And breaks in the relationship between emissions per head and GDP per head have taken place, as seen in Figure 7.4 for the USA, at income levels around \$6000 per head, \$12000 per head and \$22000 per head.

Figure 7.4 Annual emissions of CO_2 per head vs. GDP per head, USA



Source: Huntington (2005)

If it were true that the relationship between emissions and income growth disappeared at higher income levels, emissions growth would eventually be self-limiting, reducing the need to take action on climate change if this happened fast enough. The observation that, at high incomes, some kinds of pollution start to fall is often explained by invoking the 'environmental Kuznets curve' hypothesis – see Annex 7.A. The increasing importance of the 'weightless economy' in the developed world[30], with a rising share of spending accounted for by services, shows how patterns of demand, and the resulting energy use, can change.

However, in the case of climate change, the hypothesis is not very convincing, for three reasons. First, at a global level, there has been little evidence of large voluntary reductions in emissions as a result of consumers' desire to reduce emissions as they become richer. That may change as people's understanding of climate-change risks improves, but the global nature of the externality means that the incentive for uncoordinated individual action is very low. Second, the pattern seen in Figure 7.4 partly reflects the relocation of manufacturing activity to developing countries. So, at the global level, the structural shift within richer countries has less impact on total emissions. Third, demand for some carbon-intensive goods and services – such as air transport[31] – has a high income elasticity, and will continue to grow as incomes rise. Demand for car transport in many developing countries, for example, is likely to continue to increase rapidly. For these reasons, at the global level, in the absence of policy interventions, the long-run positive relationship between income growth and emissions per head is likely to persist. Breaking the link requires significant changes in preferences, relative prices of carbon-intensive goods and services and/or breaks in technological trends. But all of these are possible with appropriate policies, as Part IV of this Review argues.

Different assumptions about the definition and growth of income produce different projections for emissions, but this does not affect the conclusion that emissions are well above levels consistent with a stable climate and are likely to remain so under 'business as usual'.

[30] Quah (1996)
[31] Air transport is particularly problematic given its impacts on the atmosphere over and above the simple CO_2 effect. The additional global warming effect of aviation is discussed in Box 15.8.

Projected trajectories for CO_2 are sensitive to long-run growth projections, but the likelihood of economic growth slowing sufficiently to reverse emissions growth by itself is small. Most models assume some decline in world growth rates in the medium to long run, as poorer countries catch up and exhaust the growth possibilities from adopting best practices in production techniques. But some go further and assume that developed-country income growth per head will actually decline. There is no strong empirical basis for this assumption. Neither is the assumption very helpful if one wishes to assess the consequences if developed economies do manage to continue to grow at post-World War II rates.

The choice of method for converting the incomes of different countries into a common currency to allow them to be aggregated also makes some difference – see Box 7.2. But given that the growth rate of global GDP was around 2.9% per year on average between 1900 and 2000, and 3.9% between 1950 and 2000, projecting world growth to continue at between 2 and 3% per year (as in the IPCC SRES scenarios, for example) does not seem unreasonable.

Box 7.2 Using market exchange rates or purchasing power parities in projections

There has been some controversy over how GDPs of different countries and regions should be compared for the purposes of making long-run emissions projections. Some method is required to convert data compiled in national currency terms into a common unit of account. Most emissions scenarios have used market exchange rates (MER), while others have argued for purchasing power parity (PPP) conversions. Castles and Henderson (2003) argue that "the mistaken use of MER-based comparisons, together with questionable assumptions about 'closing the gap' between rich countries and poor, have imparted an upward bias to projections of economic growth in developing countries, and hence to projections of total world emissions."

MER conversions suffer from two main problems. First, although competition tends to equalise the prices of internationally traded goods and services measured in a common currency using MERs, this is not true of non-traded goods and services. As the price of the latter relative to traded goods and services tends to be higher in rich countries than in poor ones, rich countries tend to have higher price levels converted at MERs. This phenomenon arises because the productivity differential between rich and poor countries tends to be larger for traded than non-traded goods and services (the 'Balassa-Samuelson' effect[32]). In this sense, the ratio of income per head between rich countries and poor countries is exaggerated if the comparison is intended to reflect purchasing power. Thus, the use of MERs will mean that developing countries' current GDP levels per head will be underestimated. If GDP levels per head are assumed to converge over some fixed time horizon, this means that the growth rates of the poor countries while they 'catch up' will be exaggerated. Henderson and Castles were concerned that this would lead to an over-estimate of the growth of emissions as well.

Second, MERs can be driven away from the levels that ensure the 'law of one price' for traded goods and services by movements across countries' capital accounts. Different degrees of firms' market power in different countries may also have this effect.

Instead of using MERs, one can try to use conversions based on purchasing power parity (PPP). These try to compare real incomes across countries by comparing the ability to purchase a standard basket of goods and services. But PPP exchange rates have their own problems, as explained by McKibbin et al (2004). PPP calculation requires detailed information about the prices in national currencies of many comparable goods and services. The resource costs are heavy. There are different ways of weighting individual countries' prices to obtain 'international prices' and aggregating volumes of output or expenditure. Different PPP conversions are needed for different purposes. For example, different baskets of products and PPP conversion rates are appropriate for comparing the incomes of old people across countries than for comparing the incomes of the young; similarly, different price indices need to be used for comparing industrial outputs. Data are only available for benchmark years, unlike MERs, which for many countries are available at high frequency.

[32] See, for example, Balassa (1964)

But efforts are under way to improve the provision of PPP data. The International Comparison Programme (ICP), launched by the World Bank when Nicholas Stern was Chief Economist, is the world's largest statistical initiative, involving 107 countries and collaboration with the OECD, Eurostat and National Statistical Offices. It produces internationally comparable price levels, economic aggregates in real terms, and Purchasing Power Parity (PPP) estimates that inform users about the relative sizes of markets, the size and structure of economies, and the relative purchasing power of currencies.

In the IPCC SRES scenarios that use MER conversions, it is not clear that the use of MERs biases upwards the projected rates of emissions growth, as the SRES calibration of the past relationship between emissions per head and GDP per head also used GDPs converted at MERs as the metric for economic activity (Holtsmark and Alfsen (2003)). Hence the scenarios are based on a lower estimate of the elasticity of emissions growth per head with respect to (the incorrectly measured) GDP growth per head. As Nakicenovic et al (2003) have argued, the use of MERs in many of the IPCC SRES scenarios is unlikely to have distorted the emissions trajectories much.

Overall, the statement that, under business as usual, global emissions will be sufficient to propel greenhouse-gas concentrations to over 550ppm CO_2e by 2050 and over 650-700ppm by the end of this century is robust to a wide range of changes in model assumptions. It is based on a conservative assumption of constant or very slowly rising annual emissions. The proposition does not, for example, rely on convergence of growth rates of GDP per head across countries, an assumption commonly made in global projections. Cross-country growth regressions suggest that on average there has been a general tendency towards convergence of growth rates[33]. But there has been a wide range of experience over time and regions, and some signs of divergence in the 1990s[34].

Total emissions are likely to increase more rapidly than emissions per head.

The UN projects world population to increase from 6.5 billion in 2005 to 9.1 billion in 2050 in its medium variant and still to be increasing slowly then (at about 0.4% per year), despite projected falls in fertility[35]. The average annual growth rate from 2005 to 2050 is projected to be 0.75%; the UN's low and high variants give corresponding rates of 0.38% and 1.11%. Population growth rates will be higher among the developing countries, which are also likely in aggregate to have more rapid emissions growth per head. This means that emissions in the developing world will grow significantly faster than in the developed world, requiring a still sharper focus on emissions abatement in the larger economies like China, India and Brazil.

Climate change itself is also likely to have an impact on energy demand and hence emissions, but the direction of the net impact is uncertain. Warmer winters in higher latitudes are likely to reduce energy demand for heating[36], but the hotter summers likely in most regions are likely to increase the demand for refrigeration and air conditioning[37].

7.5 The role of technology and efficiency in breaking the link between growth and emissions

The relationship between economic development and CO_2 emissions growth is not immutable.

Historically, there have been a number of pervasive changes in energy systems, such as the decline in steam power, the spread of the internal combustion engine and electrification. The

[33] Bosworth, B, and Collins, S (2003)
[34] See McKibbin and Stegman, op. cit.; Pritchett, L (1997)
[35] Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2005)
[36] See Neumayer, op. cit.
[37] Asadoorian et al (2006)

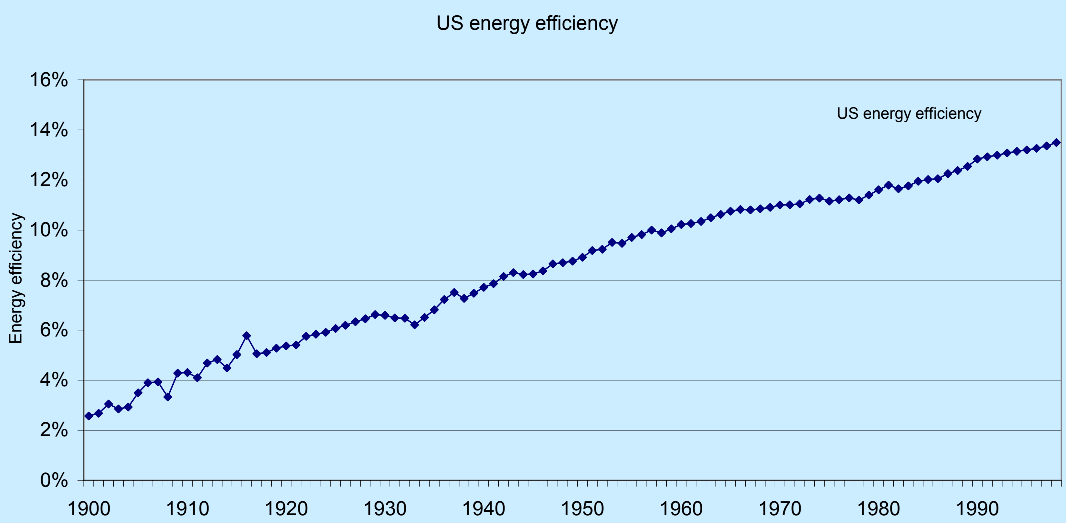
adoption of successive technologies changed the physical relationship between energy use and emissions. A number of authors have identified in several countries structural breaks in the observed relationship that are likely to have been the result of such switches[38]. Using US data, Huntington (2005) found that, after allowing for these technology shifts, the positive relationship between emissions per head and income per head has remained unchanged, casting some doubt on the scope for changes in the structure of demand to reduce emissions in the absence of deliberate policy. Also, an MIT study suggests that, since 1980, changes in US industrial structure have had little effect on energy intensity[39].

Shifts usually entailed switching from relatively low-energy-density fuels (e.g. wood, coal) to higher-energy-density ones (e.g. oil), and were driven primarily by technological developments, not income growth (although cause and effect are difficult to disentangle, and changes in the pattern of demand for goods and services may also have played a role). The energy innovations and their diffusion were largely driven by their advantages in terms of costs, convenience and suitability for powering new products (with some local environmental concerns, such as smog in London or Los Angeles, occasionally playing a part). As the discussion of technology below suggests (see Chapter 16), given the current state of knowledge, alternative technologies do not appear, on balance, to have the inherent advantages over fossil-fuel technologies (e.g. in costs, energy density or suitability for use in transport) necessary if decarbonisation were to be brought about purely by private commercial decisions. Strong policy will therefore be needed to provide the necessary incentives.

Technical progress in the energy sector and increased energy efficiency are also likely to moderate emissions growth. Figure 7.5, for instance, illustrates that the efficiency with which energy inputs are converted into useful energy services in the United States has increased seven-fold in the past century. One study has found that innovations embodied in information technology and electrical equipment capital stocks have played a key part in reducing energy intensity over the long term[40]. But, in the absence of appropriate policy, incremental improvements in efficiency alone will not overwhelm the income effect. For example, a review of projections for China carried out for the Stern Review suggests that energy demand is very likely to increase substantially in 'business as usual' scenarios, despite major reductions in energy intensity[41]. And in the USA, emissions per head are projected to rise whenever income per head grows at more than 1.8% per year[42]. But the scale of potential cost-effective energy efficiency improvements, which will be explored elsewhere in this Review, indicates that energy efficiency and reductions in energy intensity constitute an important and powerful part of a wider strategy.

[38] See, for example, Lanne and Liski (2004) and Huntington, op. cit. The former study 16 countries but use a very limited set of explanatory variables.
[39] Sue Wing and Eckaus (2004)
[40] Sue Wing and Eckaus (2004)
[41] Understanding China's Energy Policy: Background Paper Prepared for Stern Review on the Economics of Climate Change by the Research Centre for Sustainable Development, Chinese Academy of Social Sciences
[42] Huntington, op. cit.

Figure 7.5 Energy conversion efficiencies, USA, 1900–1998



Source: Ayres et al (2005) and Ayres and Warr (2005) This graph shows the efficiency with which power from fossil-fuel, hydroelectric and nuclear sources is converted into useful energy services. The percentages reflect the ratio of useful work output to energy input.

Chapter 9 will set out in more detail the potential for improvements in efficiency and technology; Part IV of this report will look at how policy frameworks can be designed to make this happen.

7.6 The impact of fossil-fuel scarcity on emissions growth

This chapter has argued that, without action on climate change, economic growth and development are likely to generate levels of greenhouse-gas emissions that would be very damaging. Development is likely to lead to increasing demand for fossil-fuel energy, and, without appropriate international collective action, producers and consumers will not modify their behaviour to reduce the adverse impacts. But is the increase in energy use implied actually technically feasible? In other words, are the stocks of fossil fuels in the world large enough to satisfy the demand implied by the BAU scenarios? Or will increasing scarcity drive up the relative prices of fossil fuels sufficiently to choke off demand fast enough to provide a 'laissez faire' answer to the climate-change problem?

There is enough fossil fuel in the ground to meet world consumption demand at reasonable cost until at least 2050.

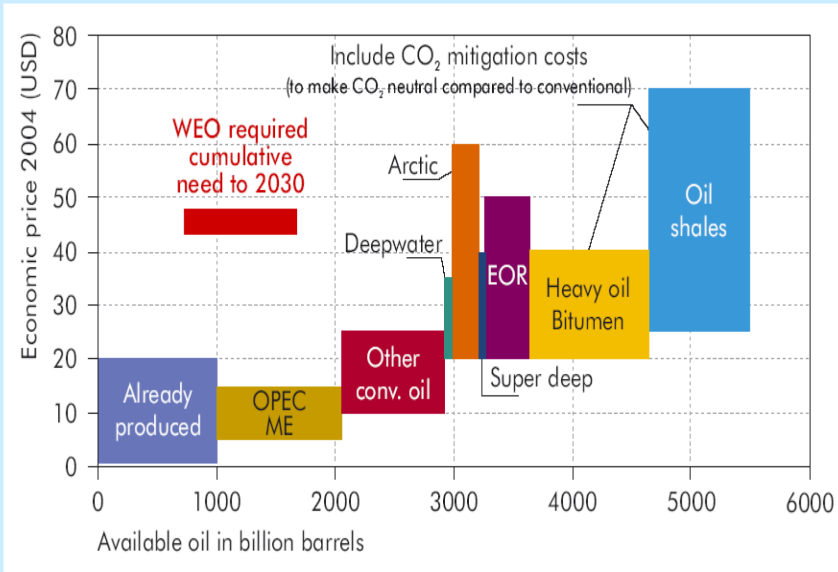
To date, about 2.7 trillion barrels of oil equivalent (boe) of oil, gas and coal have been used up[43]. At least another 40 trillion boe remain in the ground, of which around 7 trillion boe can reasonably be considered economically recoverable[44]. This is comfortably enough to satisfy the BAU demand for fossil fuels in the period to 2050 (4.7 trillion boe)[45].

The IEA has looked at where the economically recoverable reserves of oil might come from in the next few decades and the associated extraction costs (see Figure 7.7). Demand for oil in the

[43] World Energy Council (2000)
[44] World Energy Council (2000)
[45] IEA (2006)

period to 2050 is expected to be 1.8 trillion boe[46]; this could be extracted at less than $30/barrel. This alone would be enough to raise the concentration of CO_2e in the atmosphere by 50ppm[47].

Figure 7.6 Availability of oil by price[48]



Source: International Energy Agency

There appears to be no good reason, then, to expect large increases in real fossil-fuel prices to be necessary to bring forth supply. Yet big increases in price would be required to hold energy demand and emissions growth in check if no other method were also available. The IEA emissions projections envisage an average annual rate of increase of 1.7% to 2030. If the price elasticity of energy demand were -0.23, an estimate in the middle of the range in the literature[49], the prices of fossil fuels would have to increase by over 7% per year in real terms merely to bring the rate of emissions growth back to zero, implying a more-than-six-fold rise in the real price of energy.

'Carbon capture and storage' technology is important, as it would allow some continued use of fossil fuels and help guard against the risk of fossil-fuel prices falling in response to global climate-change policy, undermining its effectiveness.

There are three major implications for policy. First, it is important to provide incentives to redirect research, development and investment away from the fossil fuels that are currently more difficult to extract (see Grubb (2001)). The initial costs of development provide a hurdle to the exploitation of some of the more carbon-intensive fuels like oil shales and synfuels. This obstacle can be used to help divert R,D&D efforts towards low-carbon energy resources. Second, the low resource costs of much of the remaining stock of fossil fuels have to be taken into account in climate-change policy[50]. Third, as there is a significant element of rent in the current prices of exhaustible fossil-fuel resources, particularly those of oil and natural gas, there is a danger that fossil-fuel prices could fall in response to the strengthening of climate-change policy, undermining its

[46] IEA (2006)
[47] This assumes that half of CO_2 emissions are absorbed, as discussed in Chapter 1.
[48] IEA (2005)
[49] See Hunt et al (2003)
[50] In calculating the costs of climate-change mitigation to the world as a whole, fossil-fuel energy should be valued at its marginal resource cost, excluding the scarcity rents, not at its market price. Some estimates of cost savings from introducing alternative energy technologies ignore this point and consequently overestimate the global cost savings.

effectiveness[51]. Extensive carbon capture and storage would maintain the viability of fossil fuels for many uses in a manner compatible with deep cuts in emissions, and thereby help guard against this risk.

[51] A downward shift in the demand curve for an exhaustible natural resource is likely to lead to a fall in the current and future price of the resource. In the case of resources for which the marginal extraction costs are very low, this fall could continue until the demand for the fossil fuel is restored. Pindyck (1999) found that the behaviour of oil prices has been broadly consistent with the theory of exhaustible natural resource pricing. See also Chapter 2 references on the pricing of exhaustible natural resources.

References

The World Resources Institute (2005) publication “Navigating the Numbers” provides a very good overview of global GHG emissions, by source and country. The WRI also provides a very user-friendly database in its Climate Analysis Indicators Tool. The International Energy Agency’s publications provide an excellent source of information about fossil-fuel emissions and analysis of the medium-term outlook for emissions, energy demand and supply. The US Environmental Protection Agency produces estimates of historical and projected non-CO_2 emissions. Houghton (2005) is a good source of data and information on emissions due to land-use change.

The IPCC’s Special Report on Emission Scenarios considers possible longer-term outlooks for emissions and discusses many of the complex issues that arise with any long-term projections. Its scenarios provide the foundation for many of the benchmark ‘business as usual’ scenarios used in the literature. Some of the difficult challenges posed by the need to make long-term projections have been pursued in the academic literature, for example, in the two papers co-authored by Warwick McKibbin and referenced here and the paper by Schmalensee et al (1998). There have been lively methodological exchanges, including the debates between Castles and Henderson (2003a,b), Nakicenovic et al (2003) and Holtsmark and Alfsen (2005) on how to aggregate incomes across countries. A good example of the Integrated Assessment Model approach to projections can be found in Paltsev et al (2005). Some of the difficulties of untangling the impacts of income and technology on emissions growth are tackled in Huntington (2005), among others.

The World Energy Council (2000) is a good source of information on availability of fossil fuels. The IEA (1995) have also produced an excellent report on this. The extraction costs of fossil fuels are also considered by Rogner (1997). The issues posed by exhaustible fossil fuels in the context of climate change are analysed in papers referenced in Chapter 2.

An, F. and A. Sauer, (2004): 'Comparison of passenger vehicle fuel economy and GHG emission standards around the world', Prepared for the Pew Centre on Global Climate Change, Virginia: Pew Centre.

Asadoorian, M.O., R.S. Eckaus and C.A. Schlosser (2006): ‘Modeling climate feedbacks to energy demand: The case of China’ MIT Global Change Joint Program Report 135, June, Cambridge, MA: MIT.

Ayres, R. U., Ayres, L. W. and Pokrovsky, V. (2005): ‘On the efficiency of US electricity usage since 1900’, Energy, 30(7): 1092-1145

Ayres and Warr (2005): ‘Accounting for growth: the role of physical work’, Structural Change and Economic Dynamics, 16(2): 181-209

Balassa, B. (1964): ‘The purchasing power parity doctrine: a reappraisal’, Journal of Political Economy, **72**: 584-596

Bosworth, B.P. and S.M. Collins (2003): ‘The empirics of growth: an update’, Brookings Papers on Economic Activity, No. 2, 2003.

Castles, I. and D. Henderson (2003a): ‘The IPCC emissions scenarios: an economic-statistical critique’, Energy and Environment,**14**(2-3) May: 159-185

Castles, I. and D. Henderson (2003b): ‘Economics, emissions scenarios and the work of the IPCC’, Energy and Environment, **14**(4) July: 415-435

Chinese Academy of Social Sciences (2005): ‘Understanding China’s Energy Policy’, Background Paper Prepared for Stern Review on the Economics of Climate Change by the Research Centre for Sustainable Development

EPA (forthcoming): 'Global anthropogenic non-CO_2 greenhouse-gas emissions: 1990-2020', US Environmental Protection Agency, Washington DC. Figures quoted from draft December 2005 version.

Grubb, M. (2001): 'Who's afraid of atmospheric stabilisation? Making the link between energy resources and climate change', Energy Policy, **29**: 837-845

Harbaugh, B., A. Levinson and D. Wilson (2002): 'Reexamining the empirical evidence for an environmental Kuznets Curve,' Review of Economics and Statistics, **84**(3) August.

Holtsmark, B.J. (2006): 'Are global per capita CO_2 emissions likely to remain stable?', Energy & Environment, **17**(2) March.

Holtsmark, B.J. and K.H. Alfsen (2005): 'PPP correction of the IPCC emissions scenarios – does it matter?', Climatic Change, **68**(1-2) January: 11-19

Holtz-Eakin, D. and T.M. Selden (1995): 'Stoking the fires? CO_2 emissions and economic growth', Journal of Public Economics, **57**, May: 85-101

Houghton, R.A. (2005): 'Tropical deforestation as a source of greenhouse-gas emissions', Tropical Deforestation and Climate Change, (eds.) P. Moutinho and S. Schwartzman, Belém: IPAM - Instituto de Pesquisa Ambiental da Amazônia ; Washington DC - USA : Environmental Defense.
See:
www.environmentaldefense.org/documents/4930_TropicalDeforestation_and_ClimateChange.pdf

Hunt, L.C., G. Judge, and Y. Ninomiya (2003): 'Modelling underlying energy demand trends', Chapter 9 in L.C. Hunt (ed). Energy in a competitive market: essays in honour of Colin Robinson. Cheltenham: Edward Elgar.

Huntington, H.G. (2005): 'US carbon emissions, technological progress and economic growth since 1870', Int. J. Global Energy Issues, **23**(4): 292-306

International Energy Agency (2005): 'Resources to reserves: oil and gas technologies for the energy markets of the future', Paris: OECD/IEA.

International Energy Agency (2006): 'Energy technology perspectives - scenarios & strategies to 2050', Paris: OECD/IEA.

International Energy Agency (in press): World Energy Outlook 2006, Paris: OECD/IEA.

Intergovernmental Panel on Climate change (2000): 'Emissions Scenarios', Special Report, [N. Nakicenovic and R. Swart (eds.)], Cambridge: Cambridge University Press.

Kaya, Y. (1990): 'Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios', paper presented to IPCC Energy and Industry Sub-Group, Response Strategies Working Group.

Lanne, M. and M. Liski (2004): 'Trends and breaks in per-capita carbon dioxide emissions, 1870-2028', The Energy Journal, **25**(4): 41-65

McKibbin, W., D. Pearce, and A. Stegman (2004): 'Long-run projections for climate-change scenarios', Brookings Discussion Papers in International Economics No 160, April, Washington, DC: The Brookings Institution.

McKibbin, W. and A. Stegman (2005): 'Convergence and per capita carbon emissions', Working Paper in International Economics No 4.05, May, Sydney: Lowy Institute fore International Policy.

McKitrick, R. and M., C. Strazicich (2005). ‘Stationarity of global per capita carbon dioxide emissions: implications for global warming scenarios’, University of Guelph Department of Economics Discussion Paper 2005-03.

Nakicenovic, N., A. Grübler, S. Gaffin et al. (2003): ‘IPCC SRES revisited: a response’, Energy & Environment, **14**(2-3) May: 187-214

Neumayer, E. (2004): ‘National carbon dioxide emissions: geography matters’, Area, **36**(1): 33-40

Paltsev, S., J.M. Reilly, H.D. Jacoby, et al. (2005): ‘The MIT emissions prediction and policy analysis (EPPA) model: version 4’, MIT Global Change Joint Program Report No. 125, August, Cambridge, MA: MIT.

Pindyck, R.S. (1999): ‘The long-run evolution of energy prices’, The Energy Journal, **20**(2): 1-27

Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2005): ‘World population prospects: the 2004 revision highlights’ New York: United Nations.

Pritchett, L. (1997): ‘Divergence, big time’, Journal of Economic Perspectives, **11**(3): 3-17

Quah, D. (1996): 'The invisible hand and the weightless economy', London: London School of Economics Centre for Economic Performance.

Rogner, H.H. (1997): ‘An assessment of world hydrocarbon resources’, Annual Reviews of Energy and the Environment (22): 217-262

Schmalensee, R., T.M. Stoker and R.A. Judson (1998): ‘World carbon dioxide emissions: 1950-2050’, Review of Economics and Statistics, **80**: 15-27

Seldon, T., and D. Song (1994): ‘Environmental quality and development: is there a Kuznets curve for air pollution emissions?’, Journal of Environmental Economics and Management, **27**:7-162

Sue Wing, I. and R.S. Eckaus (2004): ‘Explaining long-run changes in the energy intensity of the US economy’, MIT Global Change Joint Program, Report No 116, September, Cambridge, MA: MIT.

World Energy Council (2000): World Energy Assessment: Energy and the challenge of sustainability, New York: United Nations Development Programme.

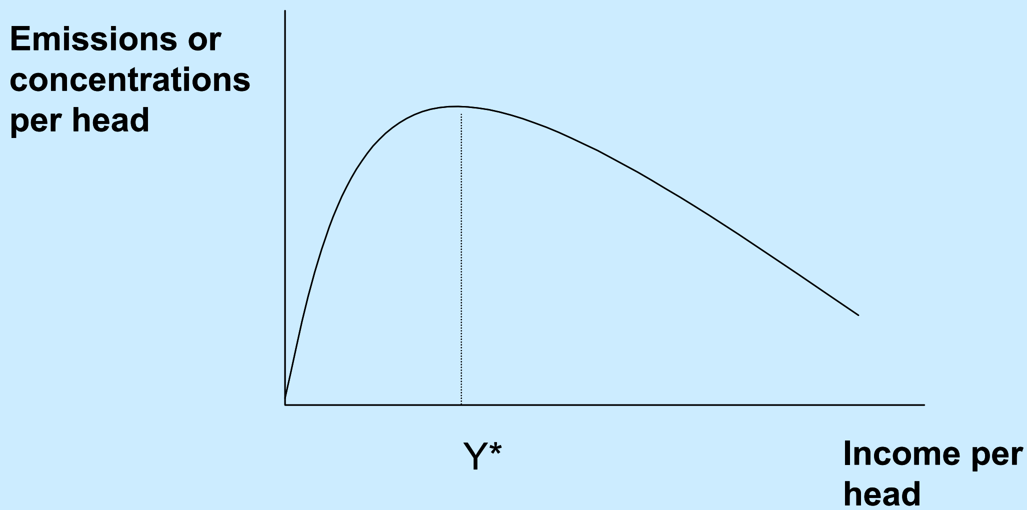
World Resources Institute (2005): ‘Navigating the numbers’, World Resources Institute, Washington DC.

World Resources Institute (2006): Climate Analysis Indicators Tool (CAIT) on-line database version 3.0., Washington, DC: World Resources Institute, available at: http://cait.wri.org

Annex 7A Climate Change and the Environmental Kuznets Curve

Some evidence indicates that, for local pollutants like oxides of nitrogen, sulphur dioxide and heavy metals, there is an inverted-U shaped relationship between income per head and emissions per head: the so-called 'environmental Kuznets curve', illustrated in Figure 7.7[52]. The usual rationale for such a curve is that the demand for environmental improvements is income elastic, although explanations based on structural changes in the economy have also been put forward. So the question arises, is there such a relationship for CO_2? If so, economic development would ultimately lead to falls in global emissions (although that would be highly unlikely before GHG concentrations had risen to destructive levels).

Figure 7A.1 'A hypothetical environmental Kuznets curve'

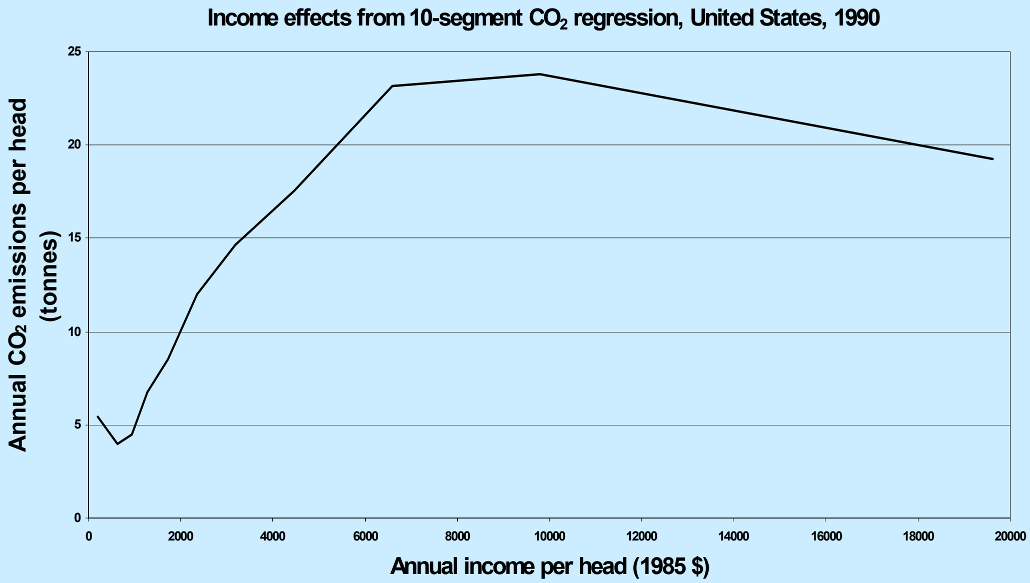


In the case of greenhouse gases, this argument is not very convincing. As societies become richer, they may want to improve their own environment, but they can do little about climate change by reducing their own CO_2 emissions alone. With CO_2, the global nature of the externality means that people in any particular high-income country cannot by themselves significantly affect global emissions and hence their own climate. This contrasts with the situation for the local pollutants for which environmental Kuznets curves have been estimated. It is easier than with greenhouse gases for the people affected to set up abatement incentives and appropriate political and regulatory mechanisms. Second, CO_2 had not been identified as a pollutant until around 20 years ago, so an explanation of past data based on the demand for environmental improvements does not convince.

Nevertheless, patterns like the one in Figure 7.4 suggest that further empirical investigation of the relationship between income and emissions is warranted. The relationship could reflect changes in the structure of production as countries become better off, as well as or instead of changes in the pattern of demand for environmental improvements. Several empirical studies[53] have found that a relationship looking something like the first half of an environmental Kuznets curve exists for CO_2 (after allowing for some other explanatory factors in some, but not all, cases). Figure 7.8 illustrates this, using Schmalensee et al's estimates for the United States.

[52] See Seldon and Song (1994) and Harbaugh et al (2002)
[53] See, inter alia, Neumayer, op. cit., Holtz-Eakin and Selden (1995) and Schmalensee et al, op. cit.

Figure 7A. 2 'Income effects from 10-segment CO_2 regression, USA, 1990'



Source: Schmalensee et al (1998)

Even if this finding *were* robust, however, it does not imply that the global relationship between GDP per head and CO_2 emissions per head is likely to disappear soon. The estimated turning points at which CO_2 emissions start to fall are at very high incomes (for example, between $55.000 and $90,000 in Neumayer's cross-country study, in which the maximum income level observed in the data was $41,354). Poor and middle-income countries will have to grow for a long time before they get anywhere near these levels. Schmalensee et al found that, using their estimates – *with* an implied inverted-U shape – as the basis for a projection of future emissions, emissions growth was likely to be positive up to their forecast horizon of 2050; indeed, they forecast more rapid growth than in nearly all the 1992 IPCC scenarios, using the same assumptions as the IPCC for future population and income growth.

In any case, it is not clear that the link between emissions and income does disappear at high incomes. First, the apparent turning points in some of the studies may simply be statistical artefacts, reflecting the particular functional forms for the relationship assumed by the researchers[54]. Second, the apparent weakening of the link may result from ignoring the implications of past changes in energy technology; after controlling for the adoption of new technologies that, incidentally, were less carbon-intensive, the link may reappear, as argued by Huntington (2005).

[54] This is not the case with the 'piecewise segments' approach of Schmalensee et al.