2 Greenhouse gas emissions

What is covered in this chapter?

This is a book about controlling man-made climate change. Therefore we start with the man-made gases and aerosols that are responsible for climate change. They fall into two categories: (1) the six gases covered under the Kyoto Protocol: carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, perfluorinated compounds, and hydrofluorocarbons; (2) ozone, chlorofluorocarbons, and aerosols. Their emissions sources are discussed in terms of the processes and the sectors of the economy where they emerge and the contributions of different countries. The strong increase and continuing upward trends of greenhouse gas emissions form a big challenge for emission reduction.

Contributions to warming

As discussed in Chapter 1, the contribution of gases and aerosols to warming depends on their effectiveness to retain solar radiation (called radiative properties) and their concentration in the atmosphere.

Controlling climate change therefore requires control of these concentrations. And concentrations are the combined result of input (emissions) and disappearance of gases. It is like filling a bath. If we want to control the water level, and the drain is closed, it means the tap has to be shut. And so it works with greenhouse gases (see Figure 2.1). Greenhouse gases disappear very slowly from the atmosphere. It takes 100 years before half of an amount of carbon dioxide (CO_2) put into the atmosphere has disappeared, but about 20% stays in the atmosphere for thousands of years. For methane (CH_4) it takes 12 years for two-thirds of it to disappear (called the 'lifetime'). For nitrous oxide (N_2O) this takes 110 years. For fluorinated gases the lifetime of the most common gases ranges from about 10 to several thousand years. Aerosols that contribute to cooling by comparison have a short residence time of several years. Given the slow disappearance of the most important greenhouse gases, emissions have to be reduced to very low levels if we want to prevent concentrations from rising above a certain level.

Table 2.1. Global warming potentials

Gas	Global warming potential: 20 years	100 years	500 years
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
HFC23	12000	14800	12200
SF6	16300	22800	32600

Source: IPCC Fourth Assessment Report, Working Group I, table TS.2

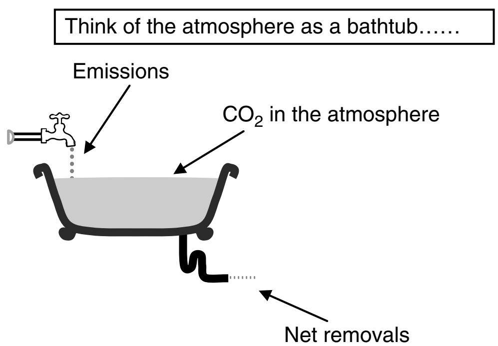


Figure 2.1 **Schematic representation of the atmosphere as a bath tub.**

The radiative properties of greenhouse gases are expressed in the global warming potential (GWP). This is the warming of an amount of that gas released into the atmosphere, compared to the warming of the same amount of CO_2 over a period of time. It captures both the radiative property of the molecules and the residence time in the atmosphere. For the most important greenhouse gases the GWPs are given in Table 2.1. The GWP for CO_2 is thus by definition equal to 1. Depending on the period of time chosen to compare the gases, the GWP of other greenhouse gases changes. For CH_4, a relatively short lived gas with powerful radiative properties, the GWP is 75 for a 20 year period, but for a 100 year period it drops to 25, because much of the CH_4 has disappeared in that period. This is of course more pronounced for a period of 500 years, which explains the GWP of 7.6. Some greenhouse gases like sulphur hexafluoride (SF6) and hydrofluorocarbon 23 (HFC23) are very powerful, with a radiative effect more than 10000 times that of CO_2.

GWPs are handy to add up the effect of different gases. If the quantities of each gas are multiplied with their respective GWPs, then adding them up gives you the total, so-called CO_2 equivalent emission. This CO_2 equivalent measure is used frequently throughout this book.

Kyoto greenhouse gases

Emission trends

The 1997 Kyoto Protocol agreement[1] focused on the major man-made contributors, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), perfluorinated fluorocarbons (PFCs), and hydrofluorocarbons (HFCs), the reason being that other gases and aerosols are much harder to control. With 75% of the warming caused by the Kyoto gases, it was also a good start at controlling climate change.

Emissions of the Kyoto gases have risen sharply over the last 35 years. The total[2] went up 70% between 1970 and 2004 with CO_2, the largest contributor, increasing by 80%.

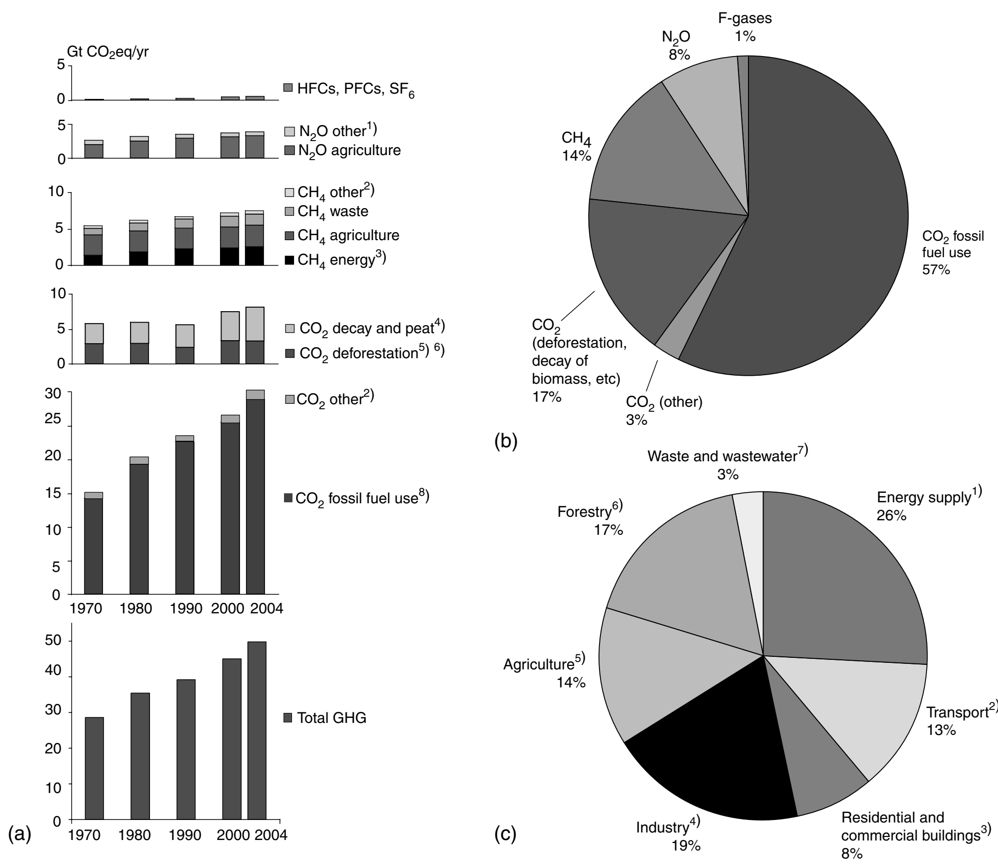


Figure 2.2 **(a) Global annual man-made emissions of greenhouse gases from 1970 to 2004. (b) Share of different gases in total emissions in 2004. (c) Share of different sectors in total emissions in 2004. Gases are weighted according to their GWP and expressed in terms of CO_2-eq.**
Source: IPCC Fourth Assessment Report, Synthesis Report, figure SPM.3.

The proportion of CO_2 in the 2004 emissions is slightly more than 75%, for CH_4 it is 15%, and for N_2O 8% (see Figure 2.2b).

Where are these emissions coming from?[3]

CO_2 comes mainly from burning coal, oil, and gas (75%). Smaller amounts are produced from turning oil and gas into plastics and other compounds that eventually are decomposed into CO_2 again (3%) as well as from manufacture of cement through decomposition of one of the main ingredients, limestone (3%). About 20% of the total CO_2 emissions comes from deforestation and decomposition of peat lands, crop residues, and organic materials in agricultural soils.

CH_4 comes from a variety of sources, the largest being livestock, particularly cattle and sheep (25%). This is followed by leaks from extraction, processing, and distribution of natural gas (15%). Other important sources are rice cultivation (12%), associated gas from coal production (10%), and decomposition of organic waste in waste water treatment (9%) and landfills (7%).

N_2O mainly comes from fertilized grasslands and croplands, where nitrogen fertilizers are decomposed in the soil (35%), followed by animal waste (26%). Surface water polluted with nitrogen accounts for about 15%. Small amounts come from chemical factories, such as those for nylon production (5%) and waste water treatment (2%). Cars with catalytic converters produce small quantities of N_2O (about 1% of the total).

Fluorinated gases (mostly HFCs) are emitted mainly from air conditioners in cars and refrigerators, as well as from the production of industrial chemicals. SF_6 is mainly used as an insulator in electrical equipment.

Economic sectors

If we organize the main sources of greenhouse gas emissions according to the sectors of the economy, we see that energy supply is the largest (26%), followed by industry (19%), the forest sector (17%), agriculture (14%), transport (13%), the building sector (8%), and waste management (3%)[4]. Emissions from electricity supply and transport are growing fastest. Figure 2.2c gives the global distribution in 2004.

Confusion can arise around sector contributions, because emissions can be counted in different ways. The numbers given above are based on emissions at the point where they enter the atmosphere (so-called 'point of emission allocation'). So emissions from electricity generation are counted under the energy supply sector. However, it can be more useful to count such emissions under the sector where that electricity is used (so-called "end-use allocation"). That can give a better picture of how electricity emissions

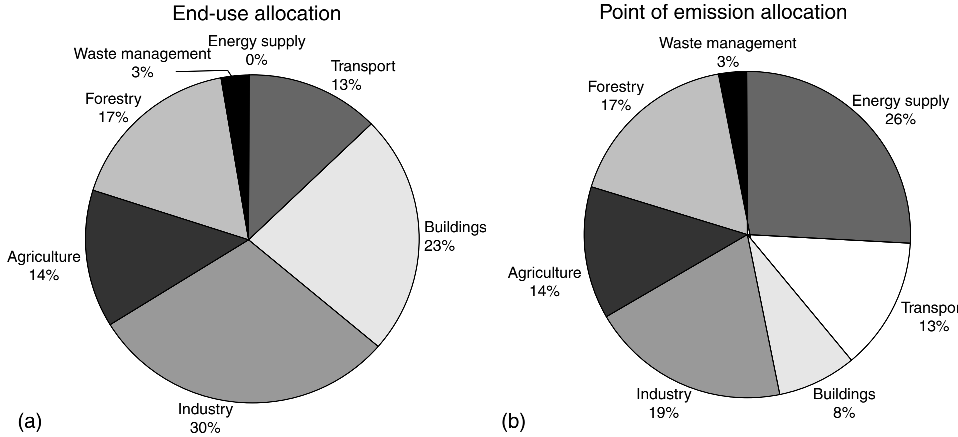


Figure 2.3 **Comparison of sector shares of global greenhouse gas emissions, according to two different allocation methods.**

can be reduced through energy savings. Counting emissions according to these so-called end-use sectors gives a very different picture, with the industry sector being the largest, followed by forestry (see Figure 2.3).

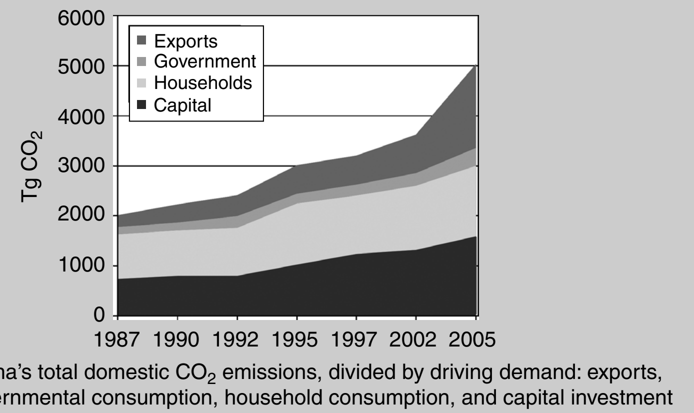
Another complicating issue is exported goods. The current accounting system for emissions, as adopted under the Climate Convention, allocates emissions of exported coal, oil, and gas to the user country, but emissions of manufacturing goods to the exporting country. The argument is that for manufactured goods such a system is simpler, because no calculations have to be made about the emissions contained in exported goods, but also that the exporting country has the economic benefits of that export. For many countries there is not a big difference between the two systems, because they are also importers, so that the effects more or less cancel out. For a country like China however, with a huge export surplus, it does matter (see Box 2.1).

Box 2.1

Greenhouse gas emissions embedded in China's exported goods

Due to China's large export of manufactured goods, about one third of its domestic CO_2 emissions are in fact related to exports (see figure). Emissions from importing countries of course would go up if the emissions from imported goods were counted there. For instance the emissions from the UK would have been about 11% higher had all imported goods from China been produced domestically. For other countries the picture can be very different of course.

If these exported goods had been manufactured in the importing countries instead, global CO_2 emissions would have been lower. The reason is the relatively high carbon intensity of China's energy supply.



CO_2 emissions from China. Exports means the emissions generated by the manufacturing of exported goods.

Source: Weber C. L. et al. The contribution of Chinese exports to climate change, Energy Policy, 2008, doi:10.1016/j.enpol.2008.06.009.

(Source: US Congressional Research Service, China's greenhouse gas emissions and mitigation policies, September 2008; You Li and C.N. Hewitt, The effect of trade between China and the UK on national and global carbon dioxide emissions, Energy Policy vol. 36, Issue 6, June 2008, pp. 1907–1914)

Which countries are responsible for greenhouse gas emissions?

The largest emitter of greenhouse gases is China, followed by the USA, the European Union, Indonesia, and India. This is the ranking for all greenhouse gases together, including land use change[5]. Leaving out emissions from land use change, which is often done when presenting country data, does change the picture significantly. Without land use change emissions, Indonesia for instance drops from place 4 to 12 and Brazil from place 7 to 13[6] (see Figure 2.4).

It is more illustrative and fairer to compare countries on the basis of average emissions per person[7], and this changes the ranking dramatically (see Figure 2.5). An average American citizen emits about 5 times as much as an average Chinese citizen and about 8 times as much as an average Indian citizen.

However, average citizens do not exist. A relatively poor country like India has a considerable number of rich people, whose consumption pattern causes much higher emissions than the average for the country, and is comparable to citizens in developed countries. And relatively wealthy countries do have poor people who produce low emissions. Out of the 6.5 billion people on earth, about 750 million have high emissions (more than 10t CO_2/yr) and a billion people very low emissions (less than 0.1 t CO_2/yr)[8]. This brings us to the issue of lifestyle.

Personal emissions and lifestyle

It is obvious that personal emissions of greenhouse gases depend on lifestyle. And that means consumption of electricity for home appliances, gas for heating and cooking, and

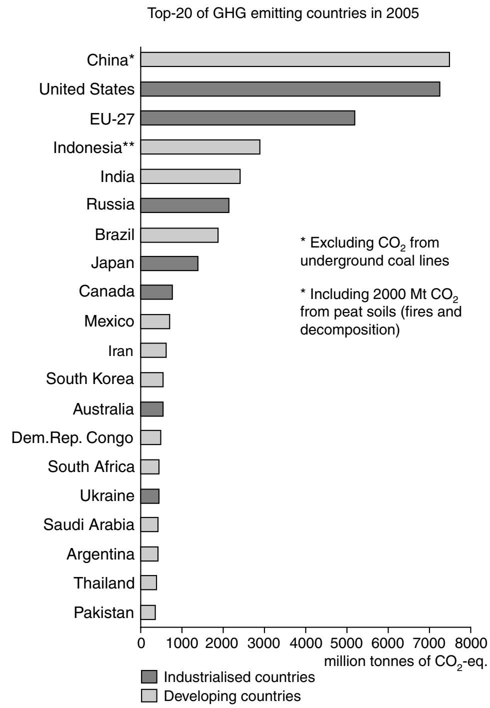


Figure 2.4 **Total greenhouse gas emissions including all Kyoto gases and including land use change in 2005 for the 20 largest emitters.**
Source: Netherlands Environmental Assessment Agency[6].

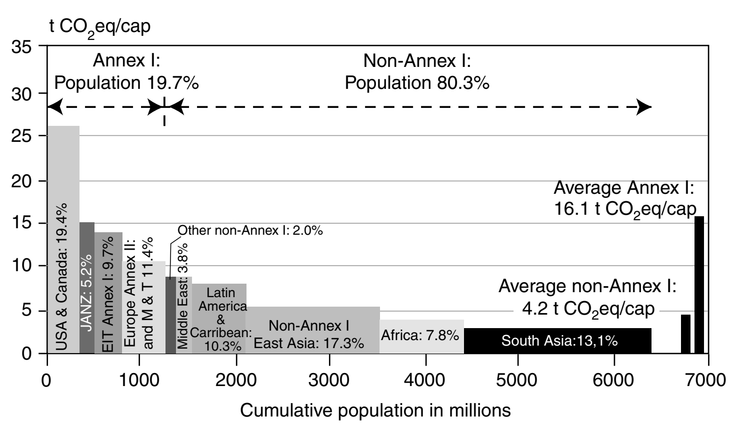


Figure 2.5 **Emission per person for various regions (2004 data). On the vertical axis the emissions per person of all greenhouse gases, expressed as t CO_2-eq, are shown; on the horizontal axis the number of people in the various regions is given. The surface area of the rectangles for each region is proportional to the total emissions. Annex-I is a term from the Climate Convention (see Chapter 12), covering 36 industrialized countries; non-Annex-I covers all other (developing) countries. The world average emission per capita is 6.5 tCO_2 eq/cap.**
Source: IPCC Fourth Assessment Report, Working Group III, figure SPM.3.a.

fuel (motorcycle, bus, car, plane), or electricity (train, tram) for transport. Food consumption also contributes, as well as the indirect emissions of consumer products and emissions generated at the workplace. What are the emissions due to these various activities?

An average UK citizen consumes about 1600 kWh of electricity per year, 740 m^3 of gas for home heating, and drives roughly 6500 km in a car. Add to that a substantial amount of hot and cold water, train and bus rides, several flights, and lavish consumption of food and other consumer goods and you get a rather greenhouse gas intensive consumption pattern. To convert these consumption data to emissions the average CO_2 emission per kilowatthour electricity and the average fuel consumption of cars, buses, and airplanes need to be used (see Box 2.2). This adds up to about 12.5 tonne of CO_2 per average UK person per year (see Table 2.2[9]). Of course, individual lifestyles vary considerably and so do personal emissions. There are many personal CO_2 calculators available online[10].

Box 2.2 **CO_2 emissions per unit of energy or activity**

Per unit of energy (GJ):
- Coal: 90 (kg/GJ)
- Oil: 70 (kg/GJ)
- Gas: 50 (kg/GJ)

Per unit of fuel:
- Litre of gasoline: 2.3 kg/l
- Litre of diesel: 2.6 kg/l
- Cubic metre of natural gas: 1.6 kg/m^3

Per km driven:
- Efficient car (1 l on 20 km; gasoline): 115 g/km; with 2 people: 57 g/km/person
- Inefficient car (1 l on 8 km; gasoline): 287 g/km with 2 people: 143 g/km/person
- Diesel vehicle (1 l on 15 km; diesel): 173 g/km
- Truck (1 l on 3 km; diesel): 870 g/km
- Bus: (1 l on 5 km; diesel): 520 g/km; with 20 people: 13 g/km/person

Per km in airplane (see note):
- Short flight: 150 g/km/person
- Long flight: 110 g/km/person

Per kilowatt hour electricity:
- From coal: 0.85–1.35 kg/kWh
- From gas: 0.4–0.52 kg/kWh
- From hydropower: 0.01–0.08 kg/kWh
- From nuclear: 0.04–0.012 kg/kWh
- From wind: 0–0.03 kg/kWh

Note: Data from UK DEFRA Company Greenhouse Gas Reporting Manual. The aviation emissions are not corrected for the multiplier effect due to release of emissions at high altitude. This multiplier is about a factor 2–4 according to the IPCC Special Report on Aviation, 2000.

Table 2.2. Personal greenhouse gas emissions for an average UK person

Activity	Average consumption per person	Emissions (tonne CO_2/person/ year)
House heating	Gas: 740 m^3/person/year	1.2
Hot water, cooking		0.4
Lighting, appliances	Electricity: 1600 kWh/person/year	0.7
Transport: motorcycle, car	6525 km/person/year	1.2
Transport: bus, rail		0.1
Transport: air		1.8
Other direct		0.6
Indirect emissions from food		2.1
Indirect emissions from consumer goods		3.1
Indirect emissions from workplace		1.3
TOTAL		12.5

Source: Goodall C. How to live a low-carbon life, Earthscan, London, 2007.

Emission intensity of the economy

Emissions can also be related to the size of the economy. Normally the size of the economy is expressed as gross domestic product (GDP). The higher the GDP, the higher the energy use and greenhouse gas emissions. But there are differences among countries. If a country has an economy that is energy and fossil fuel intensive, emissions per unit of GDP will be higher than for a country whose economy is not so dependent on energy use (see Chapter 3 for more detail).

Comparing countries' economies does entail some complexities. There are basically two ways to do it. One is to compare the GDPs by converting the local currency into a standard currency, say the US dollar. This is then called GDP at market exchange rates (GDP_{mer}). Such a comparison does not take into account the differences in local prices. People can have relatively low incomes, but with low prices for food, housing, etc. they can be better off than people in another country with higher incomes. If those things are taken into account, a corrected GDP can be calculated before it is converted to an international currency. That is the so-called GDP at purchasing power parity (GDP_{ppp}), which will be used here.

Figure 2.6 shows that industrialized countries generally have a more energy efficient economy than former communist countries in Eastern Europe and Asia (so-called economies-in-transition) and developing countries. However, the US economy is only slightly more efficient than that of India (the South Asia region) and only about 30%

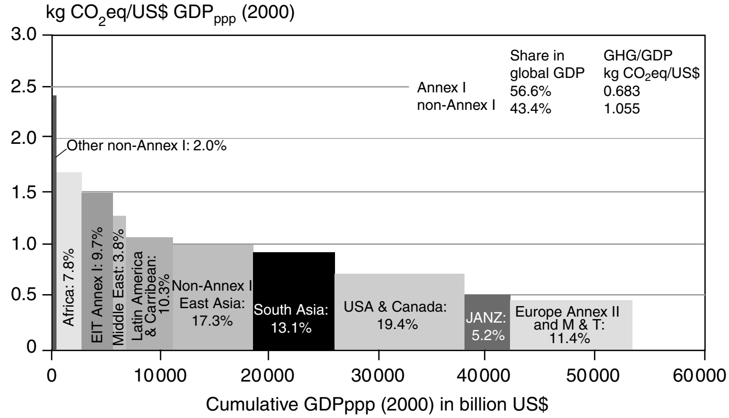


Figure 2.6 **Emission per unit of GDP_{ppp} for various regions (2004 data). On the vertical axis the emissions of all greenhouse gases per unit of GDP_{ppp}, are shown; on the horizontal axis the number of people in the various regions is given. The surface area of the rectangles for each region is proportional to the total emissions. The world average emission per unit of GDP is 0.84 kg CO_2eq/US.**
Source: IPCC Fourth Assessment Report, Working Group III, figure SPM.3.b.

more efficient than that of China. Japan and Europe are the most efficient economies, being about 25% more efficient than the US and more than three times as efficient as the so-called economies-in-transition.

For better understanding of differences between countries it can be useful to look at emissions per unit of product. For instance, steel plants differ with respect to the amount of CO_2 emissions per tonne of steel produced due to differences in processes and in the efficiency of energy use. Knowing these numbers is particularly useful in finding ways to reduce emissions (see Chapter 8 for more detail). The same approach can be followed for a whole range of energy efficient products, such as cement, glass, aluminium, paper, and others. When comparing energy use and greenhouse gas emissions in buildings it is often helpful to express energy or emissions per unit of floor space. In all cases the numbers are of course influenced by the type of fuel used or the carbon emissions of the electricity used.

Finally, it can also be enlightening to look at cumulative emissions. Due to the long life time of greenhouse gases the cumulative amount emitted to the atmosphere is directly correlated with the concentration. That means for instance that responsibility for the increased concentrations of CO_2, CH_4, N_2O, and other greenhouse gases that we see today lies predominantly with the industrialized countries, which started to emit CO_2 150 years ago. When we look at the cumulative emissions between 1950 and 2002 of CO_2 from energy only, developed countries are responsible for 71% and developing countries 29%. But when we also include CO_2 from deforestation, the shares become almost equal: developed 51%, developing 49%. Extending the period over which cumulative emissions are looked at to 1850–2002 would add the emissions from deforestation in developed countries that mostly happened before 1950. As a result the share of developed versus developing countries goes back to about 70:30 again[11].

Other gases and aerosols

As indicated above, the Kyoto gases are only responsible for 75% of the warming effect due to greenhouse gases and aerosols and they do not cause any cooling, as some other gases and many aerosols are doing[12]. So what are these other gases and aerosols and where do they come from?

Gases covered under the Montreal Protocol on protecting the ozone layer[13]

The Montreal Protocol, established in 1988, controls gases that damage the ozone layer that protects the earth against ultraviolet radiation. This layer sits in the stratosphere, 10–50 km above the earth. Most of these gases are also greenhouse gases, in particular chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, and gases like methylchloroform, methylbromide and carbontetrachloride. CFCs and HCFCs are by far the most important. They were not included under the Kyoto Protocol because they were already regulated under the Montreal Protocol. Together they are responsible for 10% of the warming and 3% of the cooling effects.

Emissions mainly come from refrigeration and air conditioning, insulating and packaging foams, fire extinguishers, and industrial cleaning agents. Total emissions of CFCs and HCFCs have been declining strongly since the Montreal Protocol came into force in 1988. As a result of the ban on CFCs, emissions went sharply down, while those of HCFCs and HFCs went up (see Figure 2.7).

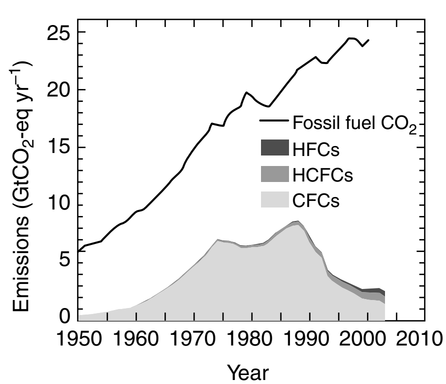


Figure 2.7 **Emissions of fluorinated gases (GWP weighted), in comparison with fossil fuel CO_2 emissions.**
Source: IPCC Special Report on Protecting the Ozone Layer and the Global Climate System, 2005.

Ozone

Ozone in the troposphere (the first 10km of the atmosphere) is responsible for slightly more than 10% of the warming (see Figure 1.6). It is not emitted as such, but formed by reactions of other pollutants in the atmosphere under the influence of sunlight. These so-called precursor gases are carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (methane and others). These gases are emitted by fossil fuel burning engines (cars, generators, etc.) and industrial furnaces, as well as from a variety of industrial sources. None of these gases are controlled under the Kyoto Protocol, but since they are well known air pollutants, there are regulatory measures in many countries affecting their emissions. Ozone itself is a primary concern from the point of view of impacts on human health, crops, and ecosystems. Average tropospheric ozone concentrations have increased by about 50% since 1860[14], but there are strong regional variations, mostly as a result of air pollution policies in Europe, North America, and Japan that led to lower emissions of precursor gases.

Ozone in the stratosphere (10–50 km above the earth) acts as a filter for harmful UV radiation. It is formed under the influence of sunlight, but is also disappearing due to reactions with so-called ozone depleting substances. CFCs are the most prominent of these ozone depleters, which is the reason they are being phased out under the Montreal protocol. Ozone depletion is most visible during September to December above the South Pole, the so-called 'Antarctic ozone hole'. As a result of this depletion process average stratospheric ozone concentrations have declined compared to 1750, contributing a little bit to cooling (see Figure 1.6).

Aerosols

There are many different aerosols with different properties that affect the extent to which they absorb or scatter solar radiation. Most aerosols have a cooling effect, but some contribute to warming. Aerosols are responsible for more than 80% of the total cooling. The effect is partially direct (solar radiation directly affected by the particles), partially indirect because aerosols enhance clouds that then reflect sunlight. The most important cooling aerosols are sulphates (formed in the atmosphere from sulphur dioxide emissions as a result of burning coal and oil; responsible for about 60% of the total cooling), nitrates (also formed in the atmosphere from nitrogen oxide; 15%), dust (from soils and roads; 15%), and organic carbon (formed due to incomplete combustion in industry, power generation, traffic, and homes as well as from agricultural waste burning; 12%). Black carbon (different from organic carbon because it originates from the burning of fossil fuel only, but is formed in the same way as organic carbon) has a warming effect that takes away about 30% of the overall aerosol cooling.

Emissions of these aerosols are not known very precisely. Historically sulphur dioxide emissions have been proportional to growing fossil fuel use. Since 1970 however air pollution abatement policies in Europe and North America have slowed down this growth considerably, even though emissions in Asia have grown with increasing fossil fuel use. The most recent global trend is a more or less stable emission of around 55–60 million tonnes of sulphur per year. Nitrogen oxide emissions showed a similar pattern, with current annual emissions around 30 million tonnes of nitrogen.

Emissions of organic and black carbon are particularly uncertain due to limited inventory studies. They have increased with increasing fossil fuel use, agriculture, and deforestation. Current estimates are 3–10 million tonnes/year for black carbon and 5–17 million tonnes/year for organic carbon. No recent trend can be identified.

None of the aerosol emissions have been regulated under any international agreement so far, because of the large uncertainty in emissions that would make agreed policy intervention very difficult.

How will emissions develop in the future?

Future emissions will of course depend on what we do about climate change. If worldwide action is taken to curb greenhouse gas emissions, the situation will be very different from a 'business as usual' future. Let us first look at this 'business as usual' or 'no action' situation.

Driving forces

In order to come up with plausible estimates of future emissions it is important to understand the forces that influence them, the so-called driving forces.

In its simplest form we can say:

$$\text{Emissions} = \text{number of people} \times \text{income per person} \times \text{emissions per unit of income}$$

Number of people or population is straightforward. Income per person (expressed as GDP[15]/capita) reflects economic development. The emissions per unit of income depend mainly on the amount and type of energy used, technology choices, land use and land use change, and lifestyle (what the money is spent on). The various driving forces will be discussed here briefly.

Population

Population projections for this century have been lowered since the early 1990s, based on falling birth rates in many parts of the world. The most recent projections suggest a world population of 8–9 billion in the year 2100, but with a fairly large uncertainty range

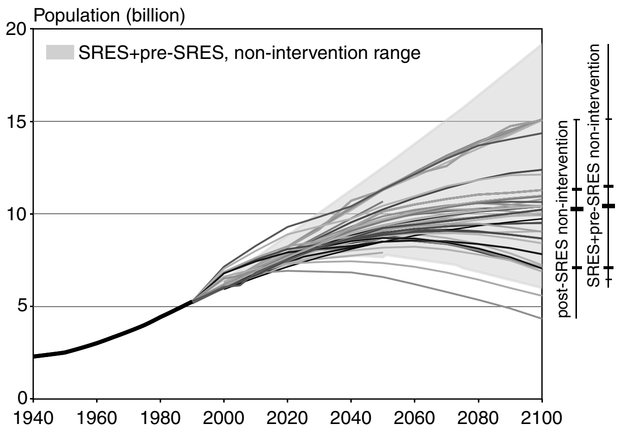


Figure 2.8 **Global population projections as reported in the IPCC Special Report on Emission Scenarios (SRES+ pre-SRES; light shaded area) and in the IPCC Fourth Assessment Report, Working Group III, chapter 3 (post-SRES non-intervention, dark shaded area).**

Source: IPCC Fourth Assessment Report, Working Group III, figure 3.1. See Plate 6 for colour version.

of 5–15 billion, caused by uncertainty about future birth rates (see Figure 2.8). Some of the lower projections even show a decline in the population after the middle of the century. To deal with this uncertainty scenarios are used. Scenarios are certain combinations of assumptions belonging to a possible future situation. A scenario for a future with high economic growth and ample attention for education and social justice would give a relatively low population growth, because birth rates are likely to go down faster in such a situation. In a low economic growth scenario without strong social policies population growth would be high.

Economic development

Economic development, expressed as global GDP, is projected to increase strongly in the future[16]. In light of the large number of people still living in poverty, this is a necessity and a matter of social justice. Overall economic growth of course does not say anything about income differences, but we leave that aside for this discussion.

In light of historic development, assumptions for future global average economic growth rates vary between 1% and 3% per year. By the end of this century that could lead to large differences in global GDP (4 to 20 times the current global income). Growth rates in different parts of the world will show even bigger differences. To deal with uncertainties scenarios are used, in which growth rates are chosen to be consistent with the kind of economic and social policies assumed. Figure 2.9 shows the range of the IPCC SRES scenarios for the period until 2030, together with some other projections from the Worldbank, the International Energy Agency, and the US Department of Energy.

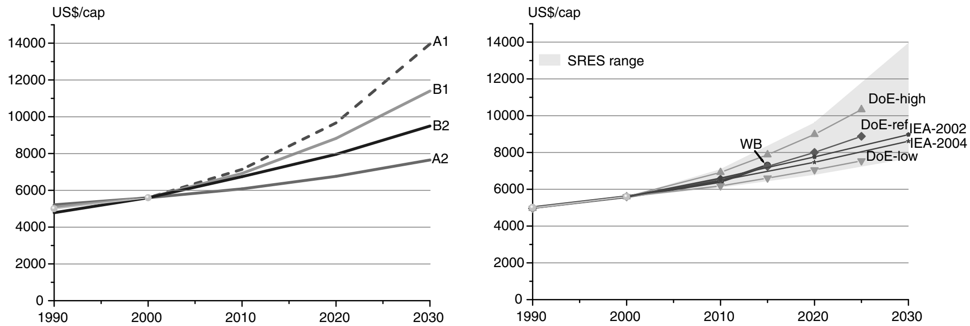


Figure 2.9 **Scenarios for development of global income (GDP) till 2030. DoE= US Dept of Energy; IEA = International Energy Agency; WB= Worldbank; shaded area is from IPCC-SRES = scenarios from IPCC Special Report on Emission Scenarios.**
Source: IPCC Fourth Assessment Report, Working Group III, figure 3.3.

Emissions per unit of income

Emissions per unit of income are driven by four important factors:

- Energy use
- Technology
- Land use
- Lifestyle

These are discussed below.

Energy use

One of the most important factors that drives emissions per unit of income is energy use[17]. Historically there has been a strong correlation between income and energy use (see Figure 2.10).

This figure tells us that energy is essential for development. It also shows that there is a fairly large spread in energy use at any given income level, meaning that certain countries managed to develop with relatively low energy use compared to others. Or, in other words, some countries have a much lower energy intensity (energy per unit of GDP) of their economy than others. Historically global energy intensity has been declining since the 1960s due to a shift towards a more service based economy and improved technology (the amount of energy used by cars, appliances, buildings, manufacturing processes, etc.). It is now about 25% lower than in 1960. Scenarios for this century estimate it will further decline by about 1% per year, leading to something like a 75% reduction by the end of the century compared to 1960. Technology and life-style (what people prefer to do with their time and money) make a difference. So energy intensity could be even lower.

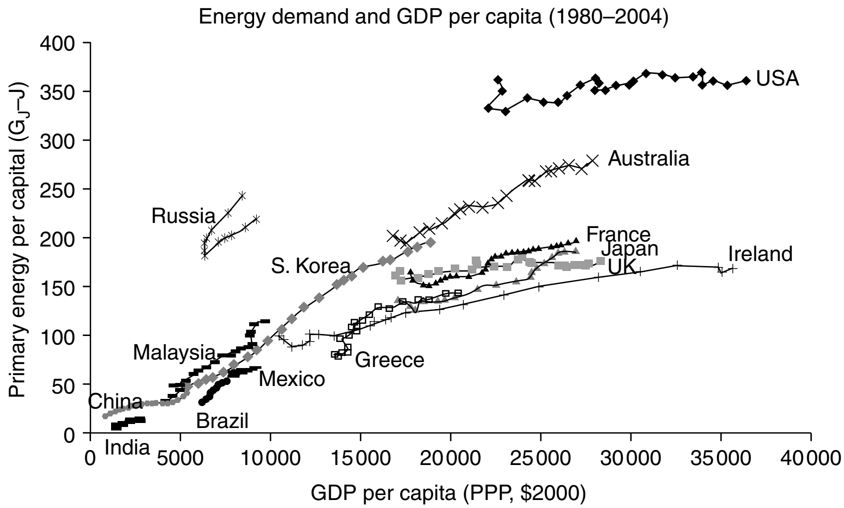


Figure 2.10 **Relationship between GDP_{ppp} per capita and primary energy use per capita for selected countries over the period 1980–2004. Russian data only 1992–2004.**

Source: Steven Koonin, Energy Trends and Technologies: facts, challenges and responses, iis-db. stanford.edu/evnts/5153/Drell_Lecture_0208.pdf ; data from UN, DOE/EIA.

The type of energy used, in particular the carbon content of it, also matters a lot. The dominant energy source since the start of the industrial revolution has been fossil fuel. First there was coal, later came oil, which was followed by natural gas. Gas produces about half the CO_2 of coal for a given amount of useful energy (see also Box 2.2). As a result the average carbon content of the world's energy use is now about 30% lower than in the year 1900. However, since the year 2000, this trend seems to have reversed. Global carbon intensity is going up due to a shift to coal because of sharply increased prices of natural gas and heavy use of coal in fast growing developing countries such as China and India[18].

Scenarios for this century still show a decline of about 0.4% per year, but with a high uncertainty. This could halve carbon intensity by the end of the century compared to 1960; however a small increase also is possible. Again, technology is playing a big role, because large scale use of nuclear power or renewable energy could make a great difference.

Figure 2.11 shows the historic CO_2 emissions as a function of income, an analogous picture to the one on energy. Note the relatively low per capita emissions of France, caused by a conscious decision after the 1970 oil crisis to develop a nuclear power based electricity sector (currently about 80% of electricity in France is nuclear).

Land use[19]

Over the past centuries human civilization has changed land cover dramatically, especially by converting forest and wilderness areas into agricultural land. This process is continuing, particularly in developing countries. Land use change is responsible for about

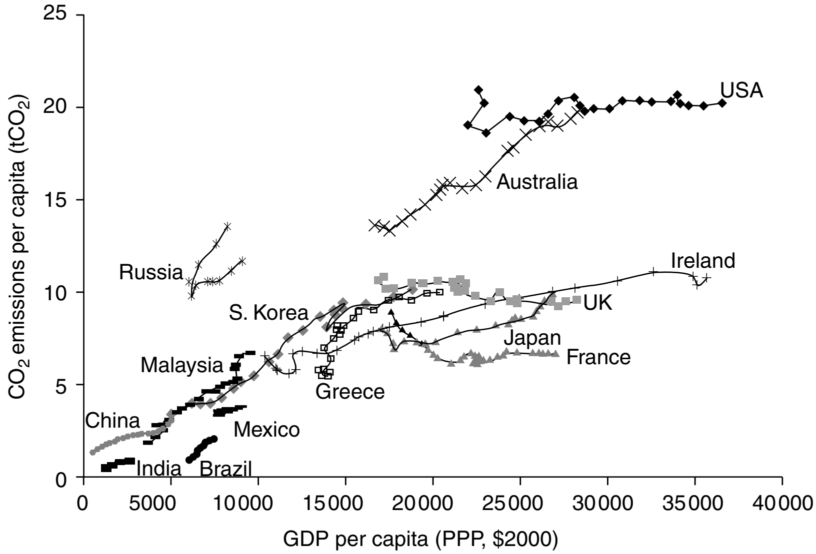


Figure 2.11 **Relationship between GDP_{ppp} per capita and CO_2 emission per capita for selected countries over the period 1980–2004. Russian data only 1992–2004.**

Source: Steven Koonin, BP, iis-db.stanford.edu/evnts/5153/Drell_Lecture_0208.pdf ; data from UN, DOE/EIA.

one-third of all of the CO_2 that was put in the atmosphere during the entire industrial era. It contributes about 20% to current global emissions. So future emissions will also depend heavily on how land use is going to develop.

Unfortunately future land use is difficult to project. Demand for food and timber and the land needed for that heavily depends on population, productivity of agriculture, and lifestyle. For a vegetarian diet about 80% less land is required to feed one person than for a meat based diet. Preservation of land for nature protection is another factor determining future land use. Scenarios for this century generally show cropland and grassland increasing and forests declining, but the spread is large. Some scenarios assume strong productivity growth in combination with lower population growth and strong forest protection policies, leading to an increase in forest land and maintenance of cropland and grassland areas. Other scenarios project increases of 40–50% in cropland and grassland areas, with up to 20% further loss of forest areas.

Emission projections

To project greenhouse gas emissions for this century all driving forces have to be combined into emissions scenarios. Since there is in principle an unlimited number of combinations of the various assumptions of all the relevant drivers, a sort of 'standardized' set of scenarios was developed by the IPCC[20], the so-called SRES scenarios. They defined four different

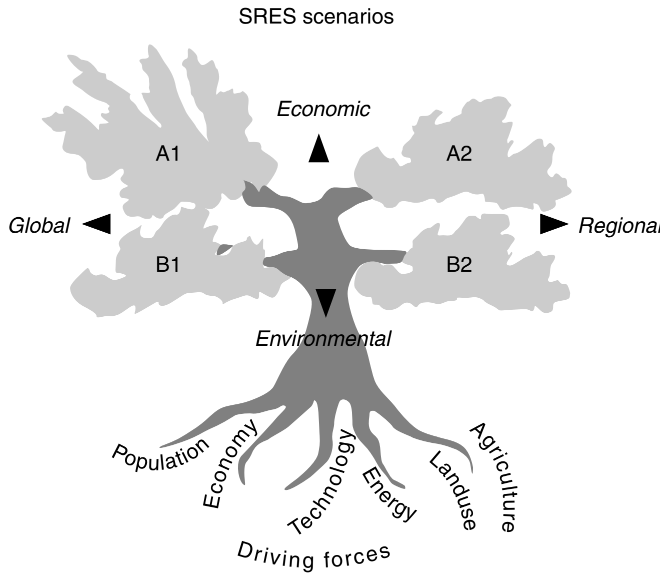


Figure 2.12 **Schematic illustration of SRES scenarios. The four scenario 'families' are shown, very simplistically, as branches of a two-dimensional tree. The value orientation (economic versus environmental) is shown on a vertical axis, the geographical orientation (global versus regional) on a horizontal one. The schematic diagram illustrates that the scenarios build on the main driving forces of GHG emissions. Each scenario family is based on a combination of value and geographical orientation. Each scenario family has a common specification of some of the main driving forces. The A1 storyline branches out into four groups of scenarios to illustrate that alternative development paths are possible within one scenario family.**
Source: IPCC Special Report on Emission Scenarios, figure TS-2.

'worlds' (or scenario families) by looking at two dimensions: (1) the value systems of societies: economic or environmental; (2) the orientation: global or regional, and then forming four different combinations (see Figure 2.12). They did *not* assume any specific policy to reduce greenhouse gas emissions.

For each of the 'worlds' consistent assumptions for the main drivers were made. For instance, high economic growth goes together with lower population growth and a faster introduction of new technology, whereas a strong environmental value system and low energy life styles are consistent. The characteristics of these four different worlds are summarized in Box 2.3.

Box 2.3

The main characteristics of the four SRES storylines and scenario families

By 2100 the world will have changed in ways that are hard to imagine – as hard as it would have been at the end of the 19th century to imagine the changes of the 100 years since. Each storyline assumes a distinctly different direction for future developments, such that the four storylines differ in increasingly irreversible ways. Together they describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving forces. They cover a wide range of key 'future' characteristics such as population growth, economic development, and technological change. For this reason, their plausibility or feasibility should not be considered solely on the basis of an extrapolation of *current* economic, technological, and social trends.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system. Two of the fossil-intensive groups were merged in the SPM.
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Based on these four different worlds, scenarios were developed to cover a wide range of possible outcomes. In addition to the four worlds described, for one world two variants were identified, to cover the range of technologies and energy choices, the so-called A1 High Tech (A1T) and A1 Fossil Intensive (A1FI) scenarios. For each of these six scenario families a representative scenario was chosen, together generally called the SRES scenarios.

Projections of greenhouse gas emissions for this century with these scenarios span a wide range, as illustrated in Figure 1.8. By the end of the century there could be up to a fourfold increase or a slight reduction compared to the year 2000. The decline of emissions in the second half of the century happens in scenarios that assume a stabilization and decline in global population. In the medium term however all scenarios show a strong increase of emissions. To bring it a bit closer to home, for the year 2030 the projected increase of all greenhouse gas emissions is somewhere between 25% and 90%.

Two-thirds to three-quarters of this increase will come from developing countries, in line with their economic development.

One important lesson from this is that socio-economic development matters a lot. The different scenarios reflect different socio-economic development paths that can in principle be influenced. So choices made in economic and social policy can make a huge difference in terms of future greenhouse gas emissions.

Are actual emissions higher than what scenarios project?

New scenarios developed after the SRES scenarios do not show a significantly different picture[21]. They lie within the range covered by the SRES scenarios. Although the newest insights lead to some differences in assumptions for population, other drivers, in particular economic growth and the carbon intensity of energy, have compensated this.

Comparing the scenarios with actual emissions over the past few years shows that they are around the high end of the scenario range. Some scientists have argued they are even significantly higher, but careful analysis of the data used shows this is probably not the case[22]. In addition, it is dangerous to draw conclusions about long term trends on the basis of data for only a few years. It is likely the years 2008 and 2009 will show a lower increase of emissions due to the worldwide economic recession. Nevertheless these findings are worrisome. It means that the necessary emission reductions to avoid major climate change damages will be more difficult to realize and the risk of short-term climate change impacts increases.

So what does this mean?

From the perspective of controlling climate change the emission trends outlined above are bad news. While drastic reductions of emissions are required to stop the atmospheric concentrations from rising, current emissions have a strong upward trend and without action projections for the future also are strongly upwards. On top of that the cooling effect from aerosols may go down, when air pollution in developing countries is addressed. So controlling climate change is an uphill battle: population increase, increasing incomes, and higher demand for energy to improve well-being in poor countries all point in the opposite direction. Action to reduce emissions has to overcome that and then bring emissions down drastically. Chapters 5 to 9 will discuss this for the most important economic sectors.

Notes

1. See for more detail on the Kyoto Protocol chapter 12.
2. Weighted according to the Global Warming Potential of each gas.

3. Ibid.
4. Tourism is covered under transport and buildings.
5. Emissions from bunker fuels used in international shipping and aviation is excluded, because no international agreement has been reached on how to allocate these emissions over the various countries.
6. http://www.mnp.nl/en/dossiers/Climatechange/FAQs/index.html?vraag=10title=Which%20are%20the%20top-20%20CO2%20or%20GHG%20emitting%20countries%3F#10
7. This includes also emissions that are not caused by individual consumption, such as everything related to export industries and international transport.
8. Chakravarty S et al. PNAS, 2009, doi:10.1073/pnas.0905232106.
9. Goodall C. How to live a low-carbon life, Earthscan, London, 2007.
10. See for instance Act-on at http://actonco2.direct.gov.uk/index.html; Conservation International at http://www.conservation.org/act/live_green/carboncalc/Pages/methodology.aspx
11. Baumert K et al. Navigating the numbers, chapter 6, WRI,Washington DC, 2005.
12. The combined cooling effect of aerosols, damage to the stratospheric ozone layer, and land use change is about half of the total warming effect of the other compounds.
13. IPCC Special Report on protecting the ozone layer and the global climate system, 2005.
14. Horowitz L. Past, present, and future concentrations of tropospheric ozone and aerosols: Methodology, ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research*, 111, 2006, D22211, doi:10.1029/2005JD006937.
15. GDP = gross domestic product, a measure of the total income of a country.
16. IPCC Fourth Assessment Report, Working Group III, chapter 3.2.1.2.
17. IPCC Fourth Assessment Report, Working Group III, chapter 3.2.1.5.
18. See chapter 5, figure 5.1.
19. IPCC Fourth Assessment Report, Working Group III, chapter 3.2.1.6.
20. IPCC Special Report on Emissions Scenarios, Cambridge University Press, 2000.
21. IPCC Fourth Assessment Report, Working Group III, chapter 3.2.2.
22. Van Vuuren D, Riahi K. Do recent emission trends imply higher emissions forever? Climatic Change, 2008, pp 1–12; doi:10.1007/s10584–008–9485-y.