The World in 2050

Implications of global growth for carbon emissions and climate change policy

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The World in 2050: implications of global growth for carbon emissions and climate change policy

Executive Summary

In March 2006, we published a report highlighting the rapid growth and increasing global significance of what we called the ‘E7’ emerging economies: China, India, Brazil, Russia, Mexico, Indonesia and Turkey. By 2050, we estimated that the E7 economies could be larger than the current G7 by between 25% and 75% depending on the measure used. As they increase in relative size, these emerging economies will increasingly provide the motor for global growth, but can the world sustain such rapid growth without serious adverse impacts on its climate? In this report, we address this question by extending our long-term economic model to incorporate the effects of world GDP growth on global energy consumption and carbon emissions. We then discuss technological and policy strategies for mitigating global carbon emissions without requiring a serious sacrifice of economic growth.

Alternative scenarios

We use our extended global economic model to estimate the implications of a range of alternative illustrative scenarios for the future evolution of global energy consumption and global carbon emissions:

- a **Baseline scenario** in which energy efficiency improves in line with trends of the past 25 years, with no change in fuel mix by country; it should be stressed that this is intended as a ‘business as usual’ scenario to act as a benchmark against which to assess the need for change, rather than as a forecast of the most likely outcome;
- a **Scorched Earth scenario** in which energy efficiency improvements are 1% per annum lower than in the baseline scenario, with no change in fuel mix; this might be associated with major technological advances leading to significantly lower fossil fuel extraction costs and associated reductions in energy prices that destroy the economic incentives for energy efficiency improvements and substitution into non-fossil fuels;
- a **Constrained Growth scenario** in which energy assumptions are as in the baseline, but GDP growth is lower, particularly in the E7 emerging economies;
- a **Greener Fuel Mix scenario** which is as in the baseline except that there is a significant shift from fossil fuels to nuclear and renewables energy by 2050;
- a **Green Growth scenario** in which the green fuel mix assumptions in the previous scenario are combined with energy efficiency improvements 1% per annum greater than in the baseline; and
- a further variant on this scenario called **Green Growth + CCS**, which also incorporates possible emission reductions due to use of carbon capture and storage (CCS) technologies.

The rationale for our choice of Baseline scenario and further details of the other scenarios are set out in Section 1 of the report. Sections 2 and 3 then present our modelling results for global GDP, primary energy consumption and carbon emissions, as summarised below.

Key results: GDP growth, primary energy consumption and carbon emissions

Table A below summarises the key results from our modelling of these six alternative scenarios. The final column shows the cumulative growth of carbon emissions between 2004 (the base year of the model) and 2050.

Table A: Projected average annual global economic and primary energy consumption growth in alternative scenarios: 2004-50 (% pa)

Growth (% pa except final column)	**GDP**	**Primary energy**	**Non-fossil fuels***	**Carbon emissions**	
				Annual average growth	**Cumulative growth to 2050 (% change)**
Scorched Earth	3.2	2.6	2.6	2.6	233
Baseline scenario	3.2	1.6	1.6	1.6	112
Greener Fuel Mix	3.2	1.6	3.6	1.1	64
Constrained Growth	2.6	1.0	1.0	1.0	61
Green Growth	3.2	0.6	2.5	0.1	4
Green Growth + CCS	3.2	0.6	2.5	-0.4	-17

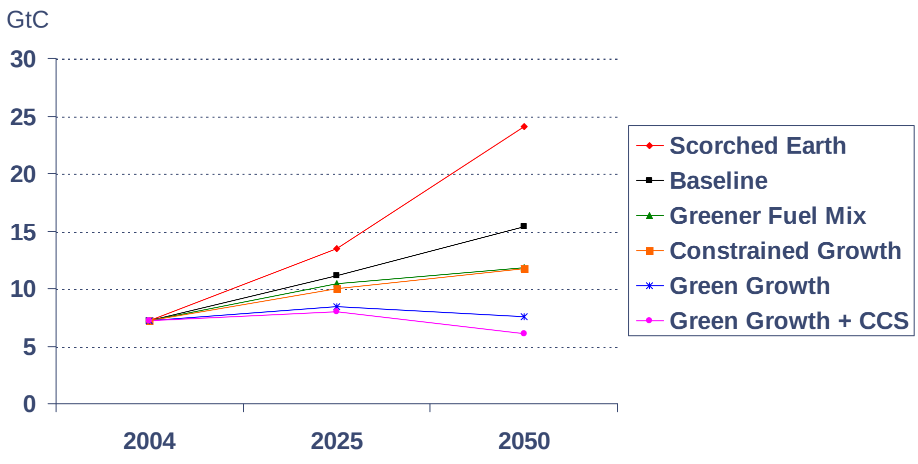
*Nuclear and renewables
Source: PwC model projections

The **Scorched Earth scenario**, despite still incorporating a modest degree of energy efficiency improvements (0.6% pa compared to the historic trend of 1.6% pa), implies a very large rise in annual carbon emissions over the period to 2050 (see Figure A). The cumulative impact of this, as illustrated in Figure B, would be for atmospheric carbon dioxide (CO2) levels[2] to rise to around 625ppm by 2050 in this model (compared to around 380ppm now), with no sign of stabilisation. By comparison, the emerging scientific consensus appears to be that stabilisation at no more than 500ppm, and preferably at around 450ppm or less, is necessary to reduce to manageable levels the risks of severe adverse impacts from global climate change that most scientists believe would be associated with global temperature increases of more than around 2˚C (e.g. sea level rises leading to flooding of coastal areas; greatly increased frequency of extreme weather events; possible impact on the Gulf stream; disruption to established agricultural sectors, particularly in developing countries;

[2] Atmospheric concentration levels of carbon dioxide are measured in parts per million (ppm) and reflect the cumulative impact of carbon emissions for as much as 200 years previously. Pre-industrial levels of CO2 were around 280ppm and this has now risen to around 380ppm. CO2 accounts for around 75% of the overall greenhouse effect according to scientific estimates, so we focus on this in the present report. This is not to deny, however, that action to reduce emissions of other greenhouse gases such as methane may also be important, particularly in terms of their short term impact on the global climate.

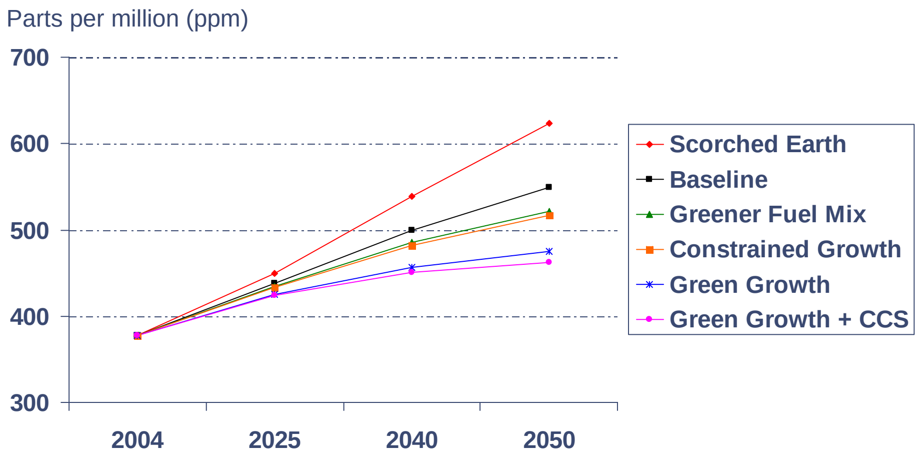
droughts in areas where temperature rises sharply; threats to biodiversity; possible feedback effects if higher temperatures reduce the capacity of oceans, soils and rainforests to act as natural sinks for carbon dioxide, so amplifying any initial adverse climate impact from increased carbon emissions etc). Given these risks, the precautionary principle might suggest that, provided the economic costs are not too great, it could be worth paying a modest 'insurance premium' now through reducing carbon emissions significantly, rather than risk much more severe, although hard to quantify, socio-economic costs at a later date.

Figure A: Projections of carbon emissions in alternative scenarios



Source: PwC model projections

Figure B: Projections of atmospheric C02 concentration levels in alternative scenarios



Source: PwC model projections

Our **Baseline scenario**, which assumes energy efficiency improvements in line with historic trends, is less severe but still implies that global carbon emissions would more than double by 2050 and atmospheric CO2 levels would reach around 550ppm by that date, with little sign of stabilisation (see Figures A and B above). Based on the scientific consensus described above, this could imply significant risks of severe adverse effects from climate change as a consequence of such C02 levels[3]. Within the projected global total in this scenario, carbon emissions from the E7 emerging economies are projected to rise by around 225% between 2004 and 2050, compared to projected growth of only around 30% in G7 carbon emissions over this period. China would account for around 25% of world carbon emissions by 2050 in this Baseline scenario, followed by the US (15%), India (11%) and the EU (9%).

One of the reasons for the outcome in our Baseline scenario is the particularly high coal intensity (and low gas and renewables intensity) of the large, relatively fast-growing Chinese and Indian economies. In practice it is probably more likely that they will shift away from coal over time, perhaps leading us closer to the **Greener Fuel Mix scenario**, although the scale of the rise in nuclear[4] and renewable energy supply in this scenario (3.6% average annual growth to 2050) might be considered relatively ambitious given the political and economic obstacles to overcome in these areas (higher gas prices might also limit the shift to gas in the shorter term, as discussed further in the main text of the report). Furthermore, as Figure B above illustrates, this Greener Fuel Mix scenario still involves atmospheric CO2 levels rising to around 520ppm by 2050, with no immediate sign of stabilisation.

The **Constrained Growth scenario** results in a rather similar projected profile for carbon emissions and atmospheric CO2 levels as the Greener Fuel Mix scenario, but at the expense of the level of global GDP in 2050 being 24% lower than in the other scenarios. To the extent that, as some environmentalists have suggested, constrained growth is seen as a policy objective, this might seem a very high economic price to pay, particularly as the burden of any such adjustment might be expected to fall relatively heavily on the emerging economies. The analysis in this and other research reports suggests that there could be much lower cost ways to control carbon emissions than restricting economic growth. Conversely, to the extent that this is just seen as a more plausible GDP growth scenario than the baseline case, it might be taken to imply less need to achieve energy efficiency improvements and adopt a less carbon-intensive energy mix. But this cannot be relied upon, so we prefer to focus on scenarios based on our baseline GDP projections.

A combination of declining fossil fuel reserves, which might be expected to put upward pressure on energy prices, and environmental concerns might also plausibly be argued to give a push towards faster energy efficiency improvements, so moving the world in the direction of the **Green Growth scenario**. These improvements might range from vehicle fuel efficiency and building design to switches in consumer behaviour related, for example, to ‘smart meters’ that allow households to monitor and adjust their domestic energy use much more easily. As Figure A shows, in this scenario global carbon emissions would peak in around 2025 (at around 15% above

[3] Stern (2006) provides a good summary of the arguments for why such a Business as Usual scenario seems unacceptable in terms of the risks involved.
[4] Some nuclear plant will also be coming to the end of its life over the next 10-20 years, so even an accelerated new build programme may not do more than stand still over this period in terms of the share of nuclear in the overall fuel mix. This is one reason why we assume (see Figure C below) that the main gains from a Greener Fuel Mix do not occur until after 2025.

current levels) and then gradually decline to close to current levels by 2050. This emission profile is consistent with an atmospheric CO2 level of around 475ppm in 2050, but this would still be gently rising (see Figure B above).

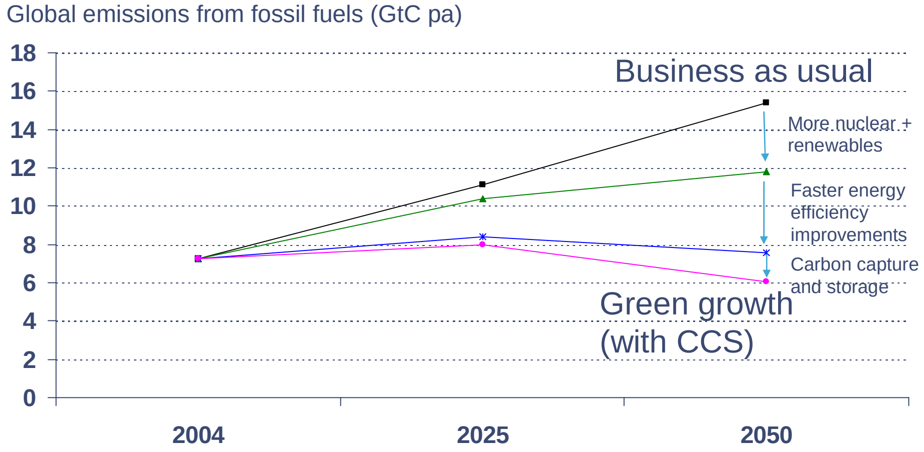
To achieve full stabilisation at close to 450ppm by 2050 would require an additional reduction of carbon emissions building up to around 1.5GtC[5] in 2050, which is what we assume could be achieved through carbon capture and storage in our **Green Growth + CCS scenario**[6]. As illustrated in Figure C, this will require a combination of the following three elements, which our analysis (and that of others such as the IPCC, the IEA and leading academic researchers) suggests are challenging but potentially achievable:

1. A shift to a much less carbon intensive fuel mix through increased nuclear and/or renewables supply (more than doubling the current non-fossil-fuel primary energy share to around 30% by 2050) and reduced fossil fuel. We estimate this could reduce carbon emissions in 2050 by around a quarter relative to our Baseline scenario.

2. Energy intensity reductions significantly faster than historic trends (2.6% per annum rather than 1.6% per annum, which would reduce carbon emissions in 2050 by around a third relative to our baseline scenario).

3. Significant investment in carbon capture and storage (CCS) technology and capacity of the order of 1.5GtC per annum by 2050, which could reduce carbon emissions by a further 20%, relative to our Green Growth scenario without CCS.

Figure C: Three steps to reduce global carbon emissions to sustainable levels by 2050



Source: PwC model projections: the four lines correspond (starting from the top) to our Baseline, Greener Fuel Mix, Green Growth, and Green Growth + CCS scenarios. 'Sustainable' is defined here as consistent with stabilising global atmospheric CO2 concentrations at around 450ppm by 2050.

The report also indicates how carbon emissions might need to evolve by country to achieve the Green Growth + CCS scenario, as summarised in Table B below. We can

[5] GtC = a thousand million tonnes of carbon.
[6] As discussed in the main part of this report, this scenario is within the plausible range for future CCS development in the IPCC's 2005 Special Report on this issue.

see that the G7 economies will need to reduce their current level of emissions by around half by 2050 to achieve this scenario, whereas the E7 economies would still be able to increase their emissions by around 30% from current levels. But this would vary considerably across the E7, with India able to more than double its emissions from current relatively low levels, while Russia would need to almost halve its emissions from current relatively high levels (compared in each case to their respective GDP levels).

Table B: Global carbon emissions from fossil fuels by country in Green Growth + CCS scenario

Country or grouping	**Carbon emissions in 2004 (GtC)**	**Green growth + CCS scenario projections**			
		2050 emissions (GtC)	**% change 2004-50**	**2004 share of global total (%)**	**2050 share of global total (%)**
US	1.66	0.84	-50	22.9	13.8
Japan	0.35	0.16	-56	4.9	2.6
Germany	0.23	0.10	-57	3.2	1.6
UK	0.15	0.07	-54	2.1	1.2
France	0.11	0.06	-43	1.5	1.0
Italy	0.13	0.06	-53	1.7	1.0
Canada	0.16	0.07	-53	2.2	1.2
G7 total	**2.80**	**1.36**	**-51**	**38.6**	**22.5**
China	1.25	1.55	+24	17.3	25.6
India	0.32	0.70	+118	4.4	11.7
Brazil	0.09	0.12	+35	1.2	2.0
Russia	0.42	0.22	-47	5.8	3.7
Mexico	0.10	0.15	+47	1.4	2.5
Indonesia	0.08	0.17	+109	1.2	2.9
Turkey	0.06	0.09	+51	0.8	1.5
E7 total	**2.33**	**3.01**	**+29**	**32.1**	**49.8**
Other*	2.12	1.68	-21	29.3	27.7
World total	**7.25**	**6.05**	**-17**	**100**	**100**
Memo: EU25	*1.08*	*0.53*	*-51*	*14.9*	*8.8*
*Memo:Big3***	*3.23*	*3.09*	*-4*	*44.6*	*51.1*

*This is only an illustrative estimate for 2050 based on scaling up from the 17 economies in the model (i.e. the G7, the E7, plus Spain, Australia and South Korea). EU25 estimate for 2050 is scaled up from largest 5 EU countries. In both cases, 2004 data is used as a basis for the scaling.

***US, China and India

Source: 2004 estimates based on data from BP Statistical Review of World Energy (2005), PwC model projections for Green Growth + CCS scenario in 2050. These are estimated carbon emissions from fossil fuels only (other emissions are included in the model only at global level).

Table B also shows the growing weight of the E7 emerging economies (particularly China and India) in global carbon emissions relative to the current G7 advanced economies. According to the model, China is set to overtake the US as the leading carbon emitter by 2010, while total E7 emissions would be more than double total G7 emissions by 2050. Together the ‘Big 3’ economies (China, US and India) are projected to account for just over half of global emissions by 2050 in both our Baseline and Green Growth + CCS scenarios (though the absolute levels of emissions are much lower in the latter case), up from around 45% today. In contrast, the EU's share of global emissions is set to decline from around 15% now to just under 9% by 2050 in this scenario.

Controlling the growth of emissions in China and India and significantly reducing the level of emissions in the US will therefore be critical to achieving any global carbon emissions target. By contrast, a country such as the UK, despite being the fifth largest economy in the world in terms of GDP at market exchange rates at present, accounts for only around 2% of global carbon emissions now and this share looks set to fall to only just over 1% by 2050. Nonetheless countries such as the UK (and the EU more generally) can play an important role in developing new technologies and approaches to carbon emissions reduction such as the EU Emissions Trading Scheme.

Technological options, policy issues and conclusions

The report also includes (in Section 4 below) a review of technological and policy options which suggests that there are reasons for cautious optimism about the prospects for achieving the kind of carbon emissions reductions envisaged in the Green Growth + CCS scenario without prohibitive economic costs. The main reasons for this are:

- the significant extent to which, as argued by Pacala and Socolow (2004) and IEA (2006), technologies already exist that could deliver significant reductions in carbon emissions, although most of these still need to be developed further to be economically viable;
- the particular scope for expanding carbon capture and storage systems, as set out in the 2005 IPCC report on this topic;
- the progress made in establishing an international carbon price through the EU Emissions Trading Scheme (ETS) and the scope for extending the scope (e.g. to transport) and geographic reach of such carbon trading schemes over time (e.g. by linking the EU ETS to other regional schemes);
- the large number of studies showing that the costs of reducing global carbon emissions by around 50-70% relative to our baseline scenario should be no more than around 4-5% of world GDP, with average estimates of around 2-3% of world GDP, equivalent to only around one year of trend growth; and
- potential learning-by-doing effects that, as demonstrated by recently developed models with induced technological change (Edenhofer et al., 2006), could further reduce these costs estimates, perhaps to around 1% of world GDP or less by 2050.

At the same time, the analysis suggests that there is no room for complacency given that:

- a large proportion of the energy efficiency improvements indicated in the Pacala and Socolow analysis are likely to be necessary just to achieve the outcome assumed in our baseline scenario in which carbon emissions nonetheless more than double by 2050; further improvements over and above this baseline may prove more challenging and costly to achieve;

- this puts more emphasis on the need to switch to lower or zero carbon alternatives, but these face a range of political and/or economic obstacles that will be challenging for both governments and energy sector companies to overcome; the opposition of many in the environmental movement to nuclear power is a case in point, as is local opposition both to large hydroelectric projects and to onshore wind farms;
- despite their theoretical attractions, carbon taxes have faced both political and practical difficulties that have often either blocked their introduction entirely, or led to exemptions that significantly blunt their impact on carbon emissions;
- while the EU ETS has been a success in terms of establishing a market, it remains to be seen how far governments will be prepared to reduce future allocations of free allowances given likely opposition from some business interests and concerns about international competitiveness effects;
- given the long lead times and even longer asset lives for major infrastructure investments in the energy, transport and construction sector, there is no time to be lost in setting in place low carbon strategies in these areas if major emission reductions are to be locked in by the middle of this century; and
- while learning-by-doing effects are powerful in theory, they do not lend themselves to easy policy solutions; instead they suggest that a broad range of pro-innovation policies will be needed, but with the effectiveness of these being hard to assess with any precision in advance.

In summary, our baseline 'business as usual' scenario implies rapidly increasing levels of carbon emissions that might be associated with significantly increased risks of adverse climate change and severe negative socio-economic effects in the long run. At the same time, there appear to be relatively low cost options for controlling carbon emissions to the atmosphere which, based on the precautionary principle, it might seem desirable to implement (and which appear to be significantly 'cheaper' in economic terms than simply constraining GDP growth). The richer OECD economies may need to take the lead in developing new technologies and reducing their emissions over the next couple of decades, given that it may not be realistic to expect much faster-growing emerging economies like China and India actually to cut their emission levels, as opposed to controlling their rate of increase, until later in their process of economic development.

Introduction

The World in 2050: Rise of the E7 economies

In March 2006 we published a report[7] on long-term growth prospects for the 17 largest economies in the world, measured in purchasing power parity (PPP) terms in 2004:

- the G7 economies (US, Japan, Germany, UK, France, Italy and Canada) plus three other advanced economies (Spain, Australia and South Korea[8]); and
- what we called the E7 emerging economies (China, India, Brazil, Russia, Indonesia, Mexico and Turkey).

Together these economies accounted for around 75% of world GDP in PPP[9] terms in 2004. In our analysis in the earlier report, we projected a major shift in the balance of global economic power over the period to 2050.

In particular, based on GDP in PPP terms, our baseline projections suggested that:

- the Chinese economy could overtake the US economy in around 2016 and be around 23% larger by 2025 and around 43% larger by 2043;
- the Indian economy could rise to more than half the size of the US economy by 2025 and around the same size by 2050;
- Brazil would be of comparable size to Germany by 2025 and to Japan by 2050;
- Indonesia (which has the fourth largest population in the world) and Mexico have the potential to catch up with Italy by 2025 and to overtake the UK and Germany by 2050;
- Russia should be of similar scale to the UK and France from 2025 onwards, though it may not make much further relative progress after that due to unfavourable demographics, while Turkey has the potential to be of similar scale to Italy by 2050; and
- the E7 economies as a whole could be around 20% larger than the G7 by 2025 and around 75% larger by 2050.

Of course, there are considerable uncertainties around any such long-term projections and they should be regarded as indicators of economic potential rather than precise forecasts. Some of the E7 economies might do even better than projected, but others may fail to fulfil this potential due to a combination of political instability, economic policy failures and environmental crises. The projections also assumed that the global economic environment remained broadly supportive of growth, notably in relation to avoiding a relapse into protectionism.

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[7] J. Hawksworth, 'The World in 2050: How big will the large emerging economies get and how can the OECD compete?', PricewaterhouseCoopers, March 2006.
[8] Referred to below as Korea for short.
[9] At market exchange rates, they accounted for around 80% of world GDP in 2004, but the PPP measure is a better indicator of the volume of energy consumption and so carbon emissions, so we focus on the PPP measure of GDP in this report.

Nonetheless, the broad conclusion that the E7 economies would become increasingly significant in the world economy over the period to 2050, and that China, and later India, would come to rival the US for global economic leadership, seemed relatively robust to alternative model assumptions, barring some kind of global catastrophe. In economic terms, we also argued that this should be a mutually beneficial development not just for the E7, where hundreds of millions of people should be lifted out of poverty by 2050, but also for the established OECD economies, who would benefit both from cheaper imports from the E7 and, as these emerging economies became more prosperous, increasing large export markets in these countries at a time when OECD domestic demand growth was likely to slow in the face of ageing populations. This relatively optimistic conclusion did, however, depend on the OECD economies remaining flexible enough to shift resources to their areas of comparative advantage, and to invest continuously in upgrading their human capital over time through education and training. It also depended on avoiding short-term political pressures for protectionist responses to the rise of the E7.

Implications for global energy consumption and carbon emissions

There was one key area, however, where the rise of the E7 and associated rapid global growth could be seen as a less favourable development from a global perspective, namely the implications for global energy consumption and thus for carbon[10] emissions and climate change. We have already seen sharp rises in oil prices in recent years that, while related in part to concerns about security of supply in the Middle East and elsewhere, are also generally recognised to be closely linked to the rapid increase in energy demand seen in China and India in particular in recent years. The role of Russia as a key source of gas supplies to Europe has also come increasingly into focus recently.

There is also an increasing focus on the climate change issue, where it is recognised that, although the US and Europe are currently the largest carbon emitters, China, India and other E7 economies may on current trends be the largest contributors to future increases in carbon emissions. In particular, as the E7 move rapidly through their industrialisation process, their economies will tend to be more energy-intensive than the increasingly service-driven economies of the established OECD countries. At the same time, many might argue that it would be unfair to expect the E7 to forgo some of the benefits of rapid economic growth for the sake of solving a carbon emissions problem that has been caused over the past two centuries or more by the established OECD countries, at least unless these countries are also taking determined action to reduce their carbon emissions.

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[10] Where we refer in this report to ‘carbon emissions’, this should be taken to refer to carbon dioxide emissions. In general, we focus in this report on carbon dioxide emissions related to fossil fuel use, though there are other influences on carbon dioxide levels in the atmosphere (e.g. natural carbon sinks such as oceans and forests) as well as other greenhouse gases such as methane and nitrous oxide that influence climate change. But carbon dioxide emissions are generally accepted to be by far the most important such influence (accounting for 75% or more of greenhouse gas effects when these are aggregated in CO2-equivalent terms) and certainly no climate change policy could be effective in the long run without reducing carbon emissions. This is not to say that others policy areas (e.g. reforestation) are not important, but it does justify the focus on carbon emissions in the present report, which is not uncommon in the economic research literature in this field.

In this report we aim to quantify some of these issues by using the GDP projections model for the 17 economies covered in our earlier study (grossed up to global level) as the basis for making global projections[11] for primary energy consumption and carbon emissions from fossil fuel use under a range of alternative assumptions on economic growth, energy intensity, fuel mix and carbon intensity. We also illustrate how these alternative carbon emissions scenarios might translate into long-term trends in atmospheric levels of carbon dioxide. This in turn leads to analysis of the implications of a range of possible technological and policy responses that might be required to keep the projected rise in these atmospheric carbon dioxide levels within reasonable bounds. Based on current scientific thinking, we interpret 'reasonable bounds' to mean that the risk of eventual global temperature rises (relative to pre-industrial levels) of more than around 2˚C should be kept to acceptable levels. Although important uncertainties remain as to how precisely to quantify these risks and what exactly is an 'acceptable' level of risk, 2˚C is the approximate level of global warming above which an increasing volume of scientific analysis[13] suggests severe adverse impacts from climate change (e.g. sea level rises leading to flooding of coastal areas; increased frequency of extreme weather events; possible impact on the Gulf stream; disruption to established agricultural sectors, particularly in developing countries; droughts in areas where temperature rises sharply; threats to biodiversity; possible feedback effects if higher temperatures reduce the capacity of oceans, soils and rainforests to act as natural sinks for carbon dioxide, so amplifying any initial adverse climate impact etc).

Structure of the report

The remainder of the report is structured as follows:

- **Section 1** describes the modelling methodology used, the key baseline assumptions and the alternative scenarios discussed in the report;
- **Section 2** presents and discusses projections for global economic growth and primary energy consumption (in total and by fuel type) to 2050 in alternative scenarios;
- **Section 3** presents and discusses the projections for global carbon emissions and atmospheric levels of carbon dioxide associated with each scenario and relates these to scientific evidence on the likely effects on global temperature levels and other aspects of climate change; and
- **Section 4** discusses some of the potential technological and policy options for controlling future carbon emissions without unduly restricting the growth potential of the world economy.

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[11] Our projections here could be seen as simplified versions of those produced by the International Panel on Climate Change (IPCC) to support their seminal 2001 report on the global challenge of climate change (albeit with updated data to reflect events since 2001). While the greater simplicity of our approach involves some loss of detail, it has compensating advantages in terms of clarity and transparency.

[13] See, for example, the discussion in IPCC (2001) and IEA (2006).

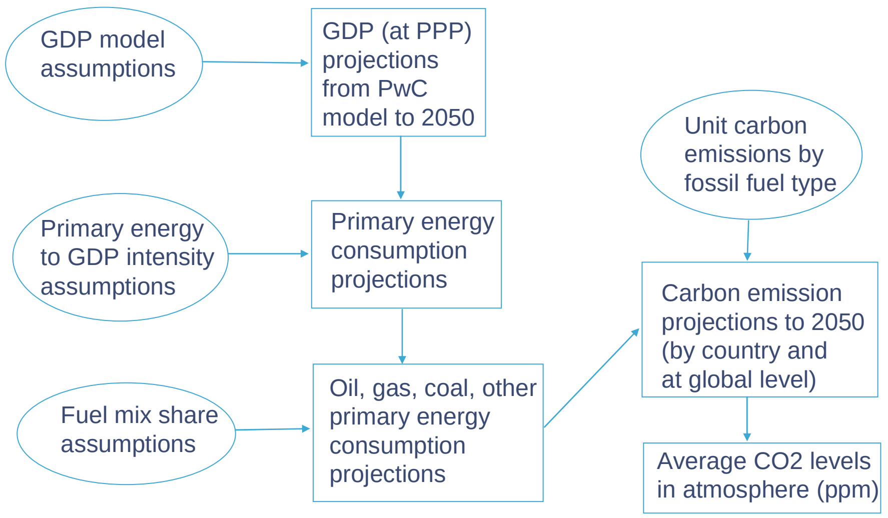
Summaries of the key results and conclusions are provided at the end of Sections 2, 3 and 4 of the report, as well as in the Executive Summary above. Further technical details of the economic growth modelling methodology are provided in an Annex. References are listed at the end of the report.

1. Methodology, baseline assumptions and alternative scenarios

1.1 Methodological approach

Figure 1.1 below summarises the structure of our model.

Figure 1.1: Outline of model structure



Note: all projections done by country then aggregated to global level

The key assumptions underlying each key element of the model are discussed in turn below. Readers less interested in this methodological detail, however, may wish to skip to the description of the alternative scenarios in Section 1.7 below (p.27) and then proceed directly to the discussion of the results for each scenario in Sections 2 and 3 of the report.

1.2 GDP growth projections

The first level of the model shown in Figure 1.1 is the same as used in our recent World in 2050 report. This uses a model of economic growth that is standard[14] in the economic literature, as described further in the Annex. The key drivers of GDP growth in this model are:

- investment in the physical capital stock (net of depreciation);
- education levels, which drive trends in the quality of labour input (which we sometimes refer to below as the average level of human capital per worker);
- working age population growth (using the latest UN projections), which determines the quantity of labour input;
- technological progress, which is assumed partly to be driven by US productivity growth and partly by country-specific catch-up rates with US productivity levels[15].

[14] Specifically, we assume a Cobb-Douglas production function with constant returns to scale and a capital share in output of a third.
[15] Productivity here refers to total factor productivity growth.

Each of the 17 countries is modelled individually, although their growth rates are linked together by the assumption on US productivity growth, which determines the 'global technological frontier' in the model. The model assumptions (aside from demographic trends taken from the 2004 UN population projections) are based on a combination of extrapolation from country-specific historic trends in investment rates and education levels, and plausible assumptions as to how productivity catch-up rates vary across countries. In the short term, for example, we assume that catch-up rates (for a given initial productivity gap) are 1.5% per annum for China, which has a 25-year history of growth-friendly economic policies, but only 0.5% for India and Indonesia, which are at an earlier stage in their development in this respect. Beyond 2030, we assume that catch-up rates converge across the emerging economies at 1.5% per annum, which is in line with estimates of around 1-2% from the academic literature[16] on past trends across a broad range of economies following policies broadly conducive to economic growth (i.e. macroeconomic stability, openness to foreign trade and investment, and a reasonably stable and predictable legal and regulatory regime).

The requirement here is not that the policy environment should be perfect in every respect, but just that it should be broadly supportive of the country building trade and investment links with the world economy and so being able to tap into advances in global technology. Many developing countries (notably in Africa and in some parts of Latin America in the past) have not sustained such broadly favourable policy environments, but our model implicitly assumes that the E7 economies remain on broadly the right track in policy terms, even if there will inevitable be ups and downs in this process over time due to the economic cycle, temporary political instability and periods of policy stasis. At the same time, the model implicitly assumes that there is no global reversion to the kind of protectionist policies that helped to derail growth in the 1930s, though clearly this is a downside risk.

The model allows real GDP growth to be calculated based either on market exchange rates (in constant US dollar terms) or PPP rates. The former are better indications of the current and potential future size of the E7 markets from the perspective of US or European companies operating in dollars, euros or sterling. For present purposes, however, we are more interested in the volume of output of the E7 economies, since this is what will drive energy consumption and so carbon emissions, and GDP in PPP terms seems more appropriate for this purpose. We assume that PPP exchange rates remain constant over time in real terms[17].

Our model produces GDP growth projections for what are currently the 17 largest economies in the world in PPP terms (according to World Bank data for 2004). These are grossed up to global levels on the assumption that their share of world GDP remains constant at 75%. This reflects the fact that, while some of the smaller OECD economies may grow less quickly than the average of the 17 considered in the model, many of the smaller developing economies may grow faster (particularly in regions such as Asia, Eastern Europe and parts of Latin America; the outlook for Africa is less

[16] See, for example, the discussion of the academic literature on comparative economic growth rates in Barro (1997) or Miles and Scott (2004).

[17] In US dollar terms, the market exchange rates of emerging economies would be expected to rise gradually over time as their price levels adjust towards OECD levels as their income levels rise; but this effect does not need to concern us here.

clear but their share of world GDP is in any event small). This assumption may or may not prove accurate, but focusing only on the 17 largest economies makes the analysis manageable and should give a broadly accurate indication of future trends.

1.3 Total primary energy consumption

The next stage in the model, as illustrated in Figure 1.1 above, is to make assumptions on trends in primary energy intensity (i.e. the ratio of primary energy consumption to GDP) in each country. An alternative might be to model in more detail the relationship between GDP growth and the different elements of final and intermediate energy demand, such as power generation, transport, other industrial and commercial use, and other household use. But this would require a much more complex model of the overall supply and demand for energy[18] without adding much to the analysis in terms of the broad order of magnitude of primary energy use, though it could help to inform assumptions on fuel mix (e.g. because transport demand is particularly oil-intensive, whereas coal use is focused in the power generation sector). In this respect, we would note that the main scenarios developed by the IPCC in 2001 did not indicate large variations between 2000 and 2050 in the ratio of final energy demand (including power generation) to primary energy consumption.

In modelling primary energy intensity, our starting point was an analysis of historic trends since the early 1980s based on data from the BP Statistical Review of World Energy 2005[19], as summarised in Table 1.1 below.

[18] PwC has done this kind of detailed energy modelling in other projects, so this is an area where more detailed work might well be possible in the future.
[19] We also looked at the IEA's Key World Energy Statistics (2005), but, in general, the data were similar from the two sources and the BP report covered one extra year (2004 vs 2003).

Table 1.1: Historic trends in primary energy intensity

% change pa in ratio of primary energy consumption to GDP	Average for all available years (1981-2004)	Average for last ten years (1995-2004)	Average for last five years (2000-2004)
US	-2.0	-2.0	-1.9
Japan	-0.8	-0.4	-1.2
Germany	-2.2	-1.4	-1.0
UK	-2.0	-2.2	-2.2
France	-0.7	-0.9	-1.2
Italy	-0.7	0.2	-0.1
Canada	-1.3	-2.0	-1.4
Spain	-0.2	0.5	0.0
Australia	-0.9	-1.4	-1.7
Korea	0.5	-0.1	-1.5
E7 economies			
China	-4.1	-2.8	3.3
India	-0.2	-1.3	-1.4
Brazil	0.9	0.9	-0.7
Russia	-1.3*	-3.3	-5.0
Mexico	0.1	-0.3	-0.6
Indonesia	1.3	1.8	-0.4
Turkey	1.0	0.1	-0.5
World average	**-1.6%**	**-1.7%**	**-1.1%**

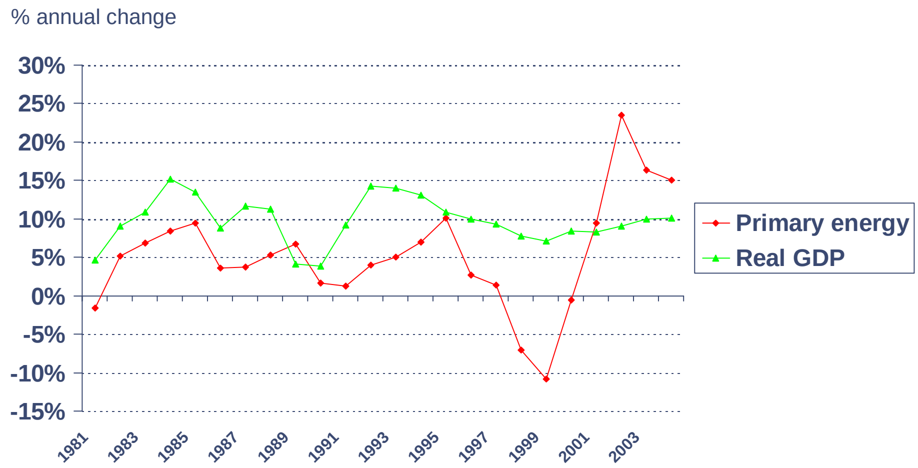
*Russian data available for 1992-2004 only. The early years of that period are also rather unusual due to the sharp downward trend in Russian GDP during the early 1990s after the collapse of the USSR.
Source: PwC calculations based on IMF GDP data and primary energy consumption data from BP Statistical Review of World Energy 2005.

As Table 1.1 illustrates, overall global primary energy intensity has declined by an average of around 1.6% per annum over the period from 1981 to 2004 and the average for the past ten years has also been similar at 1.7%. The last five years has seen a slower decline in energy intensity averaging only 1.1% per annum, but this was largely driven by an exceptional rise in energy intensity in China, as discussed further below.

Some countries (e.g. the US at around -2% per annum) have shown a fairly stable historic trend in primary energy intensity whether measured as an average over 5, 10 or 24 years. For the G7 economies, plus Australia, there is also a fairly consistent trend towards declining energy intensity over the period from 1981 to 2004, with average rates of decline varying from -0.7% per annum in France and Italy to -2.2% per annum in Germany. This reflects both a shift to more service-orientated economies across the OECD and the incentives for greater energy efficiency created by the high oil prices of the 1970s and early 1980s. Spain has been a laggard in this respect, with an average decline in primary energy intensity of only 0.2% per annum since 1981 and an increase over the past ten years, perhaps reflecting the fact that it has still been in the catch-up phase of economic growth. The same appears to be true of Korea until recently, although it is notable that its primary energy intensity declined by 1.5% per annum in the latest 5 year period, close to the OECD average rate.

Turning to the E7 economies, trends have been much more mixed both across countries and over time. Given its size, China is of particular significance here and, as illustrated in Figure 1.2 below, has recently seen a marked acceleration in primary energy consumption relative to GDP growth in 2002-4, after a sharp decline in primary energy consumption in the late 1990s and a general tendency before that for the latter to run some way below GDP growth in most years from the early 1980s to the mid-1990s.

Figure 1.2: Chinese primary energy consumption and GDP growth



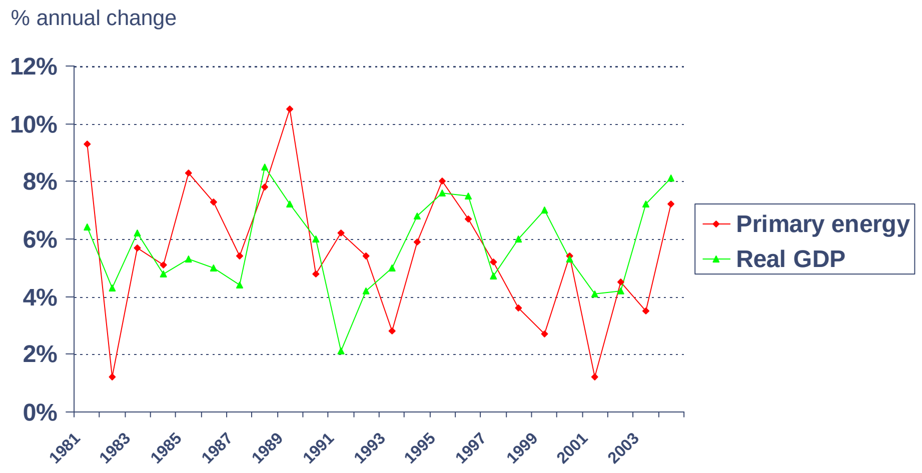
Source: PwC calculations using IMF GDP data and BP data on primary energy consumption

The recent exceptionally rapid growth in Chinese primary energy consumption, which remains heavily focused on coal but has been shifting gradually towards more use of oil and natural gas, seems likely to continue in the short run. But it may partly reflect a correction of the downward adjustment in the late 1990s and, in the longer term, we would expect a more normal relationship to reassert itself[20] with growth in primary energy consumption tending to run somewhat below GDP growth, but probably not by as much as was typical in the 1980s and 1990s. These general assumptions are reflected in the baseline scenario for China described below.

For India, the other potential emerging giant, the pattern has been rather different as illustrated in Figure 1.3 below.

[20] Particularly given an increasing recent Chinese government policy focus on energy efficiency in response to energy supply constraints and rising energy prices.

Figure 1.3: Indian primary energy consumption and GDP growth



Source: PwC calculations using IMF GDP data and BP data on primary energy consumption

For the period as a whole, primary energy consumption has averaged only 0.2% per annum less than real GDP growth, though the trend over the past ten years has been more favourable, with an average decline in primary energy intensity of 1.3% per annum over this period. We therefore decided to use this latter period as a baseline for future projections.

Brazil has also seen a turnaround in primary energy intensity over the past five years, as indicated in Table 1.1 above, and we assume this more favourable trend continues in our baseline scenario. We also give most weight in our baseline scenario to evidence of improving primary energy intensity in the last five years in Mexico, Indonesia and Turkey (by an average of 0.5% per annum across the three countries in 2000-4).

Russia is a less easy case to deal with because its initial primary energy consumption was very high relative to its economic size but has declined more rapidly than in any other country considered here over both the last ten years and particularly the last five years (see Table 1.1 above). The 5% per annum average decline in energy intensity over the period from 2000-4 seems unlikely to be sustainable for long, however, so we assume that this rate of decline decelerates gradually over the period to 2010 and then settles at around 2% per annum, similar to norms in OECD countries such as the US.

Table 1.2 sets out the assumptions we have made on primary energy intensity in our baseline projections in the light of the discussion above. These assumptions are intended to represent a ‘business as usual’ scenario where the overall average global trend in primary energy intensity of 1.6% per annum over the period from 2005 to 2050 is the same as the historic average from 1981 to 2004. After 2025, this is assumed to be uniform across countries because it seems unreasonable to try to predict country-specific trends in primary energy intensity beyond that date. Up to 2025, we make country-specific assumptions based on taking a certain view of how historic trends might be projected forward initially on a transitional basis up to 2010 and then on a more stable basis for the period from 2011-25.

Table 1.2: Baseline scenario assumptions for primary energy intensity

% change per annum	2005-10	2011-2025	2026-2050
US	-2	-2	-1.6
Japan	-0.8	-0.8	-1.6
Germany	-1.4	-1.4	-1.6
UK	-2	-2	-1.6
France	-0.9	-0.9	-1.6
Italy	From -0.1 in 2005 to -0.7 in 2010	-0.7	-1.6
Canada	-2	-2	-1.6
Spain	-0.2	-0.2	-1.6
Australia	-1.4	-1.4	-1.6
Korea	-1	-1	-1.6
E7 economies			
China	From +3 in 2005 to -2 in 2010	-2	-1.6
India	-1.3	-1.3	-1.6
Brazil	-0.7	-0.7	-1.6
Russia	From -4.5 in 2005 to -2 in 2010	-2	-1.6
Mexico	-0.5	-0.5	-1.6
Indonesia	-0.4	-0.4	-1.6
Turkey	-0.5	-0.5	-1.6
World average	**-1.1**	**-1.6**	**-1.6**

Source: PricewaterhouseCoopers assumptions (world average is a model output rather than input)

Of course, there are many uncertainties surrounding any such assumptions and they are varied in the alternative scenarios discussed below.

1.4 Fuel mix assumptions

Fuel mix matters because carbon dioxide emissions vary significantly by fuel type, with coal having the highest assumed carbon intensity, followed by oil and then natural gas. Other forms of primary energy (e.g. nuclear or renewables) tend to have much lower or even zero carbon intensity. The starting point for our fuel mix assumptions is the estimated share of different fuels in total primary energy consumption in each country in 2004, as set out in Table 1.3 below.

Table 1.3: Primary energy consumption shares by fuel type in 2004

% share of total	**Oil**	**Natural gas**	**Coal**	**Other**
US	40.2	25.0	24.2	10.6
Japan	46.9	12.6	23.5	17.0
Germany	37.4	23.4	25.9	13.3
UK	35.6	38.9	16.8	8.7
France	35.8	15.3	4.8	44.2
Italy	48.7	35.9	9.3	6.0
Canada	32.4	26.2	9.9	31.5
Spain	53.3	16.9	14.5	15.3
Australia	32.6	18.6	45.7	3.1
Korea	48.3	13.1	24.4	14.2
E7 economies				
China	22.3	2.5	69.0	6.2
India	31.7	7.7	54.5	6.1
Brazil	44.9	9.1	6.1	40.0
Russia	19.2	54.1	15.8	10.8
Mexico	58.6	29.8	6.2	5.4
Indonesia	49.9	27.6	20.3	2.2
Turkey	37.5	23.3	27.0	12.2
World average	**36.8**	**23.7**	**27.2**	**12.3**

Source: BP Statistical Review of World Energy 2005. 'Other' includes nuclear, hydroelectric and other renewables.

We can see that almost all of these 17 large economies remain heavily dependent on fossil fuels for their energy needs. The only significant exceptions are France, which has a large nuclear power programme, and Brazil and Canada, where hydroelectric power provides a significant source of energy. Even in these three countries between around 56% and around 68% of primary energy is from fossil fuels, while in all the other countries it is over 80%. Other forms of renewable energy (e.g. wind or solar power) do not make a significant contribution at present to the energy needs of any of these economies.

In relation to the E7 economies, the most important point to note is the heavy reliance on coal of India (54.5%) and particularly China (69%), with oil also being of increasing significance in both countries (and the total fossil fuel share being just under 94% in both cases). This is significant because it means that the rapid growth of China and India will be driven for the foreseeable future by the most carbon-intensive forms of energy, namely coal and oil. Natural gas usage is also increasing but from a low base, particularly in China. Hydroelectric power is also of increasing significance in China, although major projects there have raised local environmental concerns.

At the global level, fuel mix shares of primary energy have not changed that much over the past ten years, although this disguises some bigger shifts in various directions at country level. Table 1.4 below summarises some of these trends in relative energy consumption growth by fuel type in the five largest OECD economies and the E7 emerging economies.

Table 1.4: Growth in primary energy consumption by fuel type in selected large economies (1995-2004, % per annum)

% growth pa	Oil	Natural gas	Coal	Total primary energy
US	1.5	0.6	1.2	1.5
Japan	-0.8	1.8	4.0	0.7
Germany	-0.9	2.4	-1.1	0.0
UK	-0.1	4.0	-2.6	0.6
France	0.5	3.8	-0.9	1.4
E7 economies				
China	7.8	8.9	4.7	5.5
India	6.1	6.8	4.3	4.8
Brazil	2.6	15.3	1.0	3.3
Russia	-2.4	0.3	-1.8	-0.5
Mexico	0.7	5.9	7.2	2.5
Indonesia	4.0	2.1	16.5	4.9
Turkey	2.2	12.9	2.7	4.3
World	**1.7**	**2.6**	**2.4**	**2.1**
OECD	1.0	2.2	1.1	1.3
Emerging economies (excl. Russia)	3.8	6.1	4.4	4.3

Source: BP Statistical Review of World Energy 2005.

At the global level, the most consistent trend is a rise in the share of natural gas at the expense of oil, though the US is a notable exception to this pattern with relatively low natural gas growth. The shift to gas has been particularly apparent in the EU, with Germany, France and the UK all showing gas consumption rising rapidly relative to declining coal and (except France) oil consumption over the ten years to 2004. However, with gas prices having risen even more sharply than oil prices recently, it is not clear how long this 'dash for gas' will continue in Europe.

At the global level, coal consumption has also grown somewhat faster over this period than total primary energy consumption. This appears to be driven by a combination of relatively rapid growth in coal consumption in some large Asian economies, notably Japan and Indonesia, together with the rise in the relative share in global energy consumption of China and India, which remain highly dependent on coal as discussed above (despite a modest decline in coal's share of their total primary energy consumption since 1994). As the most carbon-intensive fuel, the continued strength of coal consumption in most regions of the world outside Europe poses obvious problems from a climate change perspective.

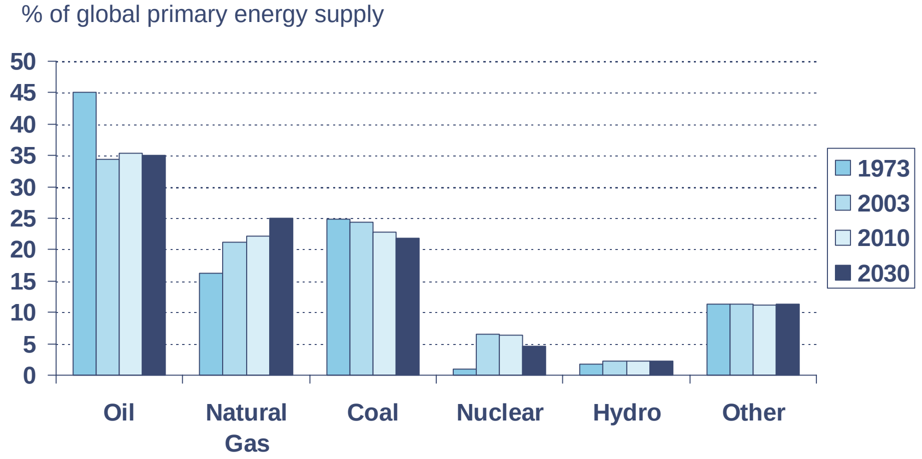
Looking ahead, there is considerable uncertainty as to future trends in global fuel mix depending in particular:

- on trends in the composition of final and intermediate energy demand (e.g. as between power generation, transport and other uses); and
- the relative price of different types of fuel, which will depend also on supply side trends in the energy extraction sector (e.g. how far will new technologies allow new supplies of oil and gas to be extracted more cheaply, so reducing

fears that economically viable reserves may be largely exhausted for oil by 2050 and severely depleted for natural gas by that time[21]).

The IPCC's 2001 climate change scenarios therefore encompassed almost every possible combination of fuel mix trends over the 21st century, from a significant shift towards gas and/or renewables to a move back to coal as oil and gas reserves decline and renewables prove uneconomic. A reasonable consensual view might, however, be represented by the main scenario in the IEA's 2005 World Energy Outlook report, as summarised in Figure 1.4 below in relation to fuel mix shares.

Figure 1.4: Fuel mix shares of global primary energy supply in latest IEA main scenario projections



Source: IEA (2005)

Figure 1.4 includes IEA estimates of how fuel mix shares shifted between 1973 and 2003. Reflecting the sharp rise in oil prices in 1973-74 and again in 1979-80, the share of oil fell from around 45% of total primary energy to around 35%[22] now, offset by rising shares of natural gas and nuclear power. There was little change in the share of coal, hydro or other renewables between 1973 and 2003 at global level.

Looking ahead, the IEA main scenario projections suggest only relatively modest shifts in fuel shares over the period to 2030. Natural gas is projected to increase its share by just under 4 percentage points from 2003 to 2030, offset by declines of

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[21] BP estimates proven oil reserves at around 40 years at the end of 2004 at current production levels and proven natural gas reserves at around 67 years. Proven global coal reserves, by contrast, are expected to last for at least another 160 years at current production levels. New reserves may, of course, be discovered that extend these timeframes, or technological advances in extraction industries may increase the range of economically viable reserves. To the extent, however, that long-term constraints on reserves imply a shift back from oil and gas to coal in power generation in the long term, of course, this would not be good news for carbon emissions unless there were offsetting measures to develop carbon capture and storage technologies. This latter option is discussed further in Section 4 below.

[22] The IEA's estimate here is slightly lower than the 36.8% oil share estimate in the BP Statistical Review of World Energy 2005, as shown in Table 1.3 above and in our model. This reflects a wider definition of other primary energy in the IEA data, but this is of little consequence for carbon emissions projections.

around 2 percentage points in the shares of both coal and nuclear power. No significant changes are projected in the shares of oil[23], hydro or other renewables. To the extent that carbon emissions from natural gas are intermediate between those for coal and nuclear, the net effect of this fuel mix shift on the growth of carbon emissions is unlikely to be large in the IEA projections. The shift to gas they projected based on work in early 2005 may also need to be reconsidered to some degree in the light of recent rapid increases in gas prices and the increasing view of the markets that much of this rise may be of a lasting nature, both for oil and gas. If this proves correct, then the projected decline in coal and nuclear in favour of gas may not emerge to the extent projected by the IEA[24].

Bearing in mind both the uncertainties involved in long-term fuel mix projections and our focus in this report on the implications of energy use for global carbon emissions and climate change, we have therefore decided to **assume in our baseline scenario no change in fuel shares of primary energy consumption in each country**. This is not intended to represent our estimate of the most likely future outcome, although it is within the plausible range of outcomes, but it does have presentational advantages in terms of then being able to explore the implications for carbon emissions of alternative fuel mix assumptions through sensitivity and scenario analysis relative to this 'no change'/'business as usual' baseline. Since we apply the constant fuel mix assumption at country level, however, it does still allow for compositional effects at global level if faster growing countries have a bias to particular fuel types: the high coal intensities of China and India turn out to be particularly significant here, as discussed further in Section 2.3 below.

1.5 From energy use to carbon emissions

In our baseline scenario we use the following standard conversion factors, based on those used in the IPCC's 2001 report, to get from fossil fuel use to carbon emissions:

- **coal:** 0.001032 gigatonnes of carbon (GtC) per million tonnes of oil equivalent (mtoe);
- **oil:** 0.000794 GtC per mtoe; and
- **natural gas:** 0.000576 GtC per mtoe.

In other words, oil is around 75% as carbon-intensive as coal for comparable quantities and natural gas is around 55% as carbon-intensive on average. In practice, these conversion factors will vary by type of coal and oil, but these seem to be reasonable average assumptions and, together with our base data for primary energy by fuel type, give an estimate for total global carbon emissions from fossil fuels of around 7.2GtC in 2004, which is broadly in line with estimates from other sources.

[23] In the case of oil, this reflects relatively rapid anticipated transport sector demand for energy and the assumption that, at least up to 2030, replacements for oil-based fuels in this sector such as hydrogen fuel cells do not become economic on a large scale.
[24] Although some such effect may arise as a result of the legacy of past decisions not to build new coal and nuclear power plants in the 1990s.

1.6 From carbon emissions to atmospheric levels of CO_2

For the purposes of estimating potential global temperature changes and associated climate change effects, it is necessary to make assumptions on:

- trends in non-fossil-fuel carbon emissions related to land use changes; and
- the current size of, and trends in, the natural carbon 'sink' represented by the world's oceans, forest and other elements in the biosphere that remove CO2 from the atmosphere and store it.

Estimates of both these factors vary significantly and exploring these further would take us into scientific areas beyond the scope of this study. For the purposes of this report, we therefore adopt the same simplifying assumptions used by Retallack (2005), namely that:

- Non-fossil-fuel carbon emissions decline steadily from current estimates of around 1 GtC (i.e. around a seventh of fossil fuel emissions) to around zero by 2050; this scenario is broadly in line with many of the scenarios considered in the IPCC's 2001 report, most of which tended to see a gradual decline in net carbon emissions from this source.

- The natural carbon sink is assumed to be 4.2GtC in 2004, declining very gradually to around 4.1 GtC by 2050 (and 4 GtC by 2100 for illustrative longer term calculations).

Starting from latest estimates that carbon dioxide concentrations in the atmosphere were around 376 parts per million (ppm) in 2003 (as compared to pre-industrial levels of around 280ppm), we can then estimate how this changes over time using the formula[25]:

Change in ppm = (Total carbon emissions – natural sink) * 0.47

For example, with total carbon emissions estimated at 8.2GtC and the natural sink at 4.2GtC in 2004, this translates to an increase of 4*0.47 = 1.88ppm in 2004, raising the atmospheric carbon dioxide level from 376ppm to just under 378ppm. This illustrates the fact that, without either a significant reduction in total carbon emissions or a significant increase in the natural carbon sink (e.g. through a major programme of reforestation), there will be a slow but inexorable rise in atmospheric levels of CO_2.

Linking atmospheric levels of CO_2 to global temperature change involves a further wide range of scientific uncertainties, as well as trends in other greenhouse gases such as methane (though these are generally accepted to be much less significant influences on climate change than CO2). But the IPCC's 2001 report and subsequent analysis as summarised by Retallack (2005) suggests that the chances of keeping the long-term global mean surface temperature rise below the 2˚C level generally regarded[26] as

[25] Taken from Appendix 2 of Retallack (2005).
[26] For more on the scientific evidence around the 2˚C temperature rise, see IPCC (2001) and Stern (2006). The forthcoming updated IPCC report is understood, based on media reports, further to reinforce the arguments for keeping CO2 atmospheric concentrations at levels low enough to keep temperature rises to no more than around 2˚C on the balance of probabilities.

consistent with negative climate change impacts not becoming too severe (though they might still be some significant effects) would be:

- around 80% if atmospheric CO_2 levels are stabilised at around 400ppm;
- around 50% if atmospheric CO_2 levels are stabilised at around 450ppm;
- around 20% if atmospheric CO_2 levels are stabilised at around 550ppm;

Pacala and Sokolow (2004) focus on a stabilisation target of around 500ppm (based on their view of the scientific consensus at that time) and argue, drawing on results from the research literature and some simple modelling, that this requires global fossil fuel emissions to be held near current levels up to around 2050, followed by a gradual decline in emissions in the longer term. Their ideas for achieving this target are discussed further in Section 4 below, but the main point for now is that the balance of recent scientific evidence seems to suggest that this target of stabilising carbon emissions from fossil fuels is arguably the minimum that one would ideally want to aim for up to 2050 in terms of reducing the risks of severely damaging climate change in the longer term. This helps to put in context the subsequent discussion showing strong upward tendencies in carbon emissions without determined offsetting action.

1.7 Description of alternative scenarios

For this report we have focused a baseline scenario and five alternative scenarios in which one or more key assumptions are varied, as summarised in Table 1.5 below. These do not encompass the full range of possible future outcomes, but they do serve to illustrate the sensitivity of future carbon emission scenarios to these key assumptions.

Table 1.5: Alternative scenarios

Scenario	Average world real GDP growth (% pa 2005-50 using PPPs)	Average world energy intensity change (% pa 2005-50)	Fuel mix trends
Baseline	3.2*	-1.6	No change from 2004 shares in each country
Scorched Earth	3.2*	-0.6	No change from 2004 shares in each country
Greener Fuel Mix	3.2*	-1.6	In each country, coal share falls by 0.1ppt per annum to 2025 then 0.3ppt per annum to 2050; oil share falls 0.3ppt per annum to 2050; natural gas share rises 0.2ppt per annum to 2025 then stabilises; renewables share rises to offset these changes
Green Growth	3.2*	-2.6	As in Greener Fuel Mix scenario
Green Growth + Carbon Capture and Storage (CCS)	3.2*	-2.6	As in Greener Fuel Mix scenario, but with additional reduction in carbon emissions due to CCS building up to 1.5GtC by 2050
Constrained Growth	2.6 (US productivity growth down 0.25% pa; E7 catch-up rates down by 0.5% pa to 2020 and by 1% pa in longer term)	-1.6	No change from 2004 shares in each country

*GDP growth in all these scenarios is as in the base case in PwC's March 2006 World in 2050 report.
Source: PricewaterhouseCoopers assumptions

The rationale for the **Baseline Scenario** is discussed in detail above and is intended as a 'Business As Usual'-type scenario in which global GDP growth follows our base case projections, energy intensity improves in line with trends since the early 1980s and fuel mix stays constant. It is not intended as a forecast of what is likely to happen but rather an indication of the results of continuing along the current path.

The **Scorched Earth scenario** is one in which the rate of improvement in energy intensity is towards the lower end of the range considered plausible by the IPCC in their 2001 scenario projections and around 1% per annum below the average seen since the 1980s. It might be associated with a significant decline in fossil fuel prices as a result of major new discoveries of oil and gas reserves and/or significant technological advances making viable the extraction of reserves previously considered uneconomic. In a world where fossil fuel energy again seemed relatively cheap and abundant, incentives to achieve continued rapid energy efficiency gains might be limited, particularly if there was a period when evidence of further global warming became less clearcut and there were relatively few major examples of damaging climate change. This might lead to a period of complacency about the need to control carbon emissions and, particularly perhaps in the rapidly industrialising emerging economies, a general priority being given to economic growth over environmental concerns. This is not an absolute worst case scenario from the perspective of carbon emissions, but it is towards the pessimistic end of the spectrum, though from a conventional economic growth perspective it might appear relatively benign. But the world would potentially be storing up more serious environmental problems for its future if it followed this path.

The **Greener Fuel Mix scenario** is a variant on our Baseline scenario in which, as the name suggests, there is shift towards natural gas (up to 2025) and particularly renewables (throughout the period to 2050) at the expense of coal and oil. In particular, the share of nuclear and renewables in total primary energy increases in this scenario from 12.3% in 2004 (using the BP dataset described above) to around 30% by 2050, while the share of oil falls from 36.8% in 2004 to only around 21% in 2050. GDP growth and primary energy intensity trends are, however, unchanged in this scenario, which therefore indicates how much progress can be made in reducing carbon emissions just by varying the fuel mix in a broadly plausible manner.

The **Green Growth scenario** goes further than this by assuming the same long-term shift towards lower carbon fuels as in the previous scenario, but also assumes that the rate of decline in primary energy intensity is increased by an average of 1% per annum (i.e. from -1.6% to -2.6% per annum). This is actually more optimistic than any of the core scenarios considered in the 2001 IPCC report and is therefore relatively challenging.

In Section 3 below, we introduce a variant on this scenario called **Green Growth + CCS** which also allows for the possible effect of carbon capture and storage (CCS) at a global level (with pro rata allocations by country). Specifically, we assume that the annual amount of carbon captured and stored builds up gradually from close to zero now to around 1.5GtC by 2050. As discussed further in Section 4, this is likely to be an important element in any strategy for mitigating carbon emissions to the atmosphere over this time period and the magnitude of effect in this scenario is within the plausible range indicated in a recent special report by the IPCC (2005) on this issue. But there are still many important obstacles to overcome in realising this potential, as discussed further in Section 4 below.

All the above five scenarios use the same base case GDP growth projections as in our World in 2050 report, involving average global GDP growth using PPPs of around 3.2% per annum. In the **Constrained Growth scenario** we consider how carbon emissions would be affected by a plausible reduction in this average global economic growth rate to 2.6%, partly affecting all countries but also with slower productivity catch-up rates in the emerging economies. We keep assumptions on energy intensity and fuel mix the same as in our Baseline scenario in order to isolate the impact of differential economic growth alone.

Many other variants or combinations of these scenarios could of course be considered using our model, but for the next two sections of the report we limit our analysis to these six core scenarios in order to keep the analysis and the commentary manageable. Section 2 focuses on alternative projections for primary energy consumption by fuel type, while Section 3 focuses on projections for carbon emissions and associated potential atmospheric CO_2 concentration levels in alternative scenarios. The modelling results then set the context for the discussion of technological and policy options in Section 4 below.

2. Economic growth and energy consumption in alternative scenarios

2.1 Economic growth

Table 2.1 below shows our baseline projections for average annual real GDP growth by country and globally for the period from 2005 to 2050, together with the alternative Constrained Growth scenario described above.

Table 2.1: Projected real GDP growth in alternative scenarios: 2005-50 (%pa)

Country	Baseline scenario	Constrained Growth scenario	Difference
India	5.2	4.0	-1.2
Indonesia	4.8	3.6	-1.2
Turkey	4.2	3.5	-0.7
China	3.9	3.1	-0.8
Brazil	3.9	3.2	-0.7
Mexico	3.9	3.3	-0.6
Russia	2.7	2.0	-0.7
Australia	2.7	2.5	-0.2
Canada	2.6	2.4	-0.2
S. Korea	2.4	2.2	-0.2
US	2.4	2.2	-0.2
Spain	2.2	2.0	-0.2
UK	2.2	2.0	-0.2
France	2.2	2.0	-0.2
Germany	1.8	1.6	-0.2
Italy	1.6	1.4	-0.2
Japan	1.6	1.4	-0.2
World*	**3.2**	**2.6**	**-0.6**
G7 total	2.2	2.0	-0.2
E7 total	4.2	3.3	-0.9

*Assumes these 17 economies have a constant 75% share of total world GDP at PPPs, in line with 2004 World Bank estimates.
Source: PricewaterhouseCoopers GDP growth estimates (rounded to nearest 0.1%)

Our Baseline projections were described in detail in our March 2006 report on the 'World in 2050', so here we just note some key features:

- overall the E7 emerging economies are projected to grow almost twice as fast as the G7 over the period to 2050 (although this growth gap closes over time as the E7 economies also start to age and as the scope for rapid catch-up through technological imitation is used up);

- due in large part to its more favourable demographics, India grows faster than China in the long run[27]; the marked deceleration in Chinese growth also

[27] In particular, India's working age population is projected by the United Nations to grow by close to 1% per annum in 2005-50, while China's is projected to decline by around 0.5% per annum over the same period due in particular to its one child policy.

reflects our view that recent very high levels of investment (45% of GDP or higher) cannot be sustained in the long run;

- among the E7 economies, Brazil, Indonesia, Mexico and Turkey benefit from relatively favourable demographics, while the opposite is true for Russia; South Korea is not included in the E7 due to its higher income per capita levels, but also suffers from a sharply declining working age population; and

- at this stage, the differentials between the G7 economies largely reflect differences in demographics that affect labour supply trends, rather than differences in productivity growth; Italy and Japan are projected to be at the bottom of the growth league due to their rapidly declining working age populations.

As described in the previous section, our Constrained Growth scenario combines a modest reduction in global productivity growth affecting all countries with a more specific reduction in the catch-up speeds of the E7 economies. This explains why, as shown in Table 2.1, G7 growth is only 0.2% per annum lower in this scenario whereas E7 growth is 0.9% per annum lower on average. The E7 economies with the fastest projected growth rates in our base case, such as India, see the most marked reductions in our Constrained Growth scenario. There are, of course, many other possible growth scenarios we could consider, but this serves the purpose of illustrating how different assumptions on economic growth feed through to energy consumption and carbon emission scenarios.

While the reduction in average annual global GDP growth in our Constrained Growth scenario is only around 0.6%, the cumulative effect is to reduce the projected size of the world economy in 2050 by almost a quarter from around $250 trillion to around $190 billion (at 2004 prices). The estimated E7 share of world GDP (at PPPs) in 2050 also declines from around 45% in our Baseline scenario to around 40% in the Constrained Growth case, although this is still well up from the E7's estimated share of around 30% in 2005.

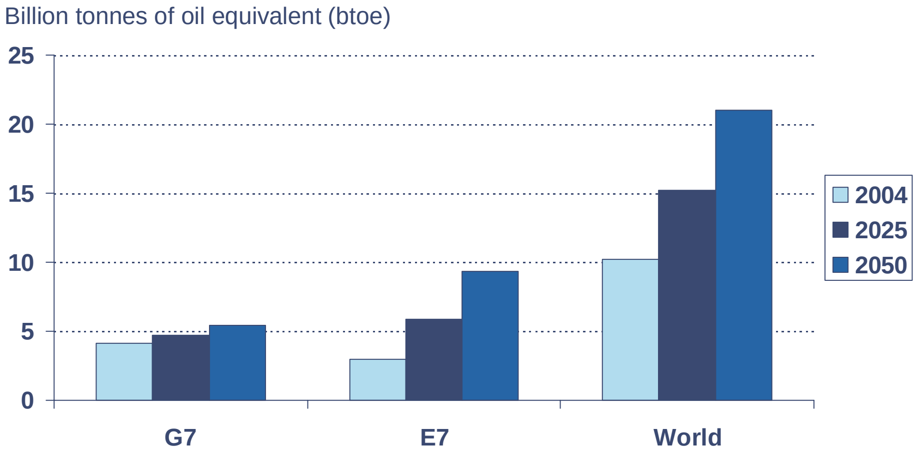
2.2 Primary energy consumption scenarios

In our baseline scenario, assumed energy efficiency improvements mean that global primary energy consumption only rises at an average of around 1.6% per annum over the period to 2050, around half the projected world GDP growth rate of 3.2% on average over the same period. Nonetheless, this still implies that global primary energy consumption more than doubles from around 10.2 billion tonnes of oil equivalent (toe) in 2004 to around 21 billion toe by 2050.

It is worth noting here that our baseline projection sees global primary energy consumption rise to around 16.3 billion toe by 2030, which is actually very close to the IEA's 2005 World Energy Outlook base case projection of around 16.5 billion toe in that year. This provides some reassurance that the simplified modelling approach adopted in this study is nonetheless producing plausible results comparable to those from the more complex IEA model.

As illustrated in Figure 2.1, this global trend disguises significant differences between established advanced economies and emerging markets. Primary energy consumption in the E7 economies is projected to rise by a cumulative 216% (2.5% per annum) by 2050, compared to an increase of only around 32% (0.6% per annum) in the G7 in our baseline scenario.

Figure 2.1: Primary energy consumption in baseline projections

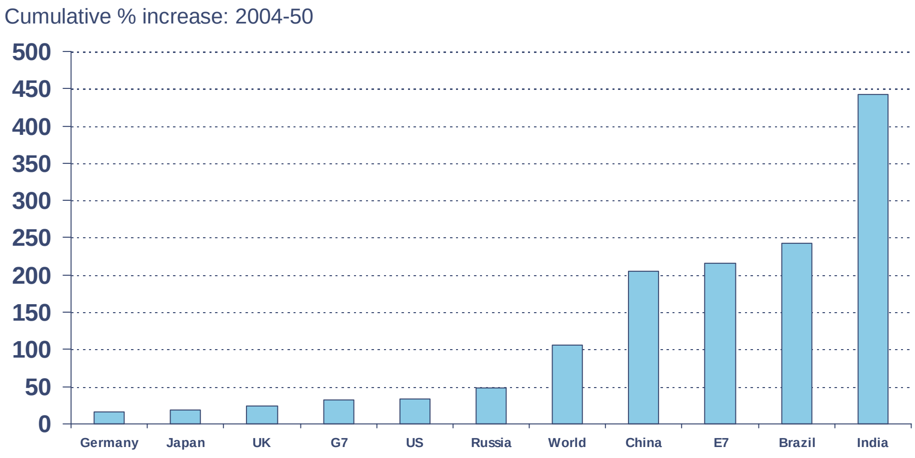


Source: BP Statistical Review data for 2004, PwC model estimates for later years

The E7 share of global primary energy consumption accordingly rises from just under 30% in 2004 to around 45% by 2050. The E7 accounts for around 60% of the total rise in global primary energy consumption in the period to 2050 in our baseline scenario.

These results for the G7 and the E7 disguise further variation within these groupings. For the 17 individual large economies considered in this study, the cumulative increase in primary energy consumption by 2050 varies from just 16% in Germany to 442% in India in our baseline scenario (see Figure 2.2 for results for selected countries). The US is slightly above the G7 average at 34%, while China is similar to the E7 average at 205%.

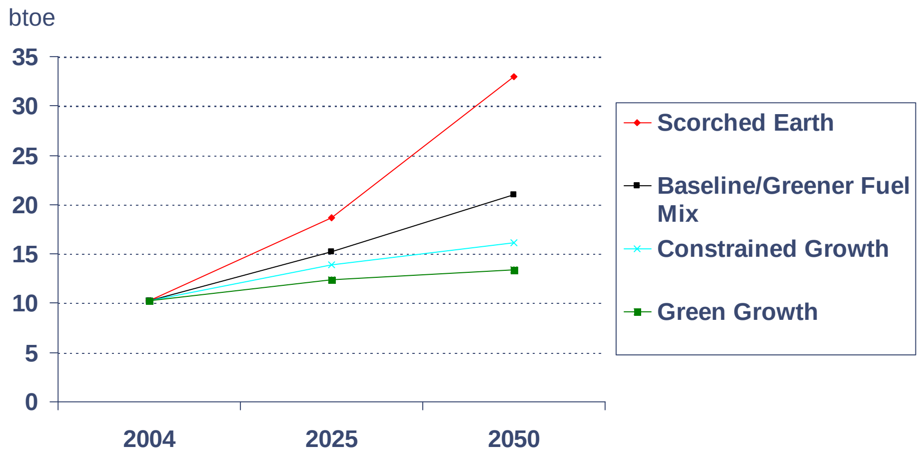
Figure 2.2: Projected growth in primary energy consumption in baseline scenario



Source: PwC model projections

Primary energy consumption in our Greener Fuel Mix scenario is the same as in the baseline scenario, but varies in our other three scenarios as illustrated in Figure 2.3 at the global level. We can see that, even in our Green Growth[28] scenario with energy intensity reductions 1% per annum greater than the historic trend, there is a rise of around 30% in primary energy consumption between 2004 and 2050, although this is down from a 106% projected increase in our baseline scenario.

Figure 2.3: Global primary energy consumption in alternative scenarios



Source: BP data for 2004, PwC model projections for later years

The share of the E7 in primary energy consumption rises and that of the G7 falls in all scenarios (see Table 2.2), although these trends are less marked in the Constrained

[28] Energy consumption projections are the same in our Green Growth and Green Growth + CCS scenarios, so we do not report results separately for the latter in this section.

Growth scenario where the economic catch-up rate of the E7 is assumed to be slower than in the other four scenarios. It is notable, however, that the E7 share of primary energy consumption is already relatively high at 29% and so only rises to around 44-45% in the four scenarios based on our main economic growth projections.

Table 2.2: Shares of G7 and E7 in global primary energy consumption in alternative scenarios

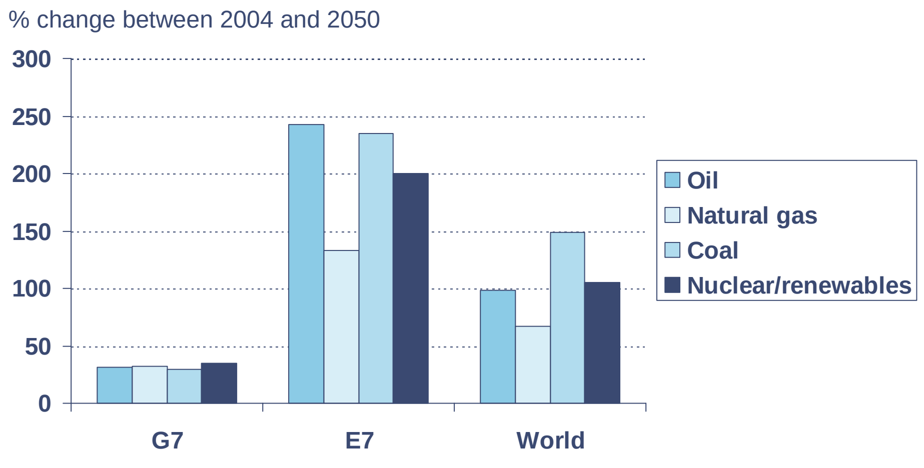
Scenarios	Share of E7 economies (%)		Share of G7 economies (%)	
	2004	2050	2004	2050
Baseline	29	44	41	26
Scorched Earth	29	44	41	26
Greener Fuel Mix	29	44	41	26
Constrained Growth	29	39	41	30
Green Growth*	29	45	41	26

*Results are the same for the Green Growth + CCS scenario
Source: BP data for 2004, PwC model projections for 2050

2.3 Primary energy consumption by fuel type

Our model also allows us to project primary energy consumption by fuel type. Figure 3.4 shows projected increases in G7, E7 and global consumption for the four major fuel types in our model up to 2050.

Figure 2.4: Projected increases in primary energy consumption by fuel type in baseline projections

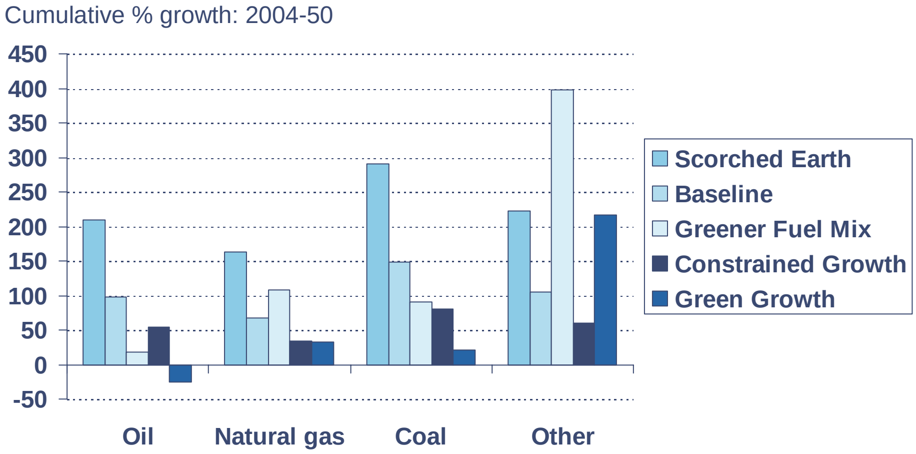


Source: PwC model projections under baseline scenario

The projections illustrate again the much faster growth in all fuel types in the E7 than in the G7. Whereas the cumulative increases between 2004 and 2050 are broadly similar at around 30% for the G7 for all fuel types, however, there are more marked differences for the E7 group that also translate into significant fuel type growth differentials at global level. This is because, as described in Section 2 above, we apply our baseline assumption of a constant fuel mix at national level (i.e. it applies to each country taken individually), but this still allows for compositional effects when aggregating to E7 or global level if energy consumption is growing much faster in absolute terms in some of these economies than others, and if fuel mix varies significantly across the economies. The key factor here is that China and India, which are by far the largest of the E7 economies in PPP terms (and in the long run are also much larger than any other economy except the US), are relatively strongly weighted to coal (and to a lesser extent oil, demand for which is likely to be boosted by increased use of cars and other motor vehicles in these emerging economies) rather than to natural gas in particular. This tends to push projected global growth in coal consumption up relative to other fuel types in our baseline scenario, as illustrated by the final set of columns in Figure 2.4 above. We would stress again, however, that this baseline scenario is intended as a starting point for analysis, not a forecast: in practice, we would expect some shift away from coal to natural gas and other fuel types in China and India, as considered in other scenarios.

Figure 2.5 illustrates how the projected cumulative global growth of consumption of different fuel types varies across alternative scenarios in the period to 2050.

Figure 2.5: Projections of global primary energy consumption growth by fuel type in alternative scenarios



Source: PwC model projections

We can see that there are very large differences between scenarios. The Scorched Earth scenario implies increases in fossil fuel consumption of a scale that, quite aside from any environmental implications, would appear inconsistent with current projections of available reserves for oil and, to a lesser extent, natural gas. Unless there are dramatic improvements in technologies that reduce extraction costs significantly and make a very large quantity of currently unviable reserves viable in the future, such rapid growth in consumption would be expected to result in large fossil fuel price rises that would be expected to choke off this demand. As such, this scenario is only plausible if these kind of major extraction cost-reducing technological advances are made. Clearly, however, this has been a field where significant advances have been made in recent decades, so this scenario (although relatively unlikely) is by no means impossible. As we will see in the next section, however, it might be ruled out on the basis that its implications for carbon emissions growth would be unacceptable in terms of the implied risks of adverse climate change in the longer term.

The other three alternative scenarios exhibit moderate, but still positive, growth in fossil fuel consumption, except in the Green Growth scenario where oil consumption actually declines due to a combination of rapid energy efficiency improvements and a switch to gas in the short term (though this could be constrained to a degree by reserve shortages and higher gas prices) and nuclear and renewables in the longer run. Overall, this latter scenario is clearly the most sustainable in terms of conserving energy resources, although it does require a more than 200% rise in primary energy supply from nuclear and renewable sources.

These results can also be presented in terms of the evolution of the global fuel mix over time, as summarised in Table 2.3 below for our Baseline and Green Growth scenarios.

Table 2.3: Evolution of global fuel mix in Baseline and Green Growth scenarios

% of total primary energy	Oil	Natural Gas	Coal	Nuclear and renewables	Total primary energy
Baseline scenario					
- 2005	36.7	23.3	27.7	12.3	100
- 2025	35.9	20.6	31.1	12.4	100
- 2050	35.5	19.3	33.0	12.3	100
Green Growth scenario					
- 2005	36.4	23.5	27.6	12.5	100
- 2025	29.3	25.3	29.3	16.1	100
- 2050	21.2	23.9	25.1	29.8	100

Source: PwC model estimates based on initial data from BP Statistical Review of World Energy 2005

The projected rising share of coal at the expense of other fossil fuels in the Baseline scenario reflects the growing significance of China and India in global energy consumption as discussed above. The Green Growth scenario also shows some rise in the share of coal (and also of natural gas at the expense of oil) in the initial period to 2025, but in the longer run all of the fossil fuels are projected to have a declining share as new nuclear plant comes on stream and a range of renewables sources are developed. The technological feasibility of achieving this kind of fuel mix shift and the policy measures to support this in terms of carbon taxes and/or carbon trading are discussed in detail in Section 4 below.

2.4 Summary: economic growth and primary energy consumption projections

The table below summarises the analysis above for our alternative scenarios in terms of projected annual average growth in the key variables considered.

Table 2.4: Projected average annual global economic and primary energy consumption growth in alternative scenarios: 2004-50 (% pa)

Scenarios	GDP	Primary energy	Oil	Natural gas	Coal	Other*
Scorched Earth	3.2	2.6	2.5	2.1	3.0	2.6
Baseline scenario	3.2	1.6	1.5	1.1	2.0	1.6
Greener Fuel Mix	3.2	1.6	0.4	1.6	1.4	3.6
Constrained Growth	2.6	1.0	1.0	0.6	1.3	1.0
Green Growth**	3.2	0.6	-0.6	0.6	0.4	2.5

*Nuclear and renewables
**Results are the same for the Green Growth + CCS scenario
Source: PwC model projections

It should be emphasised again, as discussed in Section 1.4 above, that our Baseline scenario is intended as a convenient starting point for analysis, **not** as a forecast of what we consider the most likely scenario (particularly as regards fuel mix). While the energy efficiency assumptions in this scenario are in line with historic trends since the early 1980s, the assumption of a constant fuel mix in each country leads to a projection at the global level of a rise in the share in coal relative to oil and natural gas. This is due to the particularly high coal intensity (and low gas intensity) of the large, relatively fast-growing Chinese and Indian economies, but in practice it is probably more likely that they will shift away from coal over time, perhaps leading us closer to the Green Fuel Mix scenario (although the scale of the rise in nuclear and renewable energy supply in this scenario might be considered rather ambitious). A combination of declining oil and gas reserves, which might be expected to put upward pressure on energy prices, and environmental concerns might also plausibly be argued to give a push towards faster energy efficiency improvements, so moving the world in the direction of the Green Growth scenario.

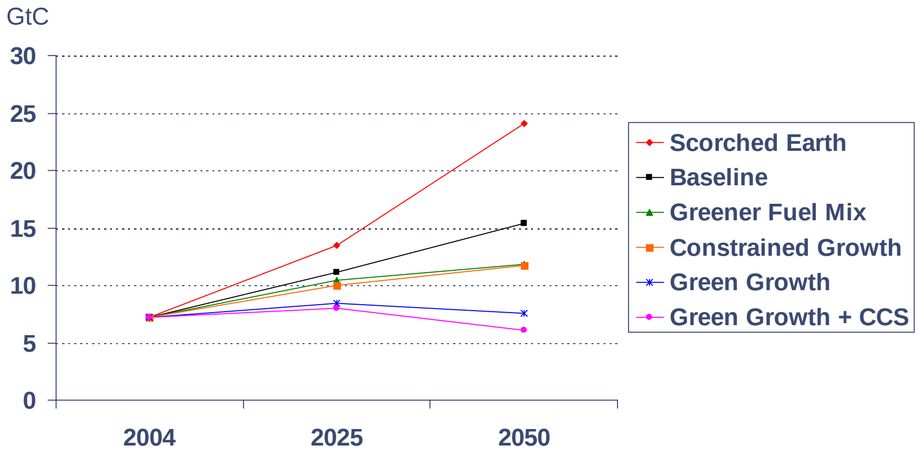
Further variants and combinations of these five scenarios could, of course, be developed. For example, a less optimistic view of global economic growth potential, particularly as regards the catch-up potential of the E7, could be combined with improved energy efficiency and a greener fuel mix to take us towards what we might call a ‘Constrained Green Growth’ scenario in which all growth rates would be around 0.6% per annum below those in the Green Growth scenario above. It is not clear that creating further scenarios would add much extra insight, however, so in the next section we continue to focus on the six scenarios described in Section 1, but extend the analysis above to look at the implications for carbon emissions and atmospheric CO2 levels.

3. Carbon emissions and atmospheric C02 levels in alternative scenarios

3.1 Global projections of carbon emissions and atmospheric C02 levels

By using the assumptions described in Section 1.5 above, we can translate our projections for primary energy consumption by fuel type in different scenarios into alternative projections for carbon emissions (see Figure 3.1).

Figure 3.1: Projections of carbon emissions in alternative scenarios



Source: PwC model projections

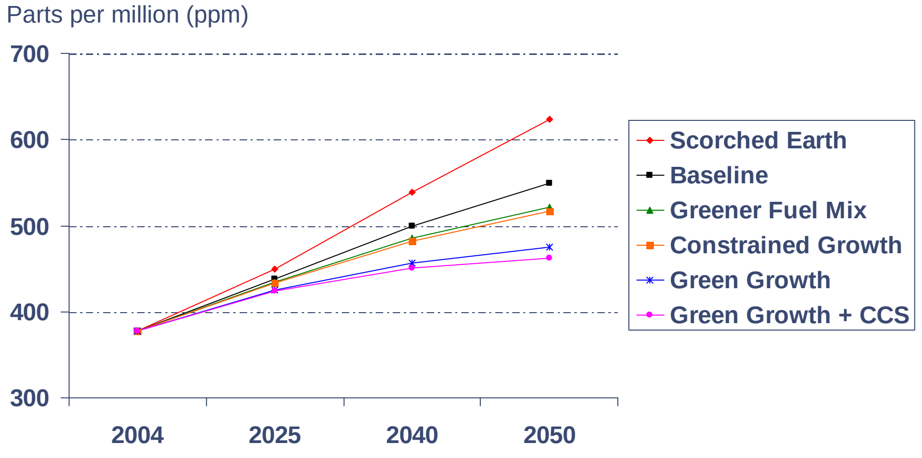
In the Scorched Earth scenario global carbon emissions would approximately double by 2025 from current levels of just over 7GtC and more than triple by 2050. This seems unlikely to be sustainable in terms of its implications for climate change.

Even the Baseline scenario, however, which is broadly comparable to ‘Business As Usual’ scenarios previously constructed by the IPCC, the IEA and others, involves a more than doubling of global carbon emissions to just over 15GtC by 2050.

The projected increase could be roughly halved (corresponding to a c.25% reduction in global carbon emissions by 2050 compared to our Baseline scenario) either by constraining global GDP growth to be 0.6 percentage points per annum lower, or by switching to a green fuel mix with the share of nuclear and renewables in total primary energy supply more than doubling by 2050. In relation to the Constrained Growth scenario, however, this would imply not just a c.25% reduction in global GDP by 2050 but a c.33% decline in E7 GDP, implying a disproportionate burden on emerging economies. Expecting these poorer countries to constrain their growth to rescue much wealthier countries from the cumulative climate change impacts of their own earlier economic development processes seems unlikely to be acceptable to these countries. In any event, as discussed further in Section 4 below, switching to a greener fuel mix gradually over time seems likely to be a much more cost-effective mechanism than crude constraints on economic growth, provided that plans to do this are put in place early. Only if this adjustment is delayed might environmental crises potentially force much larger sacrifices of economic growth at a later date.

The Greener Fuel Mix scenario may not be sufficient in itself, however, because as Figure 3.1 shows it still implies a rise in global carbon emissions of over 60% by 2050. Translating this into estimates of global atmospheric C02 concentration levels (using the methodology described in Section 1.6 above) gives the results for this and alternative scenarios shown in Figure 3.2.

Figure 3.2: Projections of atmospheric C02 concentration levels in alternative scenarios



Source: PwC model projections

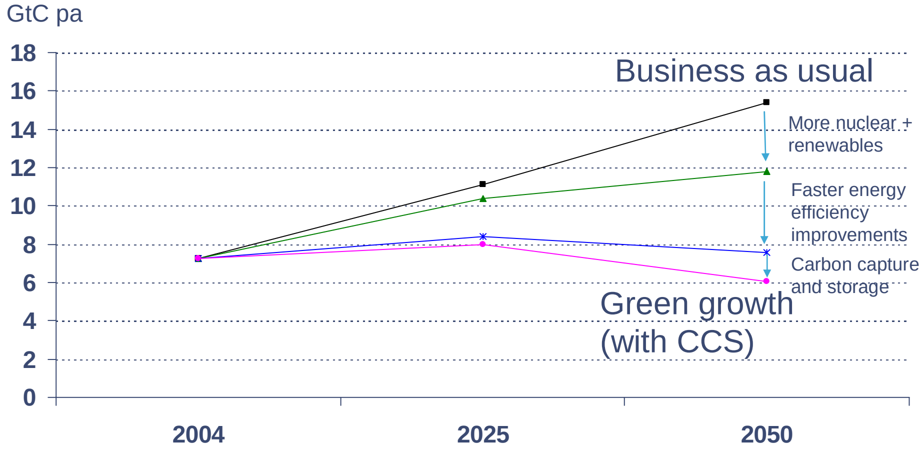
We can see that the Greener Fuel Mix scenario (or indeed the Constrained Growth scenario) would imply atmospheric C02 concentrations rising to over 500 ppm by 2050, which the majority of scientists would probably now see as the maximum level consistent with avoiding severe risks of adverse climate change effects (and many now argue for a lower maximum at 450 ppm or even 400 ppm). Furthermore, this rate of increase would be at best slightly decelerating in this scenario.

This suggests that the Green Growth scenario might be a more prudent target to aim for, implying a gradual reduction in global carbon emissions from a peak of around 8.5GtC in 2025 to around 7.5GtC in 2050, only slightly above current levels (see Figure 3.1 above). However, as Figure 3.2 illustrates, this would still imply atmospheric C02 levels of around 475ppm by 2050 and these would still be rising at around 2ppm at that time according to our model, similar to the estimated rate of increase at present. So this scenario would seem to be at best minimally acceptable and would ideally need to be complemented by a combination of carbon capture and storage to reduce emissions to the atmosphere up to 2050 and further measures to cut emissions at a faster rate beyond that date.

In relation to **carbon capture and storage (CCS)**, Figures 3.1 and 3.2 include a Green Growth + CCS scenario in which the effect of this is assumed to build up gradually to 1.5 GtC by 2050[29], so that global carbon emissions from fossil fuels peak at around 8tC in 2025 and then decline to around 6 GtC by 2050 (see Figure 3.1 above). The impact of CCS on atmospheric CO2 levels does not appear that large in Figure 3.2 because it takes time to build up, but it has the effect of significantly reducing the upward trend in atmospheric C02 levels by 2050, with the likelihood being that this level might peak by 2060 at around 465ppm and then start to decline, assuming that carbon emission trends in the 2040s continue after 2050. This Green Growth + CCS scenario might therefore be considered to satisfy the evidence from many recent scientific studies that suggests a target of stabilising C02 concentrations at not much more than 450 ppm and certainly below 500ppm[30]. In contrast, plausible extrapolations from our Green Growth scenario without CCS would suggest that atmospheric C02 levels might reach 500ppm by 2075 without clearly stabilising.

In summary, our Baseline ‘business as usual’ scenario involves carbon emissions more than doubling by 2050 and an accelerating increase in atmospheric CO2 concentrations. To reach what, according to most recent scientific studies, would be a broadly sustainable outcome would appear to require, as in our Green Growth + CCS scenario, a combination of a shift to a much less carbon-intensive fuel mix, significant energy efficiency improvements over and above the historic trend, and significant investment in carbon capture and storage (see Figure 3.3).

Figure 3.3: Three steps to reduce global carbon emissions to sustainable levels by 2050



Source: PwC model projections: the four lines correspond (starting from the top) to our Baseline, Greener Fuel Mix, Green Growth, and Green Growth + CCS scenarios. ‘Sustainable’ is defined here as consistent with stabilising global atmospheric CO2 concentrations at around 450ppm by 2050.

We look at the technological and policy options for achieving this in Section 4 below, but first we look in more detail at our carbon emission projections in this scenario as compared to our baseline scenario.

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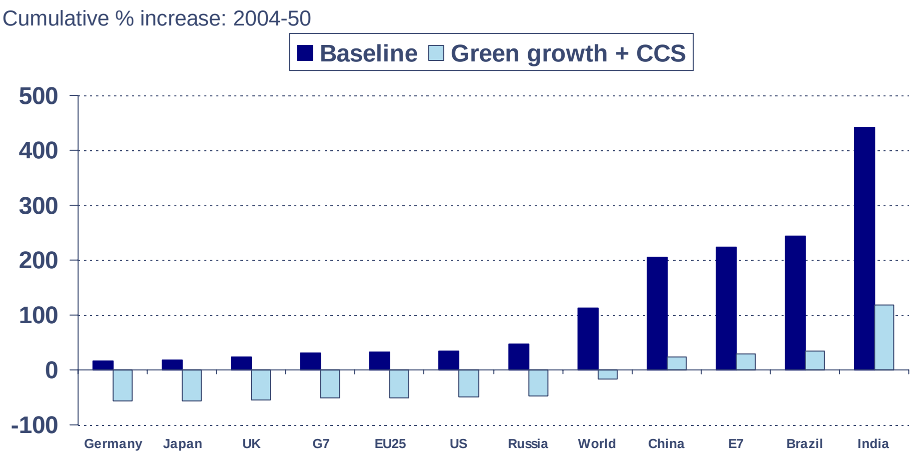
[29] This assumption is within the plausible range of feasible CCS effects considered in a 2005 IPCC report on Carbon Capture and Storage (see Section 4.1 below for more details).

[30] Although scientific views on what might be acceptable here have been steadily revised down in recent years as evidence of the speed of global warming has accumulated and concern has grown about feedback effects that could worsen the impact of a given level of C02 in the atmosphere (e.g. because this leads to higher temperatures that reduce the ability of oceans and soil to absorb C02, so feeding back to higher C02 concentrations and so on).

3.2 Carbon emissions projections by country/region

It is interesting to consider how projected carbon emissions might vary by country and region in alternative scenarios. Figure 3.4 illustrates how projected carbon emissions growth varies geographically[31] in our Baseline and Green Growth + CCS scenarios (assuming, in the absence of any actual data at this early stage, that CCS effects are spread proportionately across countries).

Figure 3.4: Projected growth in carbon emissions in baseline and Green Growth + CCS scenarios



Source: PwC model projections

For the world as a whole, the requirement is to reduce cumulative carbon emissions growth in 2004-50 from 112% in the 'business as usual' baseline scenario to -17% in the Green Growth + CCS scenario, but there is a marked difference here between the G7 economies, where reductions averaging just over 50% are required, varying from around 43% in France (where carbon emissions are kept down in our baseline scenario by its higher nuclear share of total energy) to 57% in Germany. For the US, the required reduction is around 50% and for the UK around 55%[32]. For the EU as a whole it is around 50%.

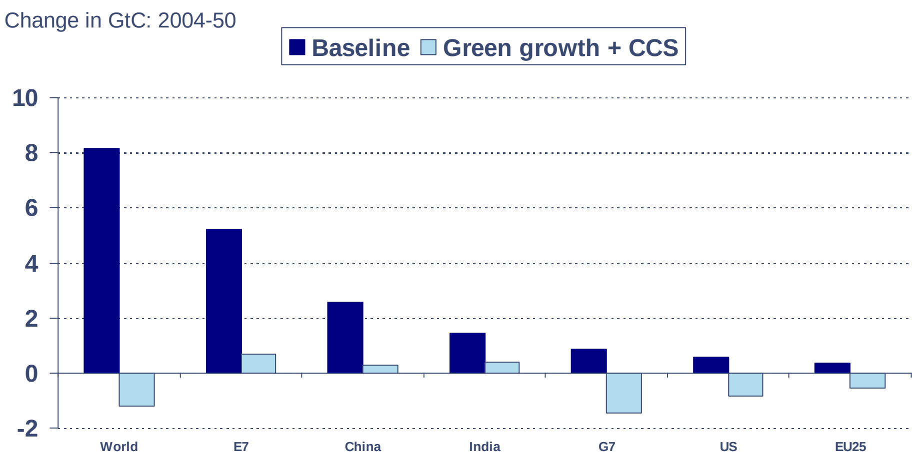
In contrast, for the E7 the requirement is for them to mitigate the growth of their carbon emissions in the period to 2050 from 224% in the baseline scenario to around 30% in the Green Growth + CCS scenario. More detailed analysis suggests, however, that E7 carbon emissions might peak in around 2030 in the latter scenario and then begin to decline gradually up to 2050 (and beyond). Within the E7, however, Figure 3.4 illustrates a wide range of projected growth rates, with the highlights being:

[31] For the purposes of this chart and others in this section, we have estimated carbon emissions for the whole of the EU25, based on extrapolating from results for the five largest EU economies, which are included in our model.
[32] In fact, the UK government is aiming for an even larger 60% reduction target, which might seem desirable to allow some margin for slippage, though the baseline is slightly different.

- a 24% increase in Chinese carbon emissions by 2050 in the Green Growth + CCS scenario (with a peak in around 2025), down from 205% in the Baseline scenario;
- a 118% increase in Indian emissions in the Green Growth + CCS scenario by 2050, compared to over 400% in the Baseline scenario, but with emissions peaking in the former scenario by around 2045; and
- in contrast to the other emerging economies, a projected decline in Russian carbon emissions by around 47% by 2050 in the Green Growth + CCS scenario, albeit from a particularly high starting point relative to GDP at present.

As well as the percentage growth figures in Figure 3.4, it is also interesting to look at projected absolute changes in carbon emissions (in GtC) between 2004 and 2050 by country/region, as summarised in Figure 3.5 for our Baseline and Green Growth scenarios. We find that the E7 accounts for around 5.2 GtC (64%) of the total 8.15GtC rise in global carbon emissions projected in our Baseline scenario between 2004 and 2050. In the Green Growth + CCS scenario, E7 carbon emissions rise much more modestly by around 0.7GtC over this period, offset by a projected 1.4GtC reduction in G7 emissions. This includes the projected impact of CCS.

Figure 3.5: Projected absolute change in carbon emissions in baseline and Green Growth + CCS scenarios



Source: PwC model projections

We can also look at how the share of global carbon emissions is set to vary across economies in these two scenarios, as summarised in Table 3.1 below. One immediate point to note is that the projected evolution of global carbon emission shares (and particularly the shift from the G7 to the E7) is not all that different in the two scenarios shown in Table 3.1, even though the absolute level of emissions is reduced by around 60% by 2050 in the Green Growth + CCS scenario relative to the Baseline scenario. The burden of adjustment is somewhat weighted to the G7 in the Green Growth + CCS scenario, but not to any very marked extent. In practice, this will no doubt require a great deal of difficult political negotiation.

Table 3.1: Projected share of global carbon emissions in key scenarios (%)

Country or grouping	Share in 2004	Baseline scenario		Green growth + CCS scenario	
		2025 share	2050 share	2025 share	2050 share
US	22.9	16.5	14.5	16.3	13.8
Japan	4.9	3.9	2.7	3.9	2.6
Germany	3.2	2.3	1.7	2.3	1.6
UK	2.1	1.5	1.2	1.4	1.2
France	1.5	1.3	1.1	1.3	1.0
Italy	1.7	1.7	1.0	1.5	1.0
Canada	2.2	1.7	1.5	1.6	1.2
G7 total	**38.6**	**28.7**	**23.7**	**28.3**	**22.5**
China	17.3	24.3	24.8	24.6	25.6
India	4.4	6.7	11.4	6.8	11.7
Brazil	1.2	1.6	2.0	1.5	2.0
Russia	5.8	4.7	4.0	4.6	3.7
Mexico	1.4	2.1	2.4	2.1	2.5
Indonesia	1.2	2.0	2.9	2.0	2.9
Turkey	0.8	1.3	1.6	1.3	1.5
E7 total	**32.1**	**42.6**	**49.0**	**42.8**	**49.8**
Other*	29.3	28.7	27.0	28.9	27.7
World total	**100**	**100**	**100**	**100**	**100**
Memo: EU25	*14.9*	*12.1*	*9.2*	*11.9*	*8.8*
*Memo:Big3***	*44.6*	*47.5*	*50.7*	*47.7*	*51.1*

*This is only an illustrative estimate based on scaling up from the 17 economies in the model (i.e. the G7, the E7, plus Spain, Australia and South Korea).
***US, China and India
Source: PwC model projections

Another notable point is the significance in total global emissions of the 'Big 3' economies of the US, China and India. These already account for around 45% of total global carbon emissions and our projections suggest that this will increase to just over 50% by 2050 in either scenario. China will take over from the US as the largest carbon emitter from around 2010 onwards according to projections and will account for almost a quarter of total global emissions by 2025, although this will then tend to flatten out as China's projected economic growth slows. India will then take over as the major motor of increased carbon emissions after 2025, assuming its economy grows as fast as we are projecting, which is not guaranteed of course.

3.3 Summary and conclusions

Our baseline 'business as usual' scenario implies that carbon emissions would more than double by 2050. To reach what, according to most recent scientific studies, would be an acceptable outcome in terms of mitigating the risk of severe adverse impacts from climate change in the longer term might require global carbon emissions to the atmosphere to peak by around 2025 at only around 10% above 2004 levels and then decline steadily to at least 15% below 2004 levels by 2050 as in our Green

Growth + CCS scenario. This could be achieved through a combination of the following three elements:

1. A shift to a much less carbon intensive fuel mix through increased nuclear and/or renewables supply (more than doubling its current primary energy share by 2050) and reduced fossil fuel. We estimate could reduce carbon emissions in 2050 by around a quarter relative to our baseline scenario.

2. Energy intensity reductions significantly faster than historic trends (say, 2.6% per annum rather than 1.6% per annum, which would reduce carbon emissions in 2050 by around a third relative to our baseline scenario).

3. Significant investment in carbon capture and storage (CCS) technology and capacity of the order of 1.5 GtC per annum by 2050, which could reduce carbon emissions by a further 20% relative to our Green Growth scenario without CCS.

For the G7 economies, this might involve a cumulative reduction in carbon emissions of at least 50% by 2050 relative to current levels.

For the fast-growing E7 economies, except perhaps Russia, it does not seem realistic to expect them to cut their carbon emissions over the next 25 years, although they could reasonably be expected to slow the pace of their growth progressively. From around 2030, E7 carbon emissions might also be expected to start to decline, although this might still leave them around 30% higher in 2050 than at present (including the impact of carbon storage and capture). There is likely to be considerable variation within the E7 here, however, with more rapid growth in emissions likely to be needed in lower income economies such as India, but with significant reductions in carbon emissions from current levels being necessary and achievable in Russia.

Having outlined the implications for carbon emissions of our alternative scenarios, the next section reviews the possible technological and policy options for achieving carbon emission reductions.

4. Technological and policy options for controlling carbon emissions

Having established the scale of the challenge, this section discusses some of the options for achieving an outcome along the lines of our Green Growth + CCS scenario (assuming, for the sake of argument, that this is a reasonable long-term objective). This is clearly a huge topic, which we can not do more than briefly summarise here based on a synthesis of the latest research literature. However, the overall message we want to convey is that there are grounds for optimism about the potential to mitigate carbon emissions significantly in the long run without unacceptable large economic costs, provided that action starts early enough on a broad range of technological and policy initiatives.

The discussion is organised as follows:

- **Section 4.1** reviews promising technological options in relation to reducing the energy intensity of GDP, reducing the carbon intensity of energy consumption and developing carbon capture and storage;
- **Section 4.2** reviews the scope for using policy instruments such as carbon taxes and tradable carbon allowances to incentivise emission reductions and considers the policy implications of induced technological change;
- **Section 4.3** summarises estimates from earlier modelling work of the likely economic cost of achieving the scale of carbon emission reductions required; and
- **Section 4.4** summarises and concludes.

4.1 Technological options for reducing carbon emissions

Pacala and Socolow (2004) argue that humanity already possesses the technological know-how to solve the carbon emissions problem over the next half century, which they take to mean stabilising emissions at no more than current levels of around 7 GtC, or atmospheric concentrations at no more than around 500ppm. Specifically they argue that under a business as usual scenario, global emissions might approximately double to around 14 GtC per annum by 2054, which is not that far away from our own baseline estimates of just over 15 GtC by 2050. They then argue that there are as many as 15 possible options, each of would potentially reduce carbon emissions by around 1 GtC per annum by 2054 relative to their 14 GtC baseline. If even around half of these 1 GtC ‘wedges’ were to prove feasible (or if all of them delivered half as much as this on average), then stabilisation of carbon emissions at around 7 GtC could be achieved. As it happens, this would be close to the outcome in our Green Growth scenario.

The 15 potential wedges identified by Pacala and Socolow are summarised in Table 4.1 below. We have added our own comments on each option in the final column of the table, drawing in part on the discussion in the original article and in part on our own analysis and assessment of the options. It should be noted that their analysis focuses on current known technologies and does not cover the issue of induced technological change (e.g. through learning-by-doing effects), which has been the subject of considerable research recently in a climate change context. We return to this latter issue in Section 4.2 below.

Table 4.1: Potential options for reducing carbon emissions in 2054 by 1 GtC

Options	Changes required to reduce carbon emissions in 2054 by 1 GtC	PwC assessment of likelihood of achieving this change and key issues
A. Energy efficiency and conservation		
1. More fuel efficient vehicles	Increase fuel economy for 2 bn cars from 30mpg to 60mpg	**Medium**: much of this may already be in the baseline
2. Reduced vehicle use	Decrease car travel for 2bn cars from 10k to 5k miles per annum	**Medium**: challenging, but road pricing, higher fuel/carbon taxes, better public transport, telecommuting could all help
3. More energy-efficient buildings and appliances	Requires 25% cut in projected energy use by buildings and major home appliances	**High/Medium**: some of this will already be in the baseline but more could be done through better designs and energy-saving practices
4. More efficient fossil fuel power plants	Improve projected efficiency of coal-fired plants from projected 40% (32% today) to 60%	**High/Medium**: some of this may already be in the baseline, but more could be done
B. Greener fuel mix		
5. Switch power plants from coal to gas	Replace 1400 GW of coal plants with gas (fourfold rise on current levels for gas plants)	**Medium**: higher gas prices have impacted relative economics; security of supply concerns
6. Nuclear power	Add 700 GW capacity (twice current levels)	**High/medium**: costs have fallen but still concerns about safety, nuclear waste, decommissioning costs, terrorism risks
7. Wind power	Add 2 million 1-MW-Peak windmills (50 times current capacity)	**Medium/Low**: technical limitations; local environmental concerns; costs if offshore.
8. Solar (PV) power	Add 2000 GW-peak PV (700 times current capacity)	**Low**: huge increase needed – viability not yet proven
9. Switch from gasoline to hydrogen fuel cells	Half of all cars run on fuel cells using hydrogen produced from renewable energy sources	**Medium/low**: only saves carbon if hydrogen produced using low or zero carbon methods
10. Switch to biofuels	Increase ethanol production by 50 times to replace gasoline	**Medium**: potential to rise but scale of increase seems very high (c. 1/6th of world cropland)
C. Carbon capture and storage		
11. Storage of carbon captured at baseload power plants	Install CCS at 800GW of coal plants (or 1600GW gas plants)	**Medium**: requires very large rise in carbon storage capacity (similarly with next 2 options)
12. Storage of carbon captured in hydrogen plants	Install CCS at hydrogen plants with 10 times current capacity	**Medium/low**: depends on increased use of hydrogen plants – technology already established
13. Storage of carbon captured at synthetic fuel plants	Introduce CCS at synfuel plants producing 30m barrels per day	**Medium**: CCS becoming standard in coal-to-liquid plants and considered for gas-to-liquid
D. Forests and agricultural soils		
14. Reduced deforestation, plus new tree plantations	Reduce tropical deforestation to zero and double current rate of new tree plantations	**Medium**: Ambitious but might be achievable with worldwide effort and consensus
15. Conservation tillage	Apply these techniques to all cropland	**Medium/low**: at present applies to only 10% of cropland,

Source: Pacala and Socolow (2004, Table 1) plus PwC assessment in final column.

The examples given by Pacala and Socolow are only intended to be illustrative of the possibilities presented by technologies that are already reasonably well established technically (even if not yet economically viable in many cases), rather than being comprehensive. Additional options such as distributed generation might also be considered here, for example. Nonetheless, their list provides a useful starting point for discussion and below we consider further in turn each of the four groups of measures shown in Table 4.1 above.

A. Energy efficiency and conservation

Particularly in relation to the vehicle and building efficiency improvements suggested, it seems likely that a significant part of the 1 GtC carbon wedges suggested by Pacala and Sokolow may already be in our baseline scenario, given that this involves extending forward historic energy efficiency improvements in these areas. Our baseline scenario, for example, assumes a trend reduction of 1.6% per annum in the ratio of primary energy consumption to GDP, in line with the global average trend since the early 1980s. This would imply a cumulative decline in energy intensity of around 50% by 2050. So the doubling of average fuel economy from 30 mpg to 60 mpg in their Option 1 might just be considered par for the course in this context.

Similar qualifications apply to their assumptions on energy efficiency improvements for buildings and home appliances (Option 3) and for power plants (Option 4). This is not to say that larger improvements than assumed in our baseline scenario will not be possible or indeed necessary: this could include very basic changes like not leaving home appliances on stand-by or using lower energy light bulbs, as highlighted recently in a report by the IEA (2006). In our Green Growth scenario, for example the required reduction in energy intensity is around 70% by 2050. An important requirement for achieving this scale of improvement will be that, as the emerging economies develop, they adopt the latest and most energy efficient designs for buildings, vehicles, factories and other major energy-using equipment. Assisting with this technology transfer might be regarded both as a policy priority for OECD governments and a significant business opportunity for OECD companies. With its rapidly growing automotive sector, however, it is also possible that China could eventually become a global technological leader in this area (and indeed in other areas like hydrogen fuel cell powered cars).

Option 2 in Table 4.1, involving a halving of average annual mileage by 2050 (but with a fourfold increase in the number of cars[33]), raises rather different issues. It is certainly not clear why people should use their cars less in future unless there are both strong financial incentives to do so and good quality alternatives. Measures such as road pricing, with the proceeds being recycled back (at least in part) into investment in public transport, might be required here. So-called ‘tailpipe trading’, aimed at reflecting the cost of carbon emissions in petrol prices, might also be considered. The

[33] The projection of a fourfold rise in the number of cars in the Pacala and Socolow paper is not implausible given a projected 328% rise in world GDP between 2004 and 2050 in our baseline scenario, and the likelihood that car ownership will rise faster than GDP in emerging economies, although the reverse might be true in advanced economies where car ownership may be close to saturation levels. There might be scope to reduce car ownership growth through appropriate tax policies and investment in public spending here.

Institute for Public Policy and Research[34], a leading UK think tank, has recently suggested that road transport could be included in the EU's Emissions Trading Scheme (ETS) via road fuel suppliers, who might be required to buy permits to cover the carbon emissions of the fossil fuels they supply each year. This might be extended to other countries if similar schemes to the EU ETS are eventually adopted there. A detailed assessment of this and other kinds of policy option is beyond the scope of this report, but the general principle that new incentives are needed to encourage the transport sector to control growth in its carbon emissions seems a sound one, bearing in mind that this is the sector where emissions growth has been particularly rapid in recent decades (e.g. the latest European Environment Agency data show EU-15 transport CO2 emissions up by 24% between 1990 and 2003, while total EU-15 CO2 emissions were down by around 1% over this period).

Overall, the energy efficiency projections in our Green Growth + CCS scenario seem challenging but achievable given determined policy efforts across a range of fronts (from vehicle fuel efficiency and building design to more energy-efficient lightbulbs and switches in consumer behaviour related, for example, to 'smart meters' that allow households to monitor and adjust their domestic energy use much more easily). This is also the broad conclusion of a recent major report by the IEA (2006), which concludes that enhanced energy efficiency improvements can cut carbon emissions by around 25-30% relative to a business as usual scenario that is broadly similar to our own Baseline scenario[35]. Certainly energy efficiency improvements are likely to be the primary source of carbon emission reductions over the next 20 years, although other options requiring greater technological innovations may play more of a role over longer time horizons, as discussed further below.

B. Greener fuel mix

It seems clear from the analysis above that energy efficiency improvements on their own, although important, are unlikely to be sufficient to produce an acceptable outcome for carbon emissions. As suggested in Table 4.1, this is likely to require a combination of:

- **Shifting from coal to natural gas in power plants** (Option 5), which would reduce carbon emissions by up to half for a given output of electricity. This is likely to be particularly important in China and India given their current heavy dependence on coal, but it could be undermined if natural gas prices rise further relative to coal prices. There are also security of supply concerns in countries that would need to rely increasingly on natural gas imports.
- **Shifting from fossil fuels to nuclear power** (Option 6), which is coming back on the agenda in several countries now (e.g. the G8 meeting in July concluded that nuclear power could play an important role in future global energy security as the did the UK's 2006 Energy Review). Nuclear power may not have been economically competitive in the 1990s, but it now appears to offer the prospect of increased future cost competitiveness given lower real discount rates (which favour nuclear due to its relatively high up-front capital costs

[34] Grayling, Gibbs and Castle (2006).
[35] It should be noted, however, that our modelling work was carried out entirely independently and was completed before the IEA report was published.

compared to gas-fired plant in particular), rising oil and gas prices in recent years, and the introduction of carbon taxes/prices[36]. Potentially this seems one of the higher likelihood option to deliver a Pacala-Sokolow 1GtC wedge, although nuclear power continues to be constrained to varying degrees in different countries by public concerns over safety (whether justifiable or not) and both political and economic issues relating to nuclear waste disposal and long-term decommissioning costs. For these reasons, take-up of nuclear power is likely to be uneven across countries, but leading economies that are already actively involved in the Generation IV International Forum (GIF) for developing the next wave of nuclear reactors include the US, China, Russia, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland and the UK.

- **Shifting from fossil fuels to renewables in electricity generation** (Options 7 and 8), although this does require both reductions in the relative costs of options like wind and solar power, which should come over time but the pace of this remains rather uncertain, and the fact that options like new dams for hydroelectric power and onshore wind farms can raise environmental concerns of their own. These are not reasons to reject these options, but it may constrain the magnitude of the renewables contribution to carbon emissions reductions. If strong enough financial incentives are put in place through carbon taxes/prices to make renewables more economically attractive, however, then there is room for optimism about their long-term potential. This is reflected in our Green Growth scenario (with or without CCS), which assumes only a modest increase in renewables share of global primary energy consumption up to 2025, but a more rapid increase after that as renewables technologies are assumed to develop and their relative costs decline (see Table 3.3 above and also the discussion on induced technological change in Section 4.2 below, which suggests that investing in renewables development now, even if it is not economic in the short run, could pay off in the long run due to 'learning-by-doing' effects). The IEA (2006) are also reasonably optimistic about the longer term potential of renewables, arguing that with the right policy incentives its capacity could as much as quadruple by 2050.
- **Shifting from gasoline to hydrogen fuel cells for cars** (Option 9), although the benefits of this in terms of carbon emissions will only arise if the hydrogen is itself produced from low or zero carbon processes (i.e. renewables, or at least natural gas, rather than coal). As pointed out by Pacala and Socolow, however, the carbon emissions reductions from using renewables to produce hydrogen for use in car fuel cells are only around half those from using renewables to produce electricity, so this option has some drawbacks to the extent that there constraints on the overall amount of renewables production that is feasible or economically viable.
- **Shifting to biofuels** (Option 10), notably in relation to using ethanol as a replacement for gasoline. Brazil is already increasing its ethanol production from sugar cane significantly, and major corn producers such as the US could also expand their production here. As Pacala and Socolow point out, however, there are limits to the scale of ethanol production arising from the land use requirements. They estimate that ethanol production would have to rise by a

[36] For further details on the improving economics of nuclear power relative to fossil fuels, see World Nuclear Association (2005).

factor of around 50 relative to current levels to produce 1GtC of carbon savings through gasoline substitution, which might require 250 million hectares of new plantations, equivalent to around a sixth of the world's total cropland on their estimates. This scale of increase appears very challenging, but that is not to say that ethanol (and other biofuels) could not make a smaller but still significant contribution to reducing future carbon emissions.

Overall, Pacala and Socolow outline the potential for up to 5 GtC of carbon emission reductions relative to their baseline scenario from the above measures, and these options could be extended (e.g. they do not include any possible effect from increased use of hydroelectric/wave power). Our own Greener Fuel Mix scenario implies a reduction of around 3.5GtC in carbon emissions relative to our baseline scenario by 2050, although this reduction would be lower if total energy consumption has already been constrained by energy efficiency improvements. Overall, this target appears challenging in terms of the scale of the switch to nuclear and renewables in particular that would be required to deliver carbon savings close to those indicated in the Pacala and Socolow analysis. The market seems unlikely to deliver such changes automatically, so government intervention in the form of some form of carbon pricing/taxation, possibly supplemented by some more specific incentives to support renewables technologies, would appear to be necessary here, as discussed further in Section 4.2 below.

C. Carbon capture and storage (CCS)

Pacala and Socolow see scope for up to 3GtC of carbon emission reductions from CCS (relative to their baseline) and a report last year by the IPCC (2005) also indicated considerable scope for carbon emission reductions from this source. The IPCC report estimates that a power plant equipped with a CCS system (and with access to suitable geological or ocean storage capacity) could reduce CO2 emissions by around 80-90%[37] compared to a plant without CCS. Carbon capture systems are currently of three main types:

- Post-combustion capture of CO2 from flue gases is already used in a small number of power plants and a similar technology is now well established in the natural gas processing industry.
- Pre-combustion capture of CO2 is based on a technology already widely applied in fertiliser manufacturing and hydrogen production.
- Oxyfuel combustion is still in the demonstration phase, but by using high purity oxygen results in high CO2 concentrations in the gas stream which make separation easier than with conventional combustion.

For power plants, it will generally be considerably more expensive and less efficient to retrofit carbon capture to existing plants than to design new plants with integrated CCS systems. Given the rapid programme of new power plant development in emerging economies like China and India at present, incorporating CCS into the designs of new plant is a priority. The additional costs involved might be offset in part where the CO2 can be injected into oil and gas fields to enhance oil recovery rates.

[37] Currently available technologies can capture around 85-95% of the CO2, but this is partly offset by a plant with CCS requiring 10-40% more energy than a plant without CCS.

We note here that CCS is already becoming a baseline option in coal-to-liquid plants planned by leading energy companies, and is being considered for gas-to-liquid plants.

Storage of CO2 in deep onshore or offshore geological formations uses many of the same technologies already well-established in the oil and gas industry and has already been shown to be economically feasible in some circumstances. It involves injecting CO2 into suitable saline formations or used oil and gas fields at depths of 800m or more. Three industrial-scale storage facilities were already in operation at the time of the IPCC report last year: the Sleipner project in an offshore saline formation in Norway, the Weyburn EOR project in Canada, and the In Salah project in a gas field in Algeria. More such projects are planned, though it should be noted that Pacala and Sokolow estimate that around 3500 storage facilities of the scale of the Sleipner project would be needed to accommodate the CO2 that would need to be captured over the period to 2050 in any of their Options 11-13 from Table 4.1 above. Whether such a huge increase in CO2 storage capacity could be achieved remains to be seen.

The IPCC report includes modelling analysis suggesting that CCS systems might be economically feasible for power plants if CO2 prices (or taxes) are at levels of around $25-30/tCO2 (which is not out of line with carbon prices in the EU ETS). The report also estimates that worldwide storage capacity could technically be at least around 2,000 GtCO2, equivalent to around 545GtC, while the economically feasible potential is estimated to be a cumulative 60-600GtC over the period to 2100, depending on the model and scenario used. The Green Growth + CCS scenario that we presented in Section 3 above, with annual effects building up to 1.5GtC between 2010 and 2050 and then stabilising, might imply a cumulative capacity requirement of around 75GtC, so it is by no means unfeasible based on the IPCC analysis.

In practice, as the IPCC notes, even where it is economically and technologically feasible, there are likely to be factors holding back CCS implementation in terms of other environmental impacts, risks of leakage, stakeholder concerns about intergenerational liabilities (i.e. the problem is just being put off to future generations), fiscal regimes, and the lack of a clear legal framework or public acceptance at this stage. But the IPCC report nonetheless concludes that CCS should be able to play a significant role in the cumulative CO2 emissions mitigation effort over the next century, accounting for perhaps 15-50% of total mitigation over this period in alternative scenarios. Our Green Growth + CCS scenario puts its contribution at around 20% of the total reduction in carbon emissions relative to our baseline scenario, so this is towards the lower end of the IPCC range.

D. Measures to boost natural carbon sinks: forests and soil management

Our focus in this report is on carbon emissions from energy use, but it is obviously important to combine mitigation efforts in this area (and other industrial processes, notably cement production) with measures to boost natural carbon sinks. It is beyond the scope of this report to cover these latter options in any detail, but Pacala and Sokolow show how significant reductions in net carbon emissions can be achieved through measures such as:

- Reducing clear-cutting of primary tropical forest to zero by 2050 (worth around 0.5GtC per annum by that year)
- Reforesting around 250 million hectares in the tropics, adding around a sixth to current areas of tropical forests globally (also worth around 0.5GtC per annum by 2050)
- Adopting conservation tillage techniques to reduce soil erosion and so the associated carbon emissions from this soil (potentially worth around 0.5-1GtC if applied globally across all cropland, although this seems rather optimistic).

Given uncertainties as to how great the action in these areas will be, however, we have not taken this additional potential into account in our model of atmospheric CO2 concentrations. This seems prudent given that recent scientific advances suggest that other factors (notably feedback mechanisms that involve global warming reducing natural carbon sinks automatically through their impacts on oceans, forests and soils) could act to worsen the long-term global warming impact of a given level of carbon emissions.

4.2 Policy issues

Many of the relevant policy options have been mentioned above, but it is worth looking at some key issues arising in a bit more detail (although it is beyond the scope of this paper to give more than an overview of these issues). The discussion focuses on three topics:

(i) carbon taxes;
(ii) carbon emissions trading; and
(iii) the policy implications of induced technological change.

(i) Carbon taxes

A standard economist's approach to the problem of environmental pollution is, following Pigou, the imposition of a tax on the source of the pollution at a level which reflects the costs to society of the negative effects ('externalities') associated with the polluting activity. In practice, however, estimating the costs to society associated with carbon emissions is very challenging because:

- while there is now a near universal scientific consensus on the fact that carbon emissions are linked to global warming, the precise quantification of the scale and timing of this effect is subject to significant uncertainties;
- the economic and social impacts of global warming are also subject to considerable uncertainties and will vary widely across different countries and regions (in some areas, for example, moderately higher temperatures might be seen as a net benefit) in a way that is not linked to emissions in those areas; and
- even if these impacts could be assessed, expressing them in financial terms in order to translate this into a tax per unit of CO2 emitted is not straightforward.

Furthermore, since climate change is a global phenomenon, it ideally requires a global decision on the level of carbon tax per unit of emissions, but this raises obvious problems of international political co-ordination, as well as fairness considerations in terms of how the burden should be shared between rich and poor countries[38]. If individual countries set their own carbon taxes, however, then concerns about adverse impacts on competitiveness of the most affected sectors could lead to significant political pressures to keep carbon tax levels down, or to allow exemptions or lower rates for carbon-intensive sectors exposed to international competition. These political pressures may be more difficult for national governments to resist in the absence of a strong international consensus on the need for carbon taxes.

In practice, the solution to the problem of international political co-ordination has been for most of the major industrialised countries, although not the US[39], to sign up to the Kyoto targets for greenhouse gas emissions to be reduced by an average of just over 5% by 2008-12 relative to a 1990 baseline (for the EU, the average target is 8%), with legally enforceable penalties if these targets are missed (although these are in terms of a 30% higher emissions reduction target in the next period after 2012, rather than any direct financial penalty).

Individual countries have then sought to meet their Kyoto targets in various ways, including carbon taxes in the case of the Netherlands, Sweden, Norway, Finland and Denmark (Switzerland has also been considering introducing a carbon tax), new energy-related taxes such as the UK climate change levy, and the EU Emissions Trading Scheme discussed further in the next sub-section. There is also scope under the Kyoto protocols for countries to meet their own targets through projects certified to reduce emissions or boost carbon absorption (e.g. through reforestation) either in developing countries through the Clean Development Mechanism (CDM) or in other industrialised countries through the Joint Implementation (JI) mechanism. However, earlier proposals for an EU-wide carbon tax in the 1990s were not adopted and recent proposals for a carbon tax in New Zealand have apparently been dropped following the 2005 election.

Two questions naturally arise here:

- How effective have carbon taxes been to date?
- What scale of carbon taxes might be required to achieve the much larger long-term emission reductions required to achieve alternative targets for stabilising atmospheric CO2 concentration levels at acceptable levels?

In relation to the first question, Norway provides an interesting case study as it introduced a relatively high carbon tax[40] as early as 1991. Bruvoll and Larsen (2002)

[38] Bearing in mind that, since CO2 stays in the atmosphere for a couple of hundred years, impacts on global warming for the next 50-100 years will in large part reflect past emissions by the current rich countries, rather than future emissions by the emerging economies like China and India.
[39] Australia, with its large coal industry, has also not yet ratified the Kyoto treaty for economic reasons, preferring to adopt a National Greenhouse Strategy. Overall, however, countries accounting for just over 60% of 1990 emissions (including Russia and some other transition economies in Eastern Europe not in the OECD) have ratified the Kyoto Protocol, so allowing it to become international law in February 2005. Some individual US states have also set targets for reducing greenhouse gas emissions (notably by 25% by 2020 in California).
[40] In 1999, the maximum tax rate was $51 per tonne of CO2 as applied to gasoline, although the weighted average tax was only $21 per tonne of CO2 after allowing for exemptions and reduced rates for some products and sectors.

carried out a detailed analysis of the factors underlying trends in Norwegian CO_2[41] emissions between 1990 (the year before the carbon tax) and 1999 (the latest data available at the time of their study). They then compared actual outcomes with a counter-factual case in which no carbon tax was introduced, based on simulations using a disaggregated general equilibrium econometric model of the Norwegian economy (MSG-6) that was specifically designed for studies of the economic and environmental effects of climate policy. Their key findings were that:

- **the negative impacts of the carbon tax on the economy were minimal**, with the level of GDP in 1999 being just 0.1% lower in the actual case with the tax relative to the counterfactual without the tax; the reduction in the level of household consumption attributable to the tax was similarly minimal at only 0.1% in 1999; *but*
- **the estimated impact of the carbon tax on CO_2 emissions in 1999 was also relatively small** at only 2.3%, as compared to total effects of around 14%[42] from reductions in energy intensity and a lower carbon fuel mix between 1990 and 1999; furthermore, excluding effects on the offshore oil and gas sector, the effect on the onshore economy was a reduction in CO_2 emissions of only around 1.5% between 1990 and 1999 due to the carbon tax.

Bruvoll and Larsen argue that these comparatively small effects were due to many of the most energy-intensive sectors (e.g. metals, industrial chemicals, cement) being exempt from the tax due to concerns about its impact on their international competitiveness. As such, the carbon tax did not provide incentives for these sectors to reduce their energy and/or carbon intensity, with more progress instead being made through direct regulation of these sectors. The authors conclude that a more broadly based, uniform carbon tax would have had more impact on emissions, although they acknowledge the difficulty of introducing this on a unilateral basis without international co-ordination for the most affected sectors to avoid adverse competitiveness effects.

More recent the Nordic Council (2006) has issued a report on the impact of carbon taxes in Nordic and Baltic countries. Results vary across countries, but they do find that, in Finland, CO_2 emissions might have been 7% higher at the end of the 1990s than without a carbon tax, while in Denmark the effects of a tax-subsidy scheme on industrial emissions may have caused emissions from affected plants to decline by around 20% over 7 years.

In relation to the second question above, available estimates are necessarily hypothetical and tend to vary considerably depending on the model used. For example, Edenhofer et al. (2006) compare results from a range of different models looking at the levels of carbon taxes/prices needed to achieve stabilisation of atmospheric CO_2 levels at around 450ppm:

- when the models do not allow for induced technological change, the range of required carbon taxes by 2050 (with varying upward profiles before then) was

[41] They also consider methane and nitrogen oxide emissions, but we focus here on their results for CO_2 for consistency with the rest of this report.
[42] These effects (and some other more minor factors) meant that CO_2 emissions rose by only 19% in Norway between 1990 and 1999, while GDP rose by around 35%.

from around \$60 to around \$750 per tonne of carbon at constant 1995 US dollars; and

- when induced technological change (e.g. learning-by-doing) was taken into account, the effects of which are discussed further below, the required carbon tax range was from around \$50 to around \$450 per tonne of carbon at constant 1995 US dollars.

Expressed in 2005 US dollars the overall range translates to around \$60-\$900 per tonne of carbon, or equivalently around \$15-250 per tonne of CO_2. The lower end of this latter range is similar to recent carbon prices in the EU Emissions Trading Scheme but somewhat below levels of carbon taxes in Norway. The upper end of the range is way above any current levels of carbon taxes/prices, although it should be stressed that the models generally assume that there is a gradual rise towards these kinds of carbon tax/price levels by 2050, rather than a sudden transition.

In summary, carbon taxes are attractive in theory, but face a number of significant practical and political problems that can either block their introduction or lead (as in the Norwegian case) to exemptions or reduced rates that mute the effects of the tax on emissions. Partly reflecting these issues, recent initiatives have tended to focus rather more on emissions trading schemes, which provide an alternative way of putting a price on carbon.

(ii) Carbon emissions trading

In contrast to carbon taxes, which seek to price emissions directly, emissions trading seeks to set the total quantity of emissions and let market supply and demand set the price. If these tradable emissions allowances do not cover total current emissions, then those with relatively low emission mitigation costs can sell them to those with higher emission mitigation costs, so encouraging emission reductions in the most cost-effective way while also establishing a market price for carbon that can act as a signal to potential future investors in low/zero carbon technologies[43].

This kind of approach is well-established in the US in relation to SO_2 trading aimed at achieving a 50% emissions reduction by 2010 and so combating acid rain and associated environmental problems, but relatively new for CO_2. The UK established a relatively small CO_2 Emissions Trading System (ETS) in 2002, but by far the largest and most significant development in the carbon trading area was the launch in January 2005 of the EU ETS, which covers almost half of all EU25 carbon emissions (it applies only to the power generation and heavy industry sectors). We therefore focus in the remainder of this sub-section on the recent experience of this system and the lessons for the future both for the EU ETS and other future schemes of this kind.

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[43] Nordhaus (2005) argues that tradable allowance schemes like the EU ETS are likely to be less economically efficient than carbon taxes and, unless allowances are auctioned, will not enable the potential ‘double dividend’ to be achieved whereby proceeds are used to reduce taxes on labour. He also argues that giving governments the monopoly power to allocate free emissions allowances could also lead, particularly if schemes are extended to developing countries, to undesirable rent-seeking behaviour by government officials. However, the alternative that Nordhaus recommends, a globally harmonised carbon tax, seems unlikely to be politically viable in the foreseeable future, even if it is theoretically attractive.

In 2005, the EU ETS market is estimated to have had a trading volume of around 322 million tonnes of CO2 with a total traded value of around €6.6 billion ($8.2 billion). After starting at just under €10/tCO2, carbon prices rose to a peak of around €30/tCO2 in mid-2005 before oscillating in a range of around €20-30/tCO2. In Spring 2006, however, verification data were released showing that, in total, allocated free allowances exceeded actual emissions by a considerable margin except in power generation. With supply revealed to exceed demand, carbon prices fell very sharply to only around €10-15/tCO2. The conclusion that (with the benefit of retrospective wisdom) many commentators have drawn is the market and verification has worked well, but that initial allocations may have been set at too high a level.

Looking ahead to the next phase of the EU ETS, which covers the critical 2008-12 period for achieving the Kyoto targets, an obvious lesson is that the amount of free allowances needs to be set some way below likely emissions levels[44], though this could be supplemented by auctioning some additional allowances (with revenues recycled into measures to support carbon emission reductions). The Carbon Trust (2006) has also suggested that allowance allocations might be based to some degree on benchmarks based on best practice technology. For existing power generation, these would need to be differentiated by plant type (e.g. more for coal than for gas plants) to avoid destroying the value of existing assets, but for new plant they could be set on a per unit of capacity basis to encourage more development of lower carbon options (including CCS).

Other desirable longer term changes might be to expand the scope of the EU ETS to cover other sectors (particularly transport) and other greenhouse gases, and to link it to other carbon trading schemes that have arisen or are being developed in other regions of the world. Hybrid carbon tax/trading schemes of the kind advocated by McKibbon and Wilcoxen (1997) might also be considered in the longer term.

(iii) Policy implications of induced technological change

As mentioned above, the introduction of induced (or endogenous) technological change has been one of the most important recent developments in economic modelling and related climate change analysis. This is related to the wider endogenous growth literature and refers to the effects of learning-by-doing and/or investment in R&D/knowledge in allowing climate policy measures to influence the direction and pace of technological development in the model, rather than this just being a fixed (exogenous) input assumption, as indeed is the case in our relatively simple model as regards the energy sector.

Grubb, Kohler and Anderson (2002) provide a survey of the evidence on this and identify a number of policy implications relative to traditional models where technological change is exogenous, as summarised in Table 4.2 below.

[44] Initial indications, however, are that some EU governments may be reluctant to do this, notably in the case of Germany (though the UK government has proposed some reductions).

Table 4.2: Policy implications of induced technological change

Implications	Exogenous technical change	Induced technological change
Economic cost of CO2 atmospheric stabilisation	Potentially significant	Low or even zero/negative in long run
Preferred policy instruments	Uniform Pigouvian tax plus government R&D	Wide mix of policies, including focus on spurring private innovation
Timing of policy action	Defer abatement until costs of low carbon technologies have fallen	Accelerate abatement so as to induce cost reductions in low carbon technologies
'First mover' economics	Up front costs with little benefits – gains go to lower cost imitators	Potentially large benefits due to learning-by-doing effects could outweigh up front costs
Spillover effects from richer to poorer countries	Generally negative (rich export carbon emissions to poor via trading etc)	Positive spillovers through technology diffusion could outweigh negative effects

Source: Based on Table E1 in Grubb, Kohler and Anderson (2002)

Cost estimates are discussed in the next section, but a general conclusion from these new model results is that there is a strong case for early action based on a diverse mix of policies. These might include carbon taxes and/or carbon trading, but would also include a range of other policies to stimulate innovation in low carbon technologies. Government-led R&D would have a role here in relation to basic science research, but there is a more general need for policies to support seedcorn investment in a broad range of new technologies. This may be particularly important in the transport sector, where (with the partial exception of biofuels) there is not yet a proven low carbon technology to replace gasoline and diesel, in contrast to the power sector where there are already a range of such technologies, even if they are not yet fully economically viable.

The role of governments here will be to facilitate this process through an appropriate fiscal and regulatory structure, possibly including time-limited subsidies for new 'infant industries', but ultimately this needs to be a private sector-led process. In this respect it may be helpful that, with learning-by-doing effects, there may be greater commercial gains to first movers who can achieve cumulative cost reductions that later entrants may not be able to readily replicate.

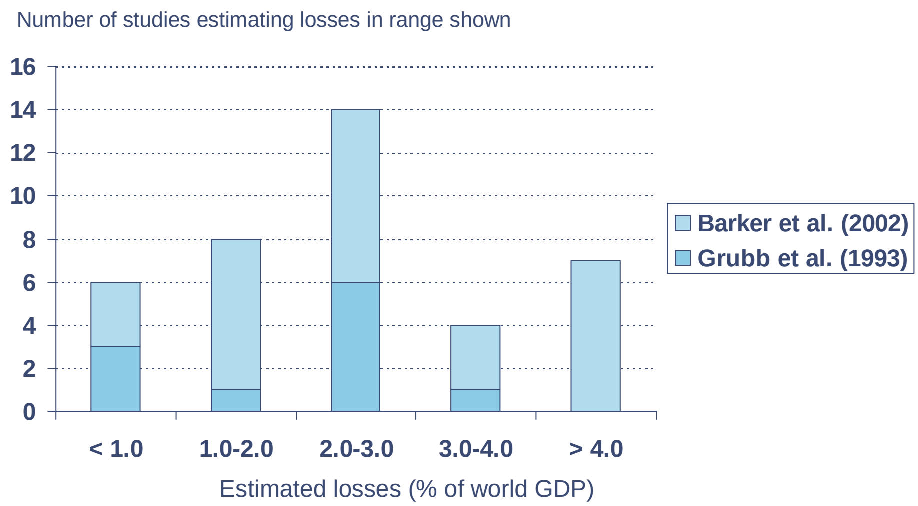
Another important feature of induced technological change highlighted in Table 4.2 relates to spillover effects. Traditional models with exogenous technological change tend to find that, if industrialised economies are encouraged to cut their emissions through a carbon tax or a 'cap and trade' system, this is likely to lead to a migration of polluting sectors to developing economies where these costs/constraints do not apply. As argued by Grubb (2000) and Grubb et al. (2002), however, this ignores the positive spillovers that are likely to occur once technological diffusion from richer to poorer countries is incorporated in models. One reason for this is that, as climate change moves up the agenda, companies in industrialised economies will be under increasing pressure from their customers and possibly also their governments to implement climate-friendly policies throughout the world not just in their home countries.

Another reason is that emerging economies like China and India are increasingly conscious of their own environmental problems and so will want to develop low carbon technologies of their own, as well as imposing higher environmental standards on inward investors. Grubb et al. (2002) note, for example, that India is now the second largest market in the world for renewable energy after the EU and it is likely that China will also become increasingly significant in this market over time. This will create many opportunities for Western companies that have developed these low carbon technologies initially for their home countries (e.g. wind power in Denmark) but now have the chance to export them globally.

4.3 Estimated economic costs of atmospheric CO2 stabilisation

Anderson and Leach (2005) provide a recent survey of the many studies that have been carried out on the costs of mitigating climate change. They argue that the net costs of a phased transition to a low carbon economy are likely to be relatively small, with most estimates in the range of -1% to 4.5% of world GDP for the next 50 years, with a mean value of around 2.5% of GDP, equivalent to around one year of trend growth. This is illustrated by the findings of two earlier literature reviews by Barker et al. (2002) and Grubb et al. (1993) as summarised in Figure 4.1 below.

Figure 4.1: Estimated % global GDP losses for a 50-70% long-term reduction in global CO2 emissions



Source: Anderson and Leach (2005)

Anderson and Leach explain these findings with reference to the fact that the energy sector accounts for around 4% of global GDP, so even if energy costs double as the result of moving to lower carbon technologies, this would only reduce world GDP by around 4%. In practice, this may be further mitigated by a gradual transition process that allows the learning-by-doing effects of induced technological change to take effect.

The generally positive implications of induced technological change were confirmed by the most recent modelling results summarised in Grubb et al. (2006) and Edenhofer et al. (2006)[45], which mostly showed that with induced technical change it was generally significantly less costly to achieve atmospheric stabilisation of CO2 levels. For a 450ppm stabilisation target, eight of the ten models reviewed showed costs by 2050 of 1% of world GDP or less, with two actually showing negative costs. There were two models with significantly higher costs, one with costs of around 3% of GDP and one with costs of around 10% of GDP, but this latter model in particular does not allow for the dynamic substitution of low carbon for carbon-intensive technologies, with the costs of the low carbon options falling over time due to learning-by-doing effects as in the other models.

The preliminary conclusion seems to be that, with induced technological change and the possibility of substituting low carbon for high carbon technologies, the costs of achieving a 450ppm stabilisation target need not be prohibitive. Indeed two of the models allow for such strong learning-by-doing effects that the costs of CO2 stabilisation actually become negative, because they assume that there is more scope for costs to be reduced further in these new technologies than the existing carbon-intensive technologies, although this is open to debate[46].

4.4 Summary and conclusions

The analysis above suggests that there are reasons for cautious optimism about the prospects for achieving the kind of carbon emissions reductions envisaged in the Green Growth + CCS scenario without prohibitive economic costs. The main reasons for this are:

- the extent to which, as shown by Pacala and Socolow, technologies already exist to allow significant reductions in carbon emissions, although most of these still need to be developed further to be economically viable;
- the particular scope for expanding carbon capture and storage systems, as set out in the 2005 IPCC report on this topic;
- the progress made in establishing an international carbon price through the EU Emissions Trading Scheme, although reductions in the number of free allowances given out (supplemented by auctions of additional allowances) are needed if this is to provide real incentives for carbon emission reductions;
- the large number of studies showing that the costs of reducing global carbon emissions by around 50-70% should be no more than around 4-5% of world GDP, with average estimates of around 2-3% of world GDP, equivalent to only around one year of trend growth; and
- the potential learning-by-doing effects that, as demonstrated by recently developed models with induced technological change, could further reduce these costs estimates, perhaps to around 1% of world GDP or less by 2050.

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[45] These two papers summarised the findings of a series of other papers by leading economic modellers in a Special Issue of *The Energy Journal* on ‘Endogenous Technological Change and the Economics of Atmospheric Stabilisation’, Spring 2006.

[46] One of the models showing negative long run costs (the E3ME model) also relies on Keynesian demand multiplier effects from increased investment in new low carbon technologies in a world economy where spare capacity is assumed to exist to absorb this additional investment demand.

At the same time, the analysis suggests that there is no room for complacency given that:

- a large proportion of the energy efficiency improvements indicated in the Pacala and Socolow analysis are likely to be necessary just to achieve the outcome assumed in our baseline scenario in which carbon emissions nonetheless more than double by 2050; further improvements over and above this baseline may prove more challenging and costly to achieve;
- this puts more emphasis on the need to switch to lower or zero carbon alternatives, but these face a range of political and/or economic obstacles that will be challenging for both governments and energy sector companies to overcome; the opposition of many in the environmental movement to nuclear power is a case in point, as is local opposition both to large hydroelectric projects and to onshore wind farms;
- despite their theoretical attractions, carbon taxes have faced both political and practical difficulties that have often either blocked their introduction entirely or led to exemptions that significantly blunt their impact on carbon emissions (as illustrated by the Norwegian case study described above);
- while the EU ETS has been a success in terms of establishing a market, it remains to be seen how far governments will be prepared to reduce future allocations of free allowances given likely opposition from business interests and concerns about international competitiveness effects;
- given the long lead times and even longer asset lives for major infrastructure investments in the energy, transport and construction sector, there is no time to be lost in setting in place low carbon strategies in these areas if major emission reductions are to be locked in for the longer term; and
- while learning-by-doing effects are powerful in theory, they do not lend themselves to easy policy solutions, suggesting instead that a broad range of pro-innovation policies will be needed, but with the effectiveness of these being hard to assess with any precision in advance.

In summary, our baseline ‘business as usual’ scenario implies sharply rising levels of carbon emissions and significant associated risks of adverse climate change and severe negative socio-economic effects in the long run. At the same time, there appear to be relatively low cost options for controlling carbon emissions to the atmosphere which, based on the precautionary principle, it might seem desirable to implement (and which appear to be significantly ‘cheaper’ in economic terms than simply constraining GDP growth). The richer OECD economies may need to take the lead in developing new technologies and reducing their emissions over the next couple of decades, given that it may not be realistic to expect much faster-growing emerging economies like China and India actually to cut their emission levels, as opposed to controlling their rate of increase, until later in their process of economic development.

Annex: Technical description of long-term economic growth model

In line with mainstream economic growth theory since the late 1950s[47], we assume that output can be modelled using a Cobb-Douglas production function with constant returns to scale and constant factor shares. Specifically output (i.e. GDP, which we denote below as Y) is given by the following equation:

$$Y = AK^{a}L^{1-a}$$

Where:

A = total factor productivity, which is determined by technological progress in the leading country (here assumed to be the US) plus a country-specific catch-up factor related to the initial productivity gap versus the US

a = the share of capital in total national income and so (1-a) is the share of labour, both of which are assumed constant over time in this model

K = the physical capital stock, which grows according to the standard formula:

$$K_t = K_{t-1}(1-d) + I_t$$

where: d = the depreciation rate; I_t = gross investment in year t

L = the quality-adjusted input of labour, which can be broken down into:

$$L = h(s)eN$$

where: h(s) is a quality adjustment related to the average years of school education of the working age population; e is the employment rate defined as a share of the working age population; and N is the number of people of working age.

Key assumptions

The key parameter assumptions we make in the baseline scenario are that:

- The parameters a and d are set at 1/3 and 5% respectively, in line with the values used in many past academic studies.
- The catch-up rate of A is assumed to converge to 1.5% per annum for all of the E7 economies in the long run, in line with the typical 1-2% estimate found in past academic studies. In the shorter term, however, catch-up speeds are lower at around 0.5-1% per annum for emerging economies that we judge to have some way to go before they achieve political, economic and institutional frameworks that are fully supportive of growth convergence. In particular, we assume a catch-up speed of only 0.5% per annum up to 2020 for India, Brazil

[47] This general approach was introduced by Solow (1956, 1957). More recent research is summarised in Barro (1997). A similar modelling approach was taken by Wilson and Purushothaman (2003) in Goldman Sachs' well known BRICs paper.

and Indonesia and 1% per annum for Mexico and Turkey. China and Russia are assumed to have catch-up speeds of 1.5% per annum from the start.

- Initial capital stock estimates (K) for the mid-1980s are taken from Levine and King (1994), updated to 2004 using data on investment to GDP ratios from the Penn World Tables (v. 6.1) and the IMF. These investment (I/Y) ratios are then projected forward assuming recent trends continue up to 2010, followed by a slow convergence to around 20% from 2025 onwards, with the exception of China (25%) and Indonesia (22%).
- Initial estimates of average education levels (s) are taken from Barro and Lee (2001) and projected forward based on a continuation of trends over the past 5-20 years (using judgement as to what to take as the appropriate reference period in each case). The calculation of the labour-quality-adjustment function h(s) follows the same approach as Hall and Jones (1998).
- The working age population projections (N) are the central case from the 2004-based United Nations (UN) projections for 15-59 year olds. Employment rates (e) are assumed to be constant over time.

Alternative assumptions on US labour productivity growth (0.25% lower) and E7 catch-up rates (0.5% lower up to 2020, increasing to 1% lower from 2030 onwards) are made in the Constrained Growth scenario as described in Section 1 above.

Exchange rate projections

Purchasing power parity (PPP) exchange rates[48] are assumed to remain constant over time in real terms, while market exchange rates converge gradually over time to these levels in the very long term. Since we focus in this paper only on results for GDP at PPP rates as the key driver of energy demand, however, the details of how this market exchange rate convergence process is modelled does not need to concern us here.

[48] Initial estimates of GDP at PPPs in 2004 were taken from the World Bank (2005), updated in some cases for more recent estimates (notably in the case of China, where historic GDP estimates were revised up significantly in December 2005).

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