80% Challenge

Delivering a low-carbon UK

Contents

Keeping human-induced average temperature rises to less than 2°C above pre-industrial levels – the UK and EU goal – will require the UK to reduce its carbon dioxide emissions by at least 80% by 2050. Taking into account the latest climate science, the current UK target of a 60% reduction is inadequate if Britain is to play its part in avoiding dangerous climate change.

Summary

In this work, the Institute of Public Policy Research (ippr), WWF and the Royal Society for the Protection of Birds (RSPB) set out to investigate whether a target of 80% can be achieved in the UK by domestic efforts alone and what the costs of doing so would be. We employed two approaches – the MARKAL-MACRO model, used by the government for the 2007 Energy White Paper, and a model developed by Professor Dennis Anderson at Imperial College, employed for the Stern Review on the economics of climate change.

We followed the same assumptions and approaches used by government, but added some constraints that we consider environmentally essential. Unlike the government, we included emissions from international aviation, with a multiplier to allow for non-carbon dioxide effects, in our targets and models. This clearly made our approach much more challenging – however, we believe it is indefensible to exclude this large and rapidly growing source of emissions from UK targets. We examined the implications of excluding new nuclear electricity generation and placed limits both on the use of biofuels and wind.

The key conclusion is that it is feasible to reduce the UK's emissions by 80% by 2050, and at costs that are not prohibitive. Both models identified pathways towards an 80% reduction that involved rapid decarbonisation of the electricity sector, achieved by major investments in wind power and other renewables, and a significant role for carbon capture and storage. Emissions from the production of heat would be reduced through a major programme of energy efficiency and potentially a move to the use of low-carbon electricity for heating. Surface transport emissions would be dealt with by major improvements in vehicle efficiency and, for cars, a move towards use of advanced biofuels derived from sustainable sources.

We must stress that the results presented here do not necessarily represent our preferred pathway to decarbonisation. This report represents only a few of many possible scenarios – including those that could include more rapid uptake of marine renewables, far higher levels of distributed energy and energy efficiency, and the achievement of energy security goals. Indeed, cost-minimisation models of the kind used here inevitably exclude some solutions that might be preferable on environmental or social grounds.

Despite these caveats, it is clear from the modelling results that it would be feasible to adopt and achieve a UK emissions reduction target of at least 80% by 2050 from 1990 levels, and to do so without new nuclear power. There are also some clear general recommendations for policies to help achieve this goal:

- A much more aggressive focus on energy efficiency should be pursued across all sectors of the economy.
- An ambitious implementation programme for renewable energy must be pursued. The government should focus on delivering, rather than weakening, the EU target for renewable energy to meet 20% of primary energy by 2020.[1]
- Government should review current policy planning tools and the current framework for energy regulation to ensure that the benefits of decentralised power generation are recognised and achieved.
- Carbon capture and storage (CCS) could play an important role. There is an urgent need to demonstrate the viability of this technology in large-scale electricity generation, and to develop a clear framework for regulation and treatment of liabilities. Certainly we cannot afford to build and run new unabated coal-fired power stations without some form of guarantee that CCS works effectively.
- Urgent action is needed to constrain significantly the forecast growth in aviation. Without such action, it will be difficult or impossible for the UK to achieve reductions in emissions consistent with avoiding a dangerous level of climate change.
- The government should apply its own sustainable development principles to the selection of climate mitigation measures in the future. This will ensure that these measures deliver best value in economic, social and environmental terms. Such an approach would, for example, ensure that biofuels were only deployed at volumes that did not pose a significant risk to the environment or food production.

The estimated cost of meeting the 80% target, including our share of international aviation emissions, ranges between approximately 2% and 3% of GDP in 2050; though energy efficiency could markedly reduce these costs, to approximately 1.5% to 2 % of GDP.

These estimates represent an upper limit on costs; and while the sums involved are large, the impact on growth of the whole economy over time is relatively minor. The economy would almost triple in size by 2050, even with an 80% cut in emissions. GDP would reach the same level as it does in 2050 under business-as-usual one and a half years later, in the spring of 2052. Costs would be significantly lower if barriers to energy efficiency are addressed successfully. The costs of achieving the 80% target are also dwarfed by the costs of unmitigated climate change. Decarbonising the UK economy by 80% would cost between one half and one tenth as much as doing nothing, based on Stern's estimate that climate change damage costs would reduce global GDP by between 5% and 20%.

A more comprehensive presentation of this study can be found in ippr's companion report *2050 Vision*.

Introduction

Can the UK reduce its carbon emissions by 80% from 1990 levels by 2050, and if so at what cost? There is a substantial amount of analysis suggesting that the impacts of human-induced climate change will become increasingly dangerous if the average global surface temperature exceeds 2°C above pre-industrial levels. While 2°C is not in itself a safe limit, and will result in significant harm to both people and wildlife, it has been widely accepted as a critical threshold, and adopted as the overall aim of the EU.

For the UK to make a fair contribution to a global emission reduction effort consistent with staying within a 2°C limit, emissions would have to be reduced by at least 80% by 2050 from 1990 levels, and possibly by 95% or more.[2]

While the scientific imperative is clear, there are major concerns that achieving such deep emissions cuts could be difficult (or even impossible), costly and damaging to the economy. The UK government's position is that a 60% reduction in carbon dioxide emissions by 2050 should be adopted in the Climate Change Bill currently before Parliament – although the Prime Minister recently stated his intention to ask the new Climate Change Committee to review the adequacy of this target.

WWF, the Institute for Public Policy Research (ippr) and the Royal Society for the Protection of Birds (RSPB) have commissioned modelling work to explore the feasibility and costs of an 80% carbon emissions reduction for the UK economy. This approach explores the case in which this reduction is achieved entirely through domestic action, with no contribution from credits purchased from abroad. It effectively establishes an upper bound on technological feasibility and costs.

Our target is considerably more ambitious than that proposed by the government – not least because we have included the UK's share of emissions from international aviation. Because these emissions are growing so rapidly, carbon emissions from land-based sources will need to fall by perhaps 90-95%.

We employed two authoritative approaches: the MARKAL-MACRO model, used by the government for the 2007 Energy White Paper; and a model developed by Professor Dennis Anderson of Imperial College for the Stern Review.

With few exceptions, we employed the same underlying assumptions as the government and the Stern Review, such as economic growth rates. However, our study differs from the official approach to UK modelling in three ways: we included emissions from international aviation, we looked at electricity generation without new nuclear power, and we imposed constraints on the extent to which both biofuels and wind generation could be used.

The modelling results show that it is technologically feasible for the UK to attain a target of 80% emissions reductions by 2050, without major reductions in mobility and while meeting national demand for energy services. They also show that the costs of doing so, while greater than those required for reaching a 60% reduction, are still of the same order of magnitude, and significantly lower than the costs of doing nothing.

Unlike the Government, we have included the UK's share of emissions from international aviation in our targets and models.

The relationship between temperature rise and emissions

The objective of reducing the UK's carbon dioxide emissions by 60% by 2050 from 1990 levels was proposed by the Royal Commission on Environmental Pollution in 2000, and was based on an assessment of what the UK needed to do to make a fair contribution to staying below 2°C warming. The government adopted the 60% goal in the 2003 Energy White Paper.

Since then, however, developments in climate modelling have allowed more precise estimates of the relationship between different atmospheric concentrations of greenhouse gases (and hence global emission reduction pathways) and temperature increases.

A recent review of these studies showed that to stand a reasonable chance (better than 50:50) of staying below two degrees, it will be necessary for concentrations of global greenhouse gas emissions to stabilise at below 450 parts per million carbon dioxide equivalent (ppm CO_2e) and probably nearer 400ppm (Meinhausen 2006[6]).

However, given that the atmospheric concentration of greenhouse gases is already near 430ppm CO_2e, greenhouse gas concentrations will have to first peak and then decline (e.g. Meinhausen 2006[7], Baer with Mastrandrea 2006[8], European Commission 2007[9], Höhne et al 2007[10]). Because the climate system takes a long time to adjust to rises in greenhouse gas emissions, as long as the peak in emissions is brief enough, temperature increase should not exceed 2°C.

These studies imply that global greenhouse gas emissions will have to fall by at least 50% from 1990 levels by 2050 if we are to have a better than 50% chance of staying below 2°C. To reduce the chance of exceeding 2°C to less than 25%, more radical cuts in global emissions would be required, of the order of 70-80% (Baer with Mastrandrea 2006[11]).

To work out the implications at the national level, it is necessary to determine what the UK's 'fair share' of global reductions should be. There are various way of doing this, including different versions of contraction and convergence, the 'triptych' system that takes national factors into account, used by the EU for its burden sharing agreement, and other formulations.

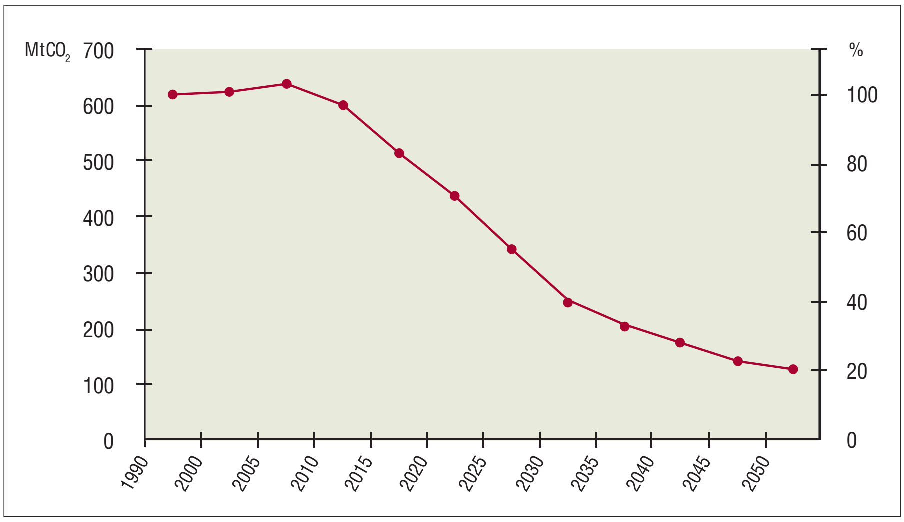


Figure 1. CO_2 emissions reductions targets for the UK

A recent review by Höhne et al (2007) for the UK government, based on a goal of stabilisation at 450ppm CO_2e, suggests that the UK should be aiming to reduce greenhouse gas emissions by 35-45% by 2020 and by 80-95% by 2050, from 1990 levels. This is in the same range as Baer and Mastrandrea (2006), who estimate that to be consistent with a low-to-medium risk (i.e. <25%) of exceeding 2°C, and under a contraction and convergence burden sharing model, the UK would have to reduce carbon dioxide emissions by between 88% and 94% from 1990 levels by 2050. It is worth noting that the review by Höhne et al (2007) concluded that even to stabilise at 550ppm CO_2e – corresponding to a likely warming in excess of 3°C – the UK's emissions would need to fall by 70-90% by 2050.

An 80% emissions reduction by 2050 from 1990 levels is therefore probably the least that the UK needs to achieve in order to make a fair contribution to a global effort to avoid dangerous climate change. In this study we have adopted this limit, with interim targets of 30% reduction by 2020 and 60% by 2030 (see Figure 1), but it should be noted that to have a lower risk of exceeding 2°C, further reductions would be needed.

In principle, some of the UK's emissions reductions could by achieved through international emissions trading and the purchase of emission reduction credits from other countries. However, it is unwise at this stage to place too much reliance on this mechanism or assume ready access to large volumes of relatively cheap credits. Although it is hoped that a robust global trading system will emerge, at present there are real concerns over the credibility of the emerging carbon markets and the Clean Development Mechanism in particular. For these reasons, in this study we assumed that emission reductions of 80% by 2050 would be achieved entirely through domestic action. This tests the upper bounds of both feasibility and cost.

This emissions trajectory can also be expressed in terms of five-year carbon budgets, in line with the Climate Change Bill proposals, from 2008 to 2028:

Budget period	Five year budget ($GtCO_2$)
2008-12	2.99
2013-17	2.58
2018-22	2.17
2023-27	1.71

The 2°C imperative

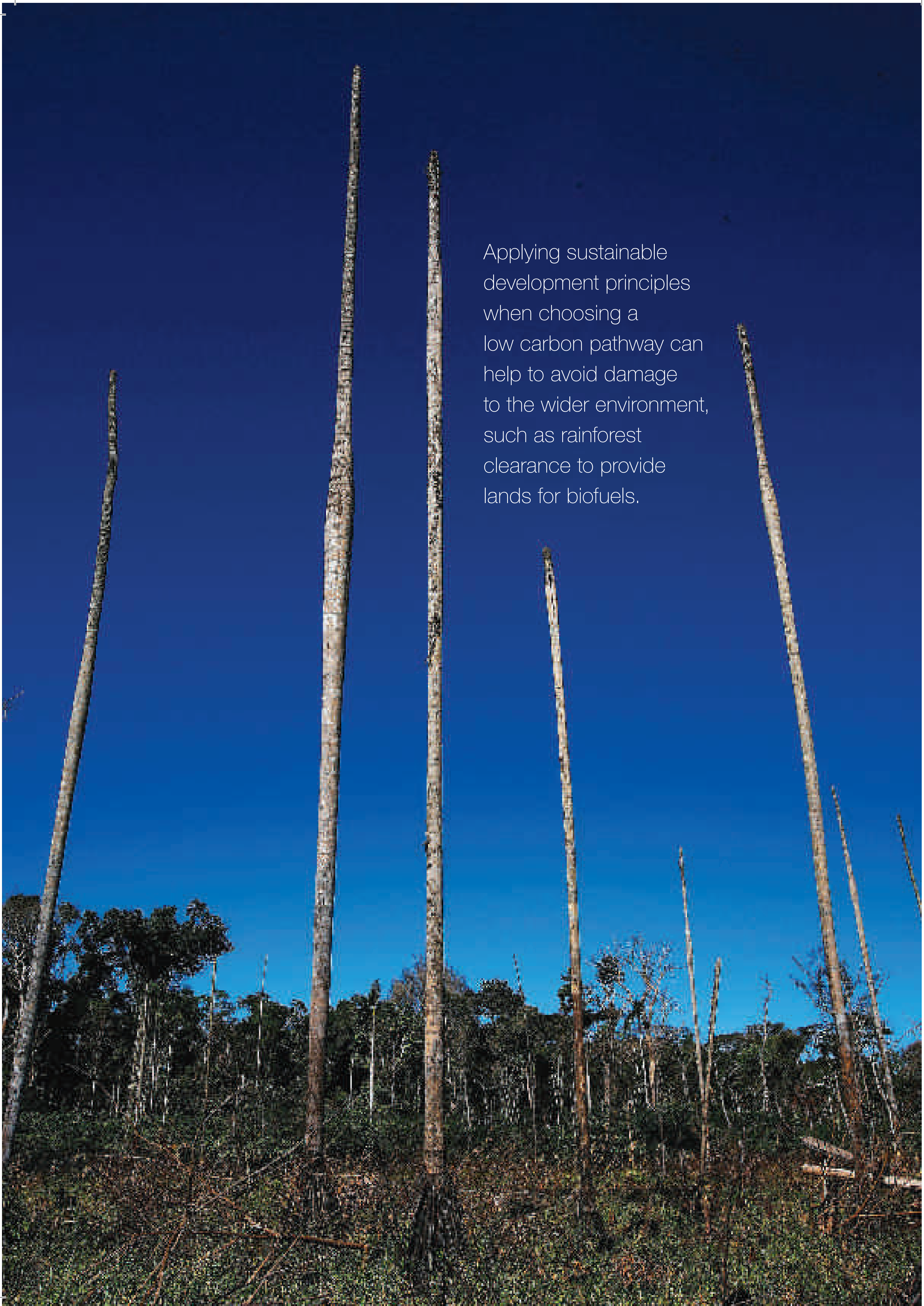
Since the industrial revolution, the world has warmed by some 0.75°C – and we are already seeing significant impacts on the world's poorest people and on biodiversity. This year's reports by the Intergovernmental Panel on Climate Change make clear that this warming is "very likely" to be a result of human activities. The IPCC concluded that without strong efforts to reduce global emissions, this century will see a probable further rise in temperature of 1.8-4°C – with a possible increase of as much as 6.4°C.[3]

In 1996, the EU adopted an objective to stabilise global temperatures at 2°C above the pre-industrial average. It has repeatedly reaffirmed this goal, most recently in the context of this year's G8 summit in Germany. Prime Minister Gordon Brown has also stated his support for the 2°C objective.

Even if warming is restricted to 2°C, the world is committed to very significant impacts to both human society and biodiversity. The IPCC concluded that at warming of just over 2°C above pre-industrial levels, some 20-30% of species face a high risk of extinction. If the rise in temperature ranges between 2-3°C, an additional 1-2 billion people will face increased water scarcity and many millions face increased risk of hunger and displacement by sea level rise and extreme weather events. We are already facing the prospect of an Arctic that is free of summer sea ice by mid-century.

Moreover, above 2°C warming we face severe risks of crossing irreversible 'tipping points' and triggering feedbacks that will further accelerate climate change.[4] These impacts include the collapse of the West Antarctic Ice Sheet and irreversible melting of the Greenland ice-sheet, which would lead respectively to eventual sea level rises of 4-6 metres and 6-7 metres. Above 2°C, the world's soils and vegetation are expected to cease being net sinks for carbon and turn into net sources – fuelling further warming. Warming above 2°C is likely to wipe out most of the world's coral reefs and could trigger drying out and die-back of the Amazon rainforest.

Some leading scientists believe that even warming of 2°C is too much. James Hansen, Director of the NASA Goddard Institute for Space Studies, argues that global warming of more than 1°C this century "will constitute 'dangerous' climate change as judged from likely effects on sea level and extermination of species".[5]



Applying sustainable development principles when choosing a low carbon pathway can help to avoid damage to the wider environment, such as rainforest clearance to provide lands for biofuels.

Environmental safeguards and modelling assumptions

THE MODELLING APPROACH

This report is based on two energy-economy modelling approaches: the MARKAL-MACRO model, used by the government for the 2007 Energy White Paper; and a model developed by Professor Dennis Anderson of Imperial College for the Stern Review.

Before describing the modelling approaches and results, it is important to spell out the nature of the exercise. The approaches used here are *not* forecasting models. They are not used to try to predict the future energy system of the UK in 50 years' time. Instead they offer ways of exploring the trade-offs between different energy systems pathways, as well as the cost, energy supply and emissions implications of these different pathways.

Both the approaches here are bottom-up models that base scenarios and cost estimates on data about individual technologies. They are transparent and open on assumptions about costs.

However, these models also have their limitations. For example, they represent the electricity system in an aggregated way. Decentralised energy may well have a greater role to play than the models suggest, but further more detailed work is needed to quantify this. Nor are energy security issues factored into the operation of the models.

More broadly, in both models it is assumed in a straightforward way that investment will flow into those technologies with the lowest cost. Investment decisions in the real world are more complex, where expected revenues and potential risks play a major role (Gross et al 2007[12]). These models should not be taken literally as a strict prediction, but rather as an indication of long-term potential patterns based on our current knowledge of technologies and costs.

Because of these limitations, and because the models seek least-cost rather than best-value options, there would be serious risks in relying on them too heavily to guide choices in climate and energy policy. A more rounded way of assessing available mitigation options might be to apply the government's sustainable development principles to any package of mitigation policies[13] under consideration. This would help to ensure that climate mitigation solutions maximise benefits for other policy objectives and minimise undesirable trade-offs.

In the MARKAL-MACRO modelling, we used, with a few exceptions, the same assumptions about technologies and costs as those made by the government. Likewise, with the Anderson model, we followed the same approach as the Stern Review, although technology cost estimates are different because they relate to the UK, rather than average global costs.

However, for both studies, some additional common changes to approach and assumptions were made: including international aviation; imposing some constraints on biofuels and wind for environmental reasons; and excluding nuclear new build.

INCLUDING INTERNATIONAL AVIATION EMISSIONS

The first difference from the government's approach was to include emissions from international aviation. Emissions from aviation already make a significant contribution to the UK's carbon dioxide emissions: their share was 6.3% in 2005, of which 0.4% was from domestic and 5.9% from international flights.[14] They are rising much more rapidly than other sources of emissions and are forecast to continue to grow considerably if unconstrained. According to the Department for Transport (DfT), under current policies by 2030 the sector's emissions are set to reach nearly four times their 1990 level.

Aviation also has a greater net impact on climate change than is implied by its carbon dioxide emissions alone, due to the behaviour of other exhaust gases at altitude and the warming effect of aircraft-induced contrails and cirrus clouds. The Intergovernmental Panel on Climate Change (IPCC) has estimated that aviation's total impact on the climate is between two and four times that of its carbon dioxide emissions alone. Although some uncertainty remains as to the exact quantification of these effects, the precautionary principle states that this should not be used as a justification for ignoring them. Accordingly, in this report we have followed the practice of the Treasury in applying a multiplier of 2.5 to aviation's carbon emissions.[15]

The government includes only domestic aviation in its emission reduction targets and the modelling work for the Energy White Paper, because emissions from international aviation are not covered by the Kyoto Protocol. Nonetheless, it recognises that they should be included and is committed to resolving the political issues that led to their exclusion from Kyoto. Since our study is driven not by politics but by the scientific imperative to limit greenhouse gas emissions, we considered that it was essential to include international aviation emissions in our work.

However, we also constrained emissions from aviation so that they should not exceed the forecast level in 2010, to reflect the likely inclusion of aviation in the EU emission trading scheme from that date. This approach to capping the sector's emissions does not constrain aviation growth per se – rather it implies that any increase in passenger kilometres flown must be matched by corresponding efficiency improvements through better technology or flight management. This is clearly ambitious, given current growth rates – but from a broader perspective aviation could be seen to be receiving favourable treatment as all other sectors of the economy will need to make very steep cuts in emissions.

We believe that it is justifiable to treat aviation as a unique case, because of its extremely rapid growth and because of the lack of readily available technological solutions. Including international aviation emissions with a multiplier in our modelling was particularly challenging. With an 80% reduction by 2050, the models suggest that a large proportion of all remaining UK emissions would be from aviation. Even with our constraints on future growth in aviation emissions, the rest of the UK economy is required to reduce its carbon emissions from a 1990 baseline by more than 40% by 2020 and by some 95% by 2050.

The ptarmigan could find its climate space disappear from the UK as conditions on mountaintops become less suitable in a changing climate.

ENVIRONMENTAL SAFEGUARDS

Environmental organisations recognise the need to tackle climate change as an overriding imperative and are fully signed up to the need to achieve 80% emissions reductions cuts. However, there are concerns that certain choices for mitigating climate change may be damaging in their broader sustainability impacts, particularly to wildlife. Such examples include badly sited wind farms that have damaged important bird of prey populations in Spain and Norway, and biofuel supplies that have accelerated the rate of deforestation in the tropics.

Because of this, one of the issues we wished to explore in deploying these models was whether or not we can still achieve an 80% reduction target with indicative environmental safeguards. We did this by constraining the amount of biofuels and wind generation (the latter also being limited by intermittency constraints in one of the models). Though this by no means takes account of all sustainability issues across different technologies, by applying those constraints here, we could limit the potential wider impacts of two significant technologies while investigating whether achieving an 80% cut in emissions would still be technologically and economically feasible.

Sustainable biomass

There are a number of concerns about the sustainability of biomass and biofuel production, especially if the fuel is imported in large amounts without adequate accreditation to ensure it meets environmental safeguards and offers significant net CO_2 savings throughout its life cycle. We therefore capped the UK's use of bioenergy at a level that we considered would not lead to significant adverse effects, such as further rainforest destruction for palm oil or soya production.

WWF International recently reviewed the evidence on biomass, and estimated that biomass with an energy content of between 110 and 250 exajoules (EJ) could sustainably be produced annually by 2050, at a global level (WWF International 2007[16]). In our study, we introduced a conservative constraint on the UK's share of that global supply of biomass based on equal per capita use, with total biomass imports limited to 1.1EJ per annum in 2050, growing linearly from zero in 2000.

Wind power

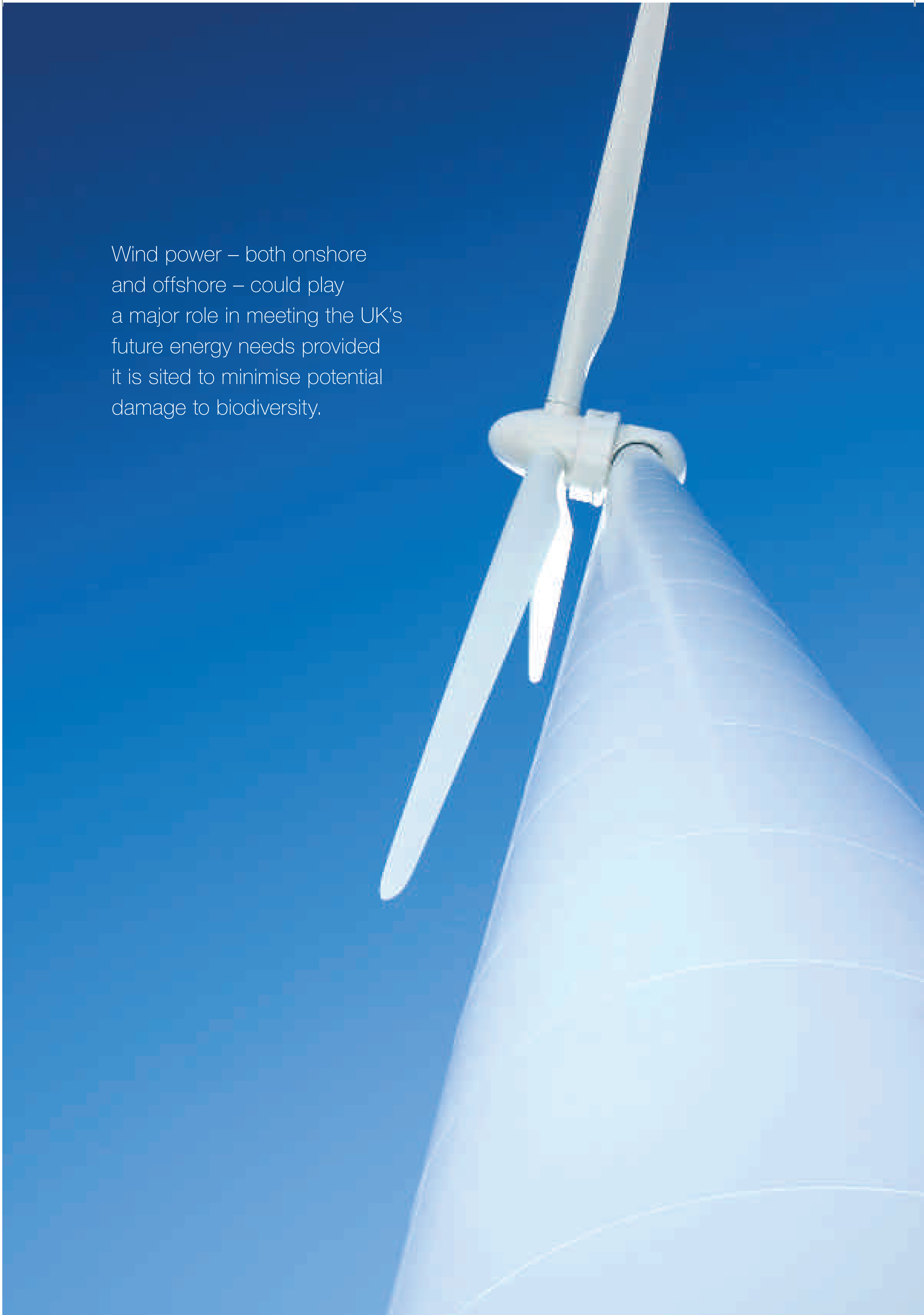
Research commissioned by the Scottish Executive has examined potential onshore wind capacity if developments avoid sensitive wildlife, landscape and military areas.[17] It concluded that even with these constraints the onshore wind capacity is more than Scotland's entire projected electricity consumption in 2020. Offshore wind has even greater potential, but it is recognised that delivering the full benefits of this form of renewable energy would require significant changes to the transmission system.

The limit on wind power to 25% of capacity on the grid employed in the MARKAL-MACRO model to reflect intermittency constraints (see below) also limits damage to wildlife but in this respect is probably conservative.[18] If the intermittency issue can be resolved in an economic way, levels of wind employed without damage to the wider environment could be significantly greater. These models do not deal with spatial data but a strategic planning approach would be the best method of ensuring the maximum deployment of wind without wider environmental damage.

EXCLUDING NUCLEAR NEW BUILD

One relatively low carbon option for electricity generation is nuclear power, and the government includes it in its forecasts. However, in the past nuclear power has proved costly and the problem of the long-term disposal of nuclear waste remains unsolved and is a large ongoing liability. Nuclear power also poses concerns about security. Other countries will look to the example of the UK, so new nuclear build here will encourage others to do likewise. But the widespread adoption of nuclear power potentially exacerbates the threat of proliferation that accompanies nuclear energy programmes (US National Security Task Force on Energy 2006)[19].

For these reasons we decided to model the feasibility of reaching an 80% target without new nuclear generation. New nuclear was excluded from the MARKAL-MACRO modelling. In both models, excluding new nuclear build does not affect the technological feasibility of attaining an 80% reduction by 2050. The Anderson model was run with and without new nuclear, allowing cost comparisons. Excluding nuclear does raise costs in the middle part of the period, but by 2050 the difference is only 0.1% of GDP.



Wind power – both onshore and offshore – could play a major role in meeting the UK's future energy needs provided it is sited to minimise potential damage to biodiversity.

The models

Both the approaches used for this study combine estimates of the costs of energy technologies with simple economic growth models. One model, known as MARKAL-MACRO, is supported by the International Energy Agency (IEA), and used by around 100 teams in over 30 countries (Strachan et al 2006). In the UK, the lead organisation running the model is the Policy Studies Institute (PSI). The Department for Trade and Industry (DTI) (now the Department for Business, Enterprise and Regulatory Reform, DBERR) commissioned MARKAL modelling work from the PSI as input into the 2007 Energy White Paper. The other model was developed at the Imperial College Centre for Energy Policy and Technology by Professor Dennis Anderson[20] for estimating the global costs of mitigating climate change for the Stern Review.

MARKAL-MACRO

MARKAL stands for MARKet ALlocation, since it mimics a market by always choosing the combination of technologies with the lowest cost. MARKAL makes estimates of future costs based on extensive literature review, peer review and stakeholder workshops. The MARKAL model can be linked to a simple economic growth model, which allows carbon prices to feed back to energy demands. The combined MARKAL-MACRO model gives estimates of future GDP, as well as the costs of carbon abatement in terms of a proportion of GDP.

The model includes assumptions about the growth in demand for energy in the baseline or business-as-usual case (i.e. without any carbon abatement). In our study, the PSI used the same set of assumptions as were used for the 2007 Energy White Paper analysis (Strachan et al 2007[22]). This includes the effects of all existing policy measures, and central DTI and DfT projections for energy use in the domestic, industrial, and surface transport sectors.

The MARKAL-MACRO model has both strengths and weaknesses. While its assumptions on data, technology pathways and constraints are transparent, not all factors can be captured fully. By optimising costs, in effect it represents a perfect energy market, and neglects barriers and other non-economic criteria that affect decisions. As a closed national economy model, it does not produce estimates of costs due to loss of international competitiveness, and as a result the cost estimates it produces may be over-optimistic. On the other hand, it also does not include any potential gains from exports of low carbon technologies.

In both the models used, much of the decarbonisation, especially initially, comes from the electricity generation sector. This implies a very large amount of investment in wind in the case of MARKAL, to levels far beyond 40% of demand. This matters because wind, like some other renewables, is an intermittent source of power. At low levels of penetration in the power system (<10%), this intermittency does not matter much. However, higher levels (>20%) of wind and some other renewables can mean higher costs, because of the need for reinforcement of the transmission and distribution system, and also balancing and/or storage costs.

The MARKAL model is not well designed to deal with such high levels of wind in the system. To overcome this problem, a requirement for energy storage was applied to intermittent renewable sources above 25% of total generating capacity.[21] In effect, this made wind and other intermittent renewables more expensive beyond this point.

THE ANDERSON MODEL

Anderson's model was originally used to estimate the global costs of reducing global greenhouse gas emissions by 25% from current levels by 2050, consistent with stabilisation at atmospheric concentrations of 500ppm CO_2. Here the model was applied to the costs to the UK of a much deeper 80% reduction in the UK's carbon emissions.

Anderson begins with estimates of the costs of different energy technologies in 2015, 2025 and 2050, in the electricity, heat and transport sectors. For many emerging technologies, such as coal with carbon capture and storage or hydrogen fuel cell vehicles, where there is uncertainty about what costs will be, the model assumes a range of possible costs with each cost within that range assigned a probability.

The model then makes assumptions about future oil prices, future economic growth, growth in the demand for energy, and likely market shares for different technologies. Again, these are not known for certain, so they are also expressed as ranges of possible values, with average values based on historical experience.

In Anderson's original base case, projected future aviation growth reflects historical experience. For this study, a version of the model with zero elasticity of demand for aviation fuel from 2010 onwards was used, to introduce the constraint on aviation emissions discussed above.

From these variables, the average cost of abating a tonne of carbon at the different dates is calculated. Multiplied by the emissions reduction requirements given in our emission abatement curve (Figure 1), this gives the total cost of abatement.

Since these cost estimates are drawn from the underlying assumptions about future technology costs, energy demand, oil prices etc., they are themselves expressed as ranges, with an average and a probability distribution. Only the averages are reported here.

Results

SECTORS AND TECHNOLOGIES
Both models show that deep reductions in emissions from the UK of 80% by 2050 from 1990 levels are technologically possible. However, they also point to the scale of the challenge of developing policies to bring forward rapid investments in energy efficiency, low carbon electricity and transport.

The models show a considerable degree of consistency in estimating the extent to which different sectors will decarbonise and which technologies will develop, given that they use different approaches. Anderson's model gives a wider range of technologies than MARKAL-MACRO, as would be expected from two models based on reasonable probabilities and least costs respectively.

Both models foresee abatement of emissions in the electricity sector as playing a central role, with emissions declining to almost zero, in spite of a large increase in the use of electricity after2030 (Figures 2.1 and 2.2). This partly reflects the fact that a range of low and zero carbon technologies in this sector are already reaching maturity, and so emission reduction costs are lower than in other sectors.

The household sector also decarbonises substantially (completely in the MARKAL-MACRO model), with zero carbon electricity replacing natural gas as the energy source for space and water heating.

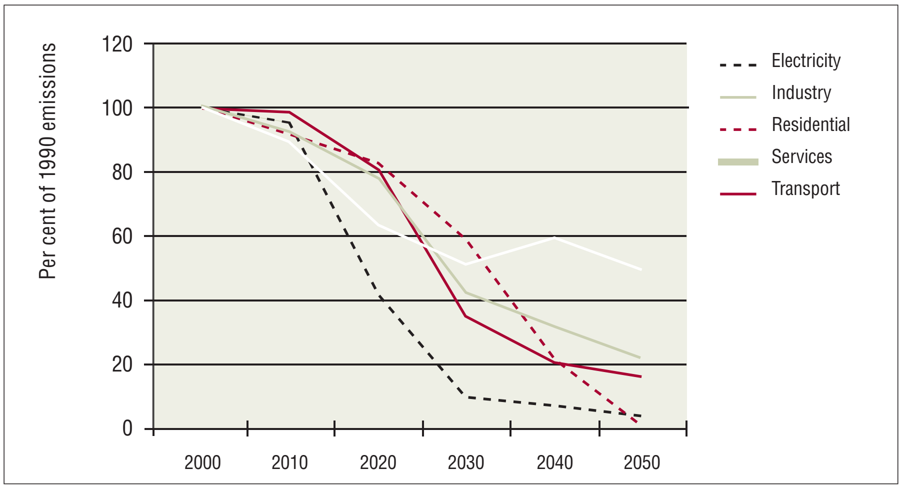


Figure 2.1 – Carbon abatement by sector, MARKAL-MACRO model

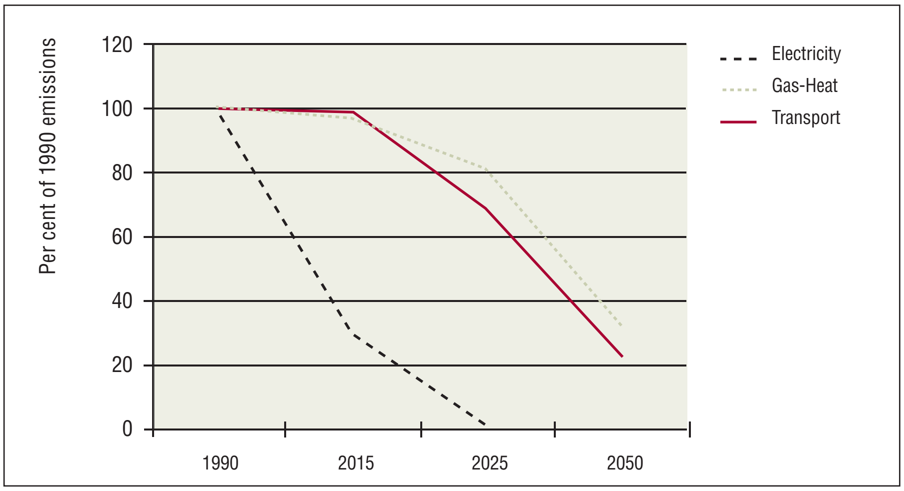
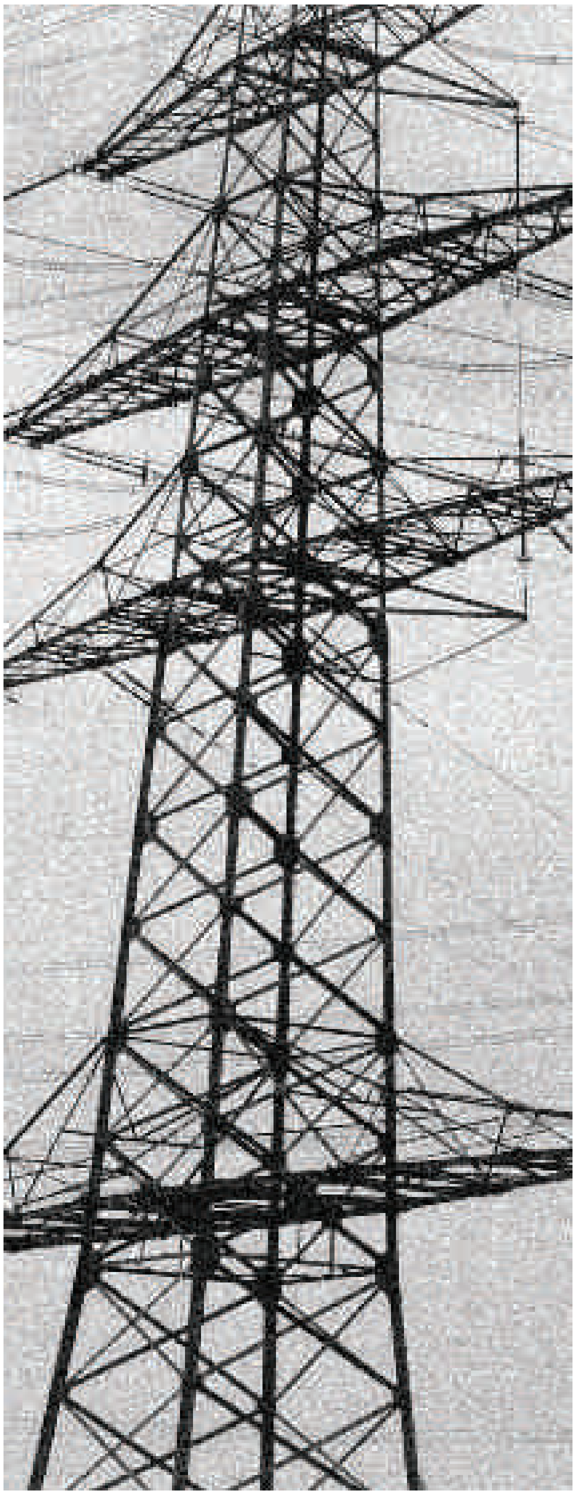


Figure 2.2 – Carbon abatement by sector, Anderson model



Electricity

While the Anderson model gives a role to micro-generation technologies, such as solar and domestic combined heat and power (dCHP), the main result of both models is that decarbonisation in the electricity sector is dominated by wind power and carbon capture and storage (Figures 3 and 4). In the MARKAL model these two technologies account for three-quarters of electricity generation by 2050.

Because transport plays virtually no role in decarbonisation before 2025 in Anderson's model, the electricity sector requires particularly rapid investment in low-carbon technologies. In illustrative scenarios, based on average market shares, our calculations, based on Anderson's model are that of the order of 70 terrawatt hours (TWh) of electricity will have to be generated from wind by 2015, mainly off-shore, requiring about 20 gigawatts (GW) of installed capacity. By comparison, the London Array has a planned capacity of 1 GW, and current plans for Round 2 of offshore wind-farm consents are in the range of 5.4-7.2 GW. However, the British Wind Energy Association (BWEA) considers that 20 GW of offshore wind alone is achievable by 2020, within the current policy context (BWEA 2006[23]).

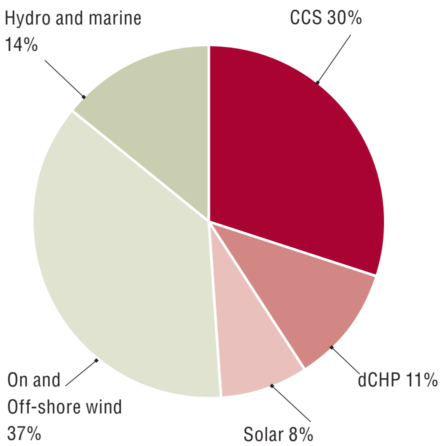
Because the transport sector starts to decarbonise earlier in the MARKAL-MACRO model, the early emphasis placed on renewables is somewhat less. Wind generation by 2020 is modelled at 20 TWh, requiring some 6 GW of capacity, in line with the government's current expectations of Round 2 of offshore wind farm development (5.4-7.2 GW). Only around 19% of electricity generation is modelled to come from renewables by 2020, also within the government's current goal.

However, there is a very sharp subsequent increase in wind capacity after 2020, rising to 82 TWh in 2030, requiring some 33 GW, and eventually to 119 TWh in 2050. By 2050, other renewables are also beginning to enter into the generation mix, with marine and various biomass and waste technologies growing in importance.

The current government aspiration for renewables is that they should be 20% of electricity generation by 2020, and the EU-wide target is to produce 20% of energy from renewables (with the UK possibly having to take on a more ambitious goal within that EU-wide figure). Thus the mid-term scenario derived from the Anderson model for renewable electricity generation shown here is far more demanding than current policy, and presents a serious medium-term challenge. A policy framework for rapid expansion of renewables would have to be adopted very soon for this scenario to be feasible in terms of new investments. By contrast, the MARKAL-MACRO scenario is within the ambitions of existing UK renewable electricity targets for 2020.

However, in March 2007, EU Heads of State signed up to a binding target for renewables to meet 20% of Europe's primary energy needs by 2020. This target will clearly require a much more rapid growth in renewables for electricity supply than implied by current UK targets. Although we applied a 25% threshold on intermittent renewables in running the MARKO-MACRO model, evidence suggests that a greater volume of wind generation could be achieved without significant environmental impact if appropriate strategic planning was undertaken now. In meeting the EU target, sustainable development principles should be applied to policy choices – including the implications of environmental limits for onshore and offshore wind – to ensure that they maximise benefits and minimise risks across a range of policy objectives.

Figure 3. Relative contributions to carbon abatement in the electricity sector by 2050, Anderson model



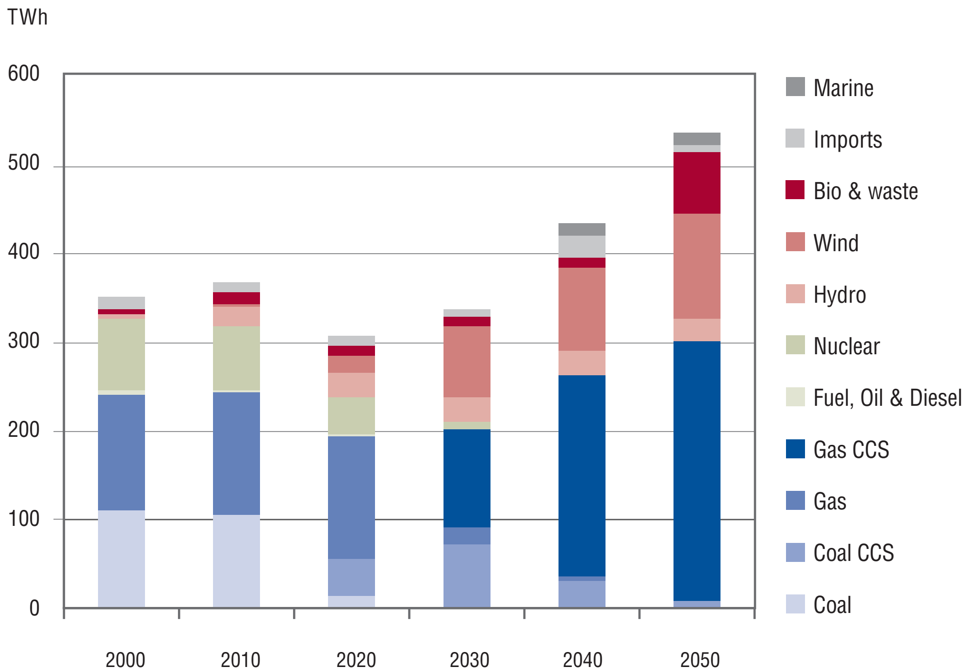


Figure 4. Electricity generation mix to 2050, MARKAL-MACRO model

The other main technology in the decarbonisation of electricity in these models is carbon capture and storage (CCS) applied to fossil fuels (see box). Our calculations, based on Anderson's model, are that by 2025, CCS plant would have to be generating over 100 TWh of electricity, or around 25% of estimated demand. This would be roughly equivalent to 15 GW of generation capacity, or some 30 medium-sized 500 MW power stations. Currently, there are plans for only one 'full-scale' demonstration plant, probably of 500 MW-1 GW, to be operational in the early years of the next decade. Getting on track for this particular scenario would therefore require a rapid deployment of the technology on a very large scale immediately after a successful demonstration.

The MARKAL-MACRO model scenario also involves the development of major CCS capacity over time. By 2020, the model requires 43 TWh of generation from 5.4 GW of coal and gas-fired plant with CCS (equivalent to 11 medium-sized 500 MW power stations). By 2050 this grows to 301 TWh, mostly from gas-fired plant with CCS.

These installation rates are ambitious, but appear to be achievable and consistent with reported carbon storage capacity in depleted North Sea oil and gas fields. A recent study concluded that with adequate political support it would be possible for CCS to reduce emissions from UK electricity generation by 45% by 2020, covering some 9-13 GW of installed capacity [24].

As noted above, neither approach models decentralised electricity generation well. In the MARKAL-MACRO model it plays virtually no part. Micro-renewable heat technologies (such as solar thermal or ground source heat pumps) do not enter the picture either. This is because, despite coming down in price over the period, they remain more expensive than heating through centralised electricity. This reflects the strict cost-optimisation aspect of the MARKAL model.

Carbon capture and storage

It is clear that to achieve the ambitious emissions reduction scenarios required to avoid dangerous climate change, a rapid transition away from fossil fuels will be essential. However, the need for rapid and deep cuts in emissions means that there may well be a role for carbon capture and storage (CCS) as a bridging technology – provided that it does not distract effort away from more sustainable approaches such as energy efficiency and renewables.

CCS entails the removal of carbon dioxide from fossil fuels before or after combustion. The captured CO_2 can then be injected into geological structures, such as depleted oil and gas wells under the North Sea or deep saline aquifers. Although CCS is new, its components are not. However, there are significant challenges to demonstrate that carbon capture can operate effectively on a large-scale integrated power plant, and that storage can be carried out in a safe and well-regulated manner.

In 2005, a major review by the Intergovernmental Panel on Climate Change concluded that CCS could contribute perhaps 15-55% of the overall global efforts to reduce emissions this century, provided that technical, economic and regulatory barriers could be addressed (IPCC 2005[25]). In March 2007, the EU stated its intention to have 10 CCS demonstration projects running by 2015 – and in the 2007 Energy White Paper the government announced a competition to build the world's first full-scale CCS power plant in the UK.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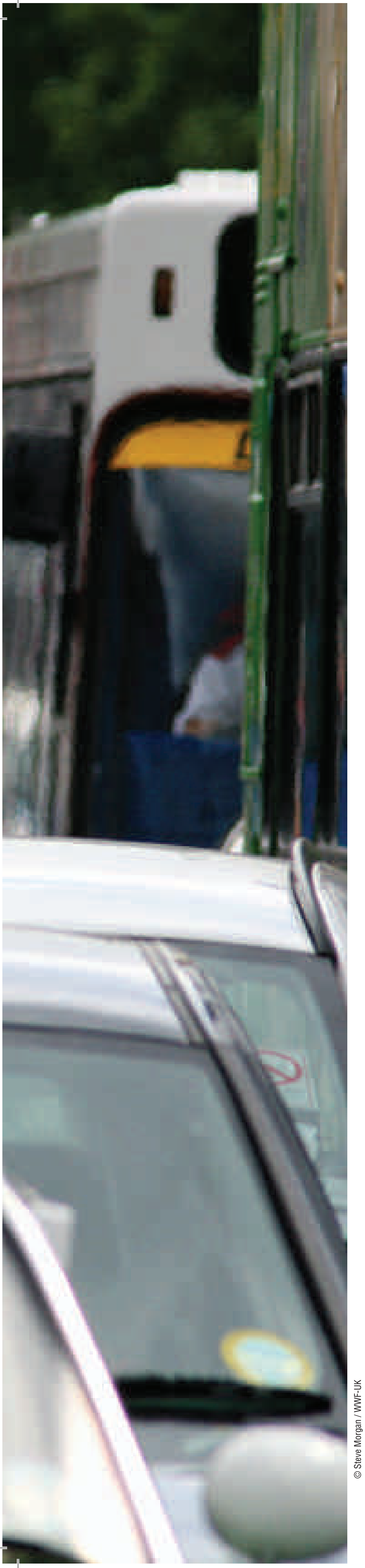

Transport

Surface transport also sees very deep emissions reductions, albeit more slowly than in the electricity sector.

In the Anderson model, the transport sector starts significant decarbonisation only after 2015. First and second generation biofuels play some role, in both surface transport and in aviation. In aviation, they make up a third of fuel used by 2050. However, hydrogen[26] also plays a substantial role in surface transport, making up almost 20% of energy used by 2050.

In the MARKAL-MACRO model, road transport also sees a major restructuring, with a move to much greater efficiency in engines in cars, and the introduction of hybrids in vans and buses. Biodiesel use (especially second-generation biodiesel[27]) begins to take off from 2010 across all vehicle classes, and by 2030 conventional diesel has been largely phased out (Figure 5).

However, there are limits to the use of first-generation biofuels in cars, with biodiesel and methanol peaking in 2050 at around 4.5 Mtoe (million tonnes of oil equivalent), or around 17% of current car fuel use. But by 2030 'Fischer-Tropsch' diesel, a second generation biofuel produced from solid biomass, is already emerging as the most important fuel in the mix for cars. By 2050, 70% of fuel used in cars is F-T diesel.

The heavy goods vehicle fleet converts to hydrogen (mainly from electrolysis from zero carbon electricity) by 2030. Rail switches over entirely from diesel (which currently accounts for 60% of energy use in rail) to electricity. Despite more efficient vehicles, overall energy use in transport increases, meaning that mobility across the economy continues to rise.

Air transport is the least transformed sector, with the least low carbon fuel substitution (none at all in the MARKAL-MACRO model), meaning that kerosene jet fuel continues to be used. However, a combination of increased fuel efficiency and the deep decarbonisation in other sectors means that a modest expansion of air travel (30% over current levels in the MARKAL-MACRO model) is still possible.

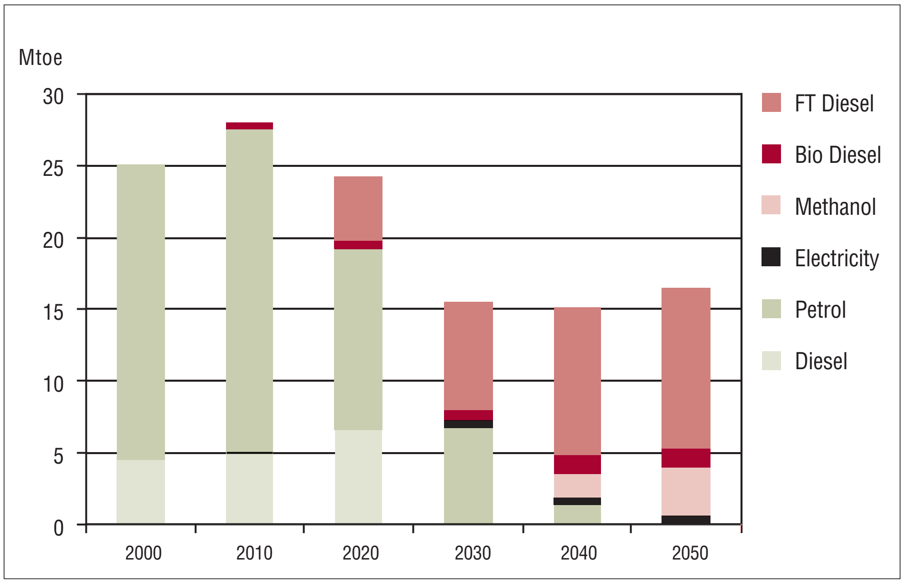

Figure 5. Fuel use in cars, MARKAL-MACRO model

Total costs

In terms of overall costs of decarbonisation (see Box) in 2050, the two models give results in the range of 2% and 3% of GDP.

In the Anderson model, the estimate of total costs of decarbonisation by 2050 is around 2.1% of GDP (the most likely value within a probability distribution ranging from under 1% to around 3%). With growth modelled as 2% per year until 2025, and then falling to 1.5%, GDP in 2050 is expected to be £2,650 billion at 2005 prices. Thus in absolute terms the costs of meeting the target will be in the region of £55 billion a year by 2050.

In the MARKAL-MACRO model, total costs in the central scenario rise to around 2.8% in 2050. Estimated GDP by 2050 in 2005 prices is £2,800 billion, so the absolute costs of achieving the 80% reduction trajectory start low, but rise to around £30 billion by 2030 and almost £80 billion by 2050.

Under both models, costs fall very significantly (by more than 25% under MARKAL-MACRO) if barriers to the uptake of energy efficiency measures are addressed successfully (see the alternative scenarios discussion in Annex I of this document).

The two models show different distributions of costs over time. Under the MARKAL-MACRO model, costs rise steadily from around 0.5% of GDP in 2020 to 1.5% in 2030 and then to around 2.8% in 2050 (Figure 6). In the Anderson model, costs peak at 2.25% of GDP in 2025 and then fall to 2.1% in 2050 (Figure 7). The difference arises because Anderson has a wider range of higher cost low carbon technologies than the MARKAL-MACRO model, and these are expensive to deploy widely in the middle of the period.

These cost estimates need to be set in context. The size of the UK economy is assumed to increase to roughly 2.5 times its present size by 2050, and the net impact on that growth of the costs discussed here are small (Figures 8 and 9). A UK economy meeting an 80% carbon emissions reduction target would reach the same GDP in 2052 as a business-as-usual UK economy would in 2050.

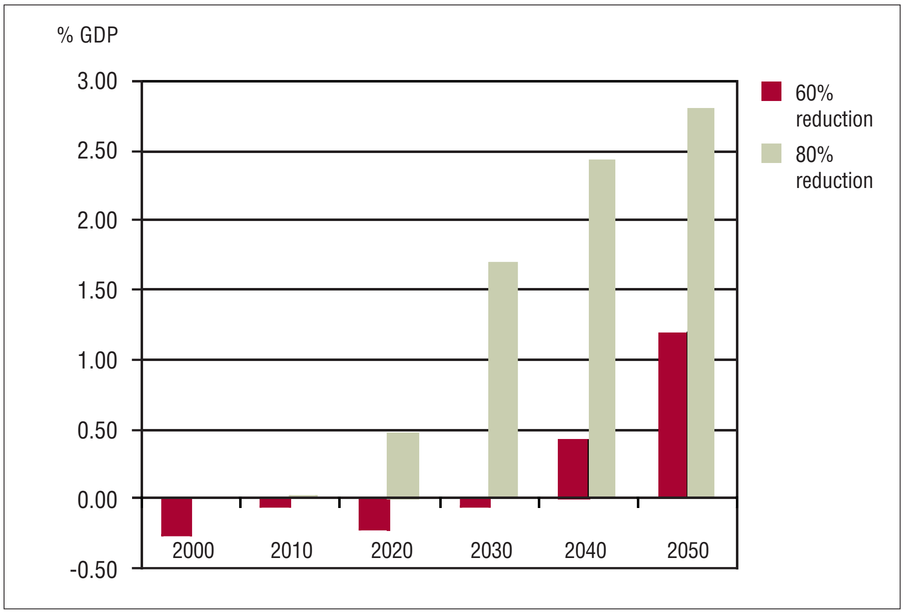

Figure 6. Total costs of abatement, MARKAL-MACRO model

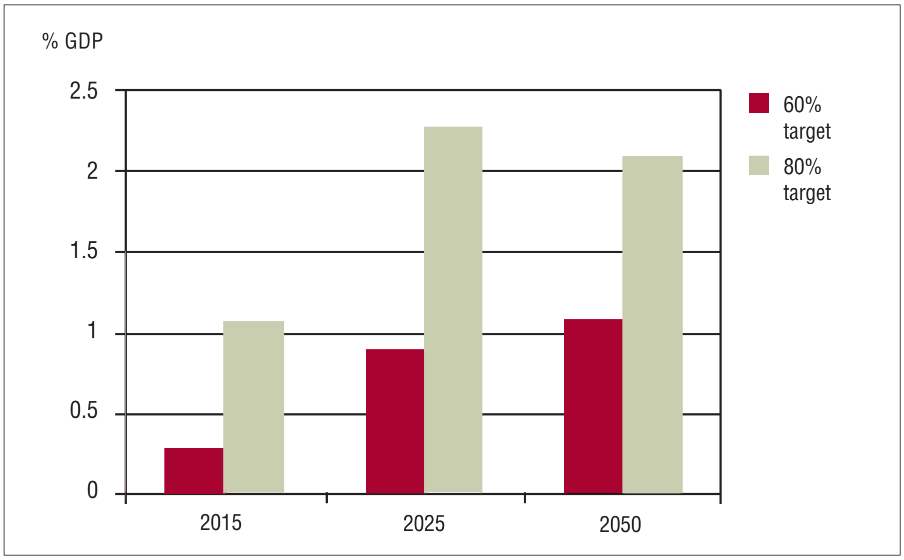

Figure 7. Total costs of abatement, Anderson model

Note: the costs of achieving the 80% and 60% targets indicated in Figures 6 and 7 are not directly comparable with the government's 60% objective, because we included international aviation emissions whereas the government did not.

The costs of doing nothing should also be remembered. The Stern Review put the damage costs of unabated climate change at a much higher range – between 5% and 20% of global GDP.

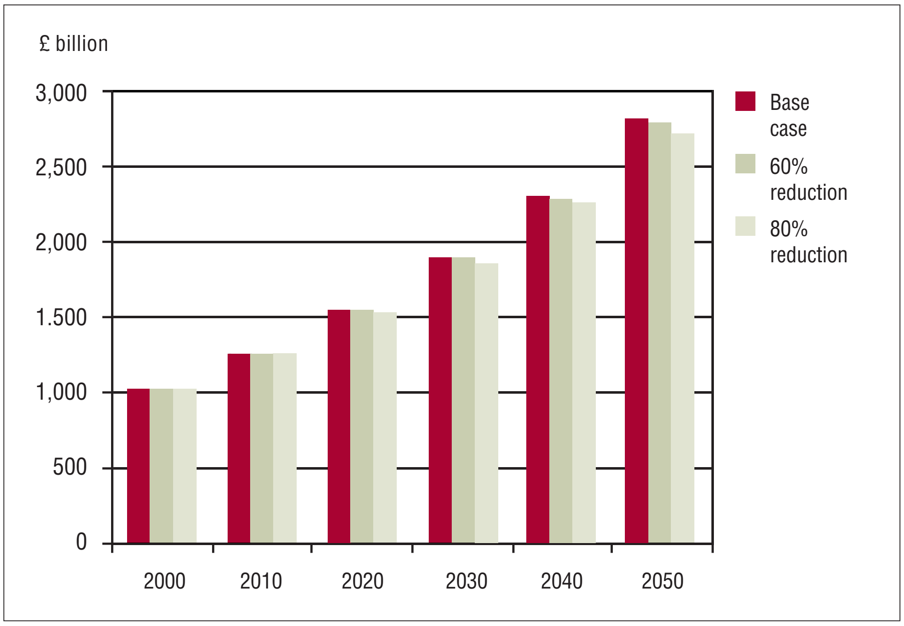

Figure 8. GDP growth with and without abatement, MARKAL-MACRO model

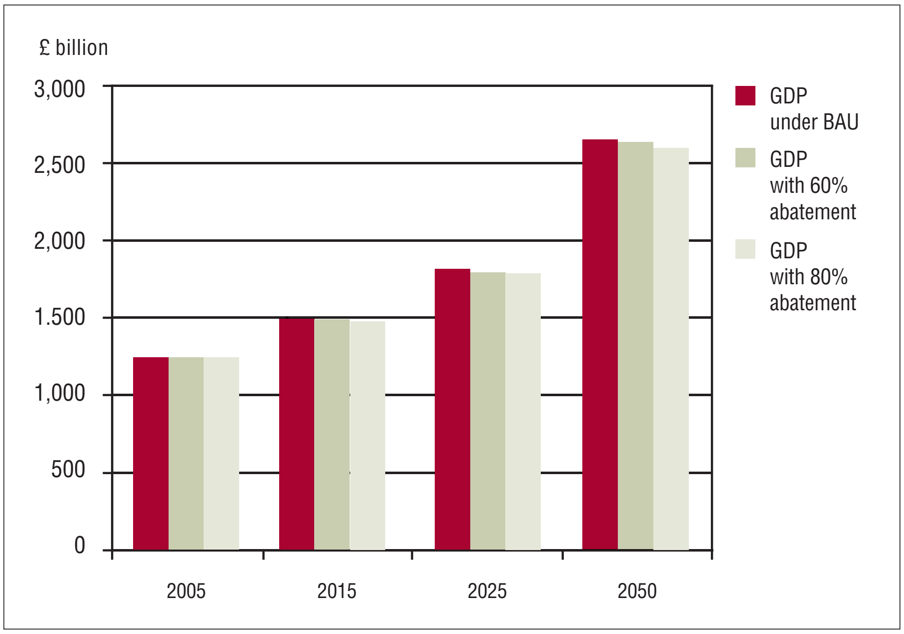

Figure 9. GDP growth with and without abatement, Anderson model

Note: the costs of achieving the 80% and 60% targets indicated in Figures 8 and 9 are not directly comparable with the government's 60% objective, because we included international aviation emissions whereas the government did not.

Treatment of costs

There are two ways of understanding the costs of decarbonising the UK economy. One is simply the additional costs of low carbon technologies over the costs of our current fossil fuel technologies. The Anderson model produces this type of cost estimate, expressed as a percentage of GDP.

The other approach is to look also at the knock-on effects on the wider economy. Bringing in higher cost low carbon technologies means that households and businesses pay more for electricity, heat and transport.

As a result, they have less to spend in other areas, and in particular end up spending less on investment. While there is increased investment in low carbon technologies in the energy and transport sectors, the net impact across the economy as a whole is to lower investment and therefore to lower economic growth. At this level, the costs of decarbonisation can be seen as growth forgone. In other words, economic growth is lower than it would be if fossil fuels had continued to be used. This is the approach taken in the MARKAL-MACRO model, which adjusts technology costs for these wider economic interactions.

However, these cost figures should not be taken too literally, but rather in a relative sense. This is because the estimates leave out factors that would lower overall costs – such as the export of low carbon technologies – and other factors that would increase costs, such as the assumption that there are no policy mistakes.

The costs of moving to a low carbon economy would not fall on everyone equally. Some groups may need special support in adapting. One would be low-income households in hard-to-heat homes, or living in areas with poor public transport. A high cost of carbon would hit them particularly hard, requiring compensation in the short term, and extra help to lower their carbon footprints over time. A second group would be energy-intensive industries open to international competition, where the danger is that production and jobs would be lost to other countries not decarbonising so deeply. Aluminium, iron and steel would be most at risk (Sato et al 2006[28]). Again, the long-term solution is to shift to lower carbon production methods (decarbonising electricity supply will help), but short-term adjustment help may be necessary.

Cost of carbon – marginal costs

As might be expected in a highly carbon-constrained world, the marginal cost of carbon – i.e. the cost of reducing the last tonne of carbon, or the implicit carbon price – is significant by 2050 in both models (Table 1). Costs rise over time in both models, although to a significantly higher level in the case of MARKAL and with a small fall in 2050 in Anderson, reflecting the peak in overall GDP costs in 2030 as described above.[29]

These marginal costs are considerably higher than those associated with attaining a 60% target *without* including aviation emissions, which for the DTI MARKAL-MACRO model for the Energy White Paper are in the range £65-176/tCO_2. Costs in this study are higher principally because the carbon constraint is tighter, and because emissions from international aviation are included. According to the Anderson model, this latter factor increases costs by 0.4% of GDP in 2050 (see Table 5 below).

These marginal costs appear high compared to the current price of carbon in the EU ETS. However, the more appropriate comparison is with the implied price of carbon in mechanisms designed to promote investment in the newer and more expensive low carbon technologies. In the case of the Renewables Obligation, for example, the effective price of carbon to consumers is currently over £100/tCO_2 (Ofgem 2006[30]). The Renewable Transport Fuel Obligation will introduce an effective price of carbon of £60-123/tCO_2 for biofuels, depending on the crop and transformation pathway. Incentives for emerging technologies in the rest of Europe, the US and Japan are of similar magnitudes (Anderson 2007[31]).

Our modelled costs should also be seen in the context of recent fossil fuel prices. High oil and gas prices have a similar effect on the economy as a carbon tax or carbon price would have, working both through the transport sector and via electricity. Table 2 shows the carbon cost equivalent of oil prices at various levels, in relation to a base case of the average 2003 oil price ($26.3/bl). For most of 2006, the Brent spot price was well over $70/bl, and peaked near $80/bl, and has recently again reached this level. This is around the equivalent of average costs estimated in Anderson's model.

ALTERNATIVE SCENARIOS

The two models explored different alternative scenarios (Tables 3 and 4) – see Annex for details of specifications.

The MARKAL-MACRO sensitivity runs explored the cost implications of more rapid cost reductions in renewable technologies, accelerated energy efficiency and high fossil fuel prices. The Anderson model also explored accelerated energy efficiency, but then looked at the implications of new nuclear build. The original base case for the Anderson model also did not constrain aviation emissions, so this can also be compared with the constrained emissions scenario.

All of the MARKAL-MACRO alternative scenarios lead to lower costs of decarbonisation. This is especially the case for accelerated energy efficiency, which reduces costs in 2050 to 2.04% of GDP, compared to 2.81% for the base case.

Accelerated energy efficiency also significantly decreases costs in the Anderson model. This confirms that policies focused on overcoming non-cost barriers to energy efficiency are key to the cost-effective delivery of emissions targets. Improvements in energy efficiency greatly reduce the onus placed on low carbon energy supply technologies to reduce emissions, as many other studies have found. This is reflected in the cost estimates for the Anderson model, where better energy efficiency cuts the costs of an 80% emissions reduction trajectory by between a half and third (impacts on the 60% reduction scenario are less dramatic). However, the figures here come with the health warning that they reflect only differences in the costs of supplying energy. Carrying out energy efficiency improvements also has a cost, which has not been estimated here.

Table 1. Marginal costs of abatement in MARKAL and Anderson models

	MARKAL MACRO marginal cost (£/tCO2)	ANDERSON marginal cost (£/tCO2)
2020	45	82
2030	177	120
2050	375	114

Oil price ($ per barrel Brent spot)	Equivalent carbon (£/tCO_2)
38	19
40	23
60	56
80	90
100	123

Table 2. Oil price and carbon price equivalence

Source: Stern et al (2006: 257)

Table 3. Costs of 80% carbon emissions reduction with different assumptions (% GDP), MARKAL-MACRO model

	2020	2030	2040	2050
Central scenario	0.46	1.70	2.43	2.81
With accelerated technological change	0.45	1.60	2.35	2.58
With higher fossil fuel prices	0.45	1.54	2.27	2.64
With accelerated technological change	-0.07	0.63	1.63	2.04

Table 4. Costs of 80% emissions reductions with different assumptions (% GDP), Anderson model

	2015	2025	2050
Central scenario	1.05	2.26	2.07
With accelerated energy efficiency	0.69	1.26	1.38
With new nuclear build	0.65	2.02	1.95
With unconstrained aviation emissions	1.23	2.95	2.47

Conclusions

Given recent climate science, and a range of burden sharing models, the current UK target of a 60% emissions reduction by 2050 is inconsistent with attaining the UK and EU goal of keeping mean global surface temperature rise to less than 2°C above pre-industrial levels. A target of 80% or more is required.

Authoritative modelling approaches (one used by the UK government and the other by the Stern Review) suggest that it would be feasible, although challenging, to adopt and achieve a UK emissions reduction target of at least 80% by 2050 from 1990 levels, solely through domestic effort. This result emerges even with the inclusion of international aviation emissions, with constraints on first generation biofuels and wind, and excluding new nuclear power. The costs of attaining an 80% target, with our added constraints, would be roughly 2 and 3 times those of attaining a 60% target without aviation emissions, but these costs would still be, at most, half the costs of adapting to climate change and perhaps nearer one tenth. Costs could be further reduced by implementing aggressive policies to improve energy efficiency.

While an 80% target is technologically feasible and affordable, achieving it would require an immediate and radical shift in the pace and scale of investments in low carbon technologies – probably initially in the electricity sector. The models point to the need for a rapid increase in the deployment of renewable energy technologies, and also for urgent action to demonstrate the effectiveness of carbon capture and storage as an economically and environmentally acceptable abatement option. It is also clear from the modelling that in the absence of new technological solutions, emissions reductions compatible with the government's international climate change goals cannot be achieved without significant constraints on the growth in aviation.

All models have their limitations, and we would emphasise that these modelling results do not represent a blueprint for a low-carbon economy – other technologies and societal choices may be equally, or more, valid. Better energy futures might well include far higher levels of distributed energy and energy efficiency, which our work shows has significant cost benefits. But these results show that, according to the best models we have available to us, the UK could in principle attain a target of 80% by 2050 through domestic action alone – and that it can do so without damaging the wider environment, and at costs that are significantly lower than the costs of doing nothing.

Annex – Additional modelling

ACCELERATION OF TECHNOLOGICAL CHANGE

New technologies – whether mobile phones or low carbon technologies such as offshore wind or fuel cells – tend to be expensive at first, but their costs come down over time. This is because of economies of scale in manufacturing, but also because manufacturers and developers learn how to cut costs over time, and as more and more units are sold. Technologies are said to have a ‘learning curve’, showing how costs come down as the technology is used increasingly widely (in electricity, for example, in installed capacity measured in MW or GW). The learning rate indicates how far costs come down with a doubling in the use of the technology. For example, International Energy Agency (IEA) estimates learning rates to be 18% for wind, 20-35% for photovoltaics, and 15% for electricity from biomass (Anderson et al 2001)[32].

The MARKAL MACRO model normally uses learning rates taken from a review of estimates (McDonald, A., and L. Schrattenholzer 2002). As in the analysis for the Energy White Paper, expected future deployments of technologies were taken from the European Commission’s World Energy Technology Outlook - 2050, but for the central model run a conservative set of estimates were used. In the additional re-run, the full estimates were substituted. These latter projections may be more realistic, as a substantial global effort on climate mitigation can be expected to drive the pace of technological development and hence cost savings.

Applying these higher estimates of rates of deployment to a range of renewables in the power sector (hydro, energy from waste, biomass, solar, wave, tidal, onshore wind, offshore wind, and micro-wind) to the same learning curves accelerates cost reductions for these technologies by 2050. For some technologies the reductions are considerable (e.g. 20-27% for wind and marine, 25-43% for biomass and wastes, and 51% for solar).

Accelerating technological change on the supply side in this way does reduce overall costs, but not by a large amount, bringing down the total cost from 2.8 to 2.6% of GDP by 2050. However, it should be noted that accelerated learning in this scenario has been applied only to a limited range of renewable energy technologies in the electricity sector. Accelerated learning in other sectors that have higher marginal costs, such as transport or carbon capture and storage, might be expected to have a greater effect on total costs.

ACCELERATED ENERGY EFFICIENCY

In the Anderson model, how fast energy efficiency improves over time is dealt with through the elasticities of demand for energy. If we assume a high rate of efficiency improvements, this is represented through a low elasticity. In our central scenario for the Anderson model, estimates of future elasticities of demand are based on past trends. However, Anderson explored an alternative set of assumptions about efficiency improvements across the economy as a whole, based on a set of engineering studies (Anderson 2007). These assumptions are still quite conservative – other studies point to the possibility of yet lower demand elasticities.

The MARKAL model accounts for energy efficiency in a different way from the Anderson model. Instead of rolling all energy efficiency measures into a single elasticity of demand variable, the MARKAL model includes a large number of separate energy efficiency technologies.

Many of these have very low (or even negative) lifetime costs, and an unconstrained cost optimisation model would normally choose them first. However, a number of barriers in reality prevent people and organisations from investing in energy efficiency measures. To reflect this, the model chooses only those energy efficiency measures that pass the hurdle of having a positive net present value with a discount rate of 25%. This is a much higher rate than that (10%) used more widely for investments in the model. The accelerated energy efficiency scenario simply drops the hurdle rate from 25% to this default rate of 10% in order to demonstrate the impact of focused polices to address non-cost barriers to the uptake of energy efficiency.

These changes have a large impact on costs, with savings in the early years and a cut in 2050 costs to around 2% of GDP. The lower hurdle rate not only boosts the uptake of efficient and conservation-supporting options in the end-use sectors, it also makes the existing measures cheaper. Greater energy efficiency has the biggest impact in the transport sector, where it cuts fuel use and also drives fuel substitution, because alternatively fuelled vehicles (e.g. those using hydrogen) are often more efficient.

HIGHER FOSSIL FUEL PRICES

In this study, DTI projections of fossil fuel prices were used. The baseline scenario uses the DTI’s central projections (DTI 2006v). For oil, these range from $40-45/bl in the next decade, rising to $55/bl after 2040. For gas prices, projections are around 35p/therm to 2015, rising to more than 40p/therm by 2040. Coal rises from around $1.9/GJ to $2.2 /GJ.

By contrast, the high price projection has oil at $72/bl in 2020, rising to $82/bl by 2050, with correspondingly higher gas and coal prices. With oil prices close to $80/bl in mid-2007, and with some in the oil industry predicting prices could rise to $150 a barrel in the next 20 years[33], this projection seems conservative.

Higher fuel prices drive both lower demand and greater movement into non-fossil fuel substitutes. However, the effect of higher fossil fuel prices on overall costs is not as large as one might expect. With the demanding emissions trajectory, and with constraints on nuclear and biomass, the model drives demand towards alternatives that are still quite costly.

ENDNOTES

1 In March, the UK signed up to a binding EU target for renewables to supply 20% of Europe’s primary energy needs by 2020. A leaked memo from the former Department of Trade and Industry confirmed that the government is seeking “statistical interpretations” of the target that would make it easier to achieve. ‘Revealed: cover-up plan on energy target’, *The Guardian*, 13 August 2007.

2 In this report we focus on CO_2 emissions from fossil fuel combustion because this is by far the biggest component (c. 85%) of the UK’s total greenhouse gas emissions; because the government is focusing solely on CO_2 emissions in its draft Climate Change Bill; and because the available models could only deal satisfactorily with abatement options for energy-related CO_2. The only exception was our inclusion of the non-CO_2 impacts of aviation, as these are inextricably linked with the sector’s fossil fuel use. Clearly, it will also be important to achieve steep reductions in the UK’s emissions of other greenhouse gases such as methane, nitrous oxide and HFCs.

3 IPCC Fourth Assessment Report (2007), www.ipcc.ch

4 Schellnhuber, H, Cramer, W, Nakicenovic, N, Wigley, T and Yohe, G (eds.) (2006) *Avoiding Dangerous Climate Change*, Cambridge University Press.

5 http://pubs.giss.nasa.gov/docs/2006/2006_Hansen_etal_1.pdf,
6 Meinhausen M (2006) 'What does a 2°C target means for greenhouse gas concentrations? A brief analysis based on multi-gas emissions pathways and several climate sensitivity uncertainty estimates', in Schellnhuber et al, eds. Avoiding Dangerous Climate Change, Cambridge University Press (2006).
7 Meinhausen (2006) ibid.
8 Baer, P, with Mastrandrea, M (2006) *High Stakes: How large and fast will cuts in greenhouse gas emissions need to be to have a high chance of avoiding dangerous climate change*, London: ippr.
9 European Commission (2007), *Limiting global climate change to 2 degrees Celsius – the way ahead for 2020 and beyond*.
10 Höhne, N, Phylipsen, D, and Moltmann, S (2007) *Factors underpinning future action – 2007 update*. Report for the Department for Environment, Food and Rural Affairs, (Cologne: Ecofys, available at http://unfccc.int/resource/docs/2007/smsn/ngo/026c.pdf)
11 Baer, P, with Mastrandrea, M (2006) High Stakes: How large and fast will cuts in greenhouse gas emissions need to be to have a high chance of avoiding dangerous climate change, London: ippr.
12 Gross, R, Heptonstall, P, and Blyth, W (2007) *Investment in electricity generation: the role of costs, incentives and risks London*: UKERC.
13 The government's sustainable development principles are living within environmental limits, ensuring a strong, healthy and just society, achieving a sustainable economy, promoting good governance and using sound science responsibly.
14 Calculated from Defra statistics available at: http://www.defra.gov.uk/environment/statistics/globatmos/gagccukem.htm
15 Pre-Budget Report 2006, para 7.82.
16 WWF International (2007) A first estimate of the global supply potential for bio-energy. A briefing study commissioned by WWF, July 2007.
17 Scotland's Renewable Resource, 2001. Garrad Hassan & Partners Ltd. Scottish Executive 2001.
18 The Anderson model generates a slightly higher penetration of wind, but of the same order.
19 US National Security Task Force on Energy 2006: 8.
20 Dennis Anderson is Emeritus Professor of Energy and Environmental Studies at Imperial College London, and was formerly the Senior Energy Adviser at the World Bank, Chief Economist at Shell, and an engineer in the electricity supply industry.
21 Placing an 80% emissions reduction constraint on the model leads to very high levels of wind generation in the electricity sector. This is partly because wind is the lowest cost low-carbon solution, but it is also due to the fact that at high penetrations, intermittent forms of electricity generation (like wind) are not modelled in a very realistic way. We therefore constrained wind generation in the MARKAL model by introducing a storage requirement on intermittent renewables above 25%. In practice this constraint is likely to be conservative – by 2050 is likely that improved grid management techniques and new energy storage technologies could permit a significantly higher penetration of intermittent renewables. It is also worth noting that this was a constraint on all intermittent generation, not just wind, although the MARKAL model soon used up other near market renewables potential, such as sewage waste, and thereafter only built wind.
22 Strachan, N, Kannan, R, and Pye, S (2007) *Final report on the DTI-Defra scenarios and sensitivities, using the UK MARKAL-MACRO energy system models*. Final report prepared by the Policy Studies Institute for the Department of Trade and Industry (DTI) and the Department of Environment, Food and Rural Affairs (Defra), London: Policy Studies Institute and UKERC.
23 British Wind Energy Association (2006), BWEA response to the consultation 'Reform of the Renewables Obligation' Appendix B: Assessment of the Ernst & Young and Oxera reports. Available at: http://www.bwea.com/pdf/070906%20Appendix%20B%20EY%20and%20Oxera.pdf
24 Scope for future CO_2 emission reductions from electricity generation through the deployment of carbon capture and storage technologies: www.stabilisation2005.com/61_Dr_Jon_Gibbins.pdf
25 *Carbon dioxide capture and storage: Summary for policymakers and Technical summary*, IPCC 2005.
26 In the Anderson model, the source of hydrogen is from fossil fuels with pre-combustion carbon capture and storage. Carbon can be captured from fossil fuels either before they are burned (pre-combustion), in which case hydrogen can be extracted from them, or after (post-combustion). Post-combustion capture, however, is much cheaper, and most early demonstration projects are likely to be of this type.
27 Currently, first generation biofuels are produced from a limited range of crops, by chemical processes such as distillation. However, second generation thermo-chemical biofuel technologies are now emerging, such as Fischer-Tropsch processing, that offer much higher yields, and allow a much wider range of raw material, as well as potentially bigger carbon dioxide emissions reductions, than first generation biofuels.
28 Sato, M, Grubb, M, Cust, J, Chan, K, Korppoo, A, and Ceppi, P (2007) 'Differentiation and dynamics of competitiveness impacts from the EU ETS', Cambridge Working Papers in Economics 0712, Faculty of Economics, University of Cambridge.
29 The models treat marginal costs in different ways. In MARKAL, they represent the cost of the most expensive carbon abatement technology at a particular time – i.e. a conventional economic view of marginal costs and indicative of likely carbon market prices. Anderson bases his estimates of marginal costs on the expansion of a portfolio of options, rather than a single technology, on the grounds that uncertainties require governments and industry to develop portfolios as opposed to one or just a few options. For this reason the marginal costs estimated here tend to be lower.
30 Ofgem (2006) Submission to the consultation on the reform of the Renewables Obligation, London: Ofgem.
31 Anderson, D (2007) *Costs and policies for a low carbon UK energy system: Findings of a study for the IPPR. Report prepared for ippr*. Available at: www.ippr.org
32 Anderson D, Clark C, Foxon T, Gross R and Jacobs M (2001) Innovation and the Environment: Challenges and Policy options for the UK Final report from workshops sponsored by the Economic and Social Research Council's Global Environmental Change Programme, London: Imperial College/Fabian Society/ESRC
33 Strahan, D (2007), 'Slippery slope', The Guardian 3 October 2007.

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