The Costs of Mitigating Climate Change

Dennis Anderson & Matt Leach

1. Introduction

It is often held that the costs of mitigating climate change would be disruptive to economic growth, and this is one reason why the US Government declined to ratify the Kyoto Accords. Yet numerous studies have estimated that the effects on the level and growth of economic output of a *phased* transition to a low-carbon economy are likely to be small, perhaps reducing gross national and world products (GDP and GWP) by –1.0% to 4.5% over the next 50 years when, in any scenario of economic success, they are likely to rise by several hundred percent. Further, depending on world oil and gas prices and on the rates of innovation, it is possible that GDPs would be *greater* not *smaller* if there were a large-scale shift to carbon-neutral energy forms. There is an exception that, if policies were such as to force the transition through abruptly, the costs could be appreciable. However, in a phased transition over two- to three generations, evidence and calculation show that the effects would likely be small.

This paper explains why a large number of studies have arrived at this conclusion. In doing so, it shows the importance of drawing on the approaches of both the physical and social sciences when making an assessment of the technological options and their economic impact; with a few notable exceptions the two—quite differing—approaches have been pursued independently. If there is an overarching finding it concerns the role of innovation in creating options and reducing costs (ICEPT, 2003 and Pacala and Socolow, 2004). In this light there is now a dialogue beginning among the G-8 on the possibilities for a new international initiative to mitigate climate change focussed directly on the development and use

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Dennis Anderson is Professor of Energy and Environmental Studies at Imperial College London. Matt Leach is a Chartered Engineer, holds a PhD in Energy Policy and is a Senior Lecturer at Imperial College London.

of carbon-neutral technologies. It offers the prospect of involving developing and industrial countries more widely in climate change mitigation policies.

To provide a background, Section 2 summarises the results of simulation studies produced for the UK Energy White Paper. The results echo those of numerous other international and national studies, summarised in Sections 3 and 4 respectively. Section 5 sums up and discusses the implications for policy.

2. The background analysis of the UK Energy White Paper

The background analysis for the 2003 UK Energy White Paper (DTI, 2003a) produced a large number of studies of the technological options for and costs of reducing UK CO_2 emissions by 60% by 2050. They used a Linear Programming algorithm to identify least cost ways of delivering energy—heat, light and motive power—to the consumer, subject to constraints set by reliability targets, environmental policies, resource availability, transmission and distribution requirements and other factors. Costs were estimated to reflect market prices, and were changed exogenously over time to allow for innovation. A large array of extraction, conversion, transmission, distribution and end-use technologies were represented in the model, covering all the major energy forms and carriers—electricity, gas, oil, coal, the full range of renewable energy technologies, and the long-standing option of hydrogen.

Over 70 model runs were undertaken to explore alternative assumptions on the following:

- the growth of energy efficiency in homes, industry, commerce and transport
- an increased use of natural gas for electricity generation
- the use of coal and natural gas for electricity generation, with the carbon dioxide being captured and stored in geological formations
- nuclear power for electricity generation
- the full range of renewable energy options—onshore and offshore wind, wave and tidal energy, solar PVs, and biomass for heat, power and liquid fuels for transport
- decentralised heat and power based on new micro generation technologies

- the production of hydrogen from gas, and coal (with the carbon being sequestered) and biomass
- the production of hydrogen by electrolysis from renewable energy and nuclear power, for use as a fuel for homes (e.g. for decentralised cogeneration), industry and transport.

Some studies assumed all these options were open or emerging and that the choices would be based on cost efficiency, subject to constraints on resource availability (e.g. land availability for biomass and the number of onshore and coastal sites available for wind) and technical factors (e.g. attainable build rates). Others repeated the exercises, but imposed constraints on, for example, the rate of uptake of energy efficiency, the supply of natural gas, and investment in carbon capture and storage. All the possibilities were also subjected to sensitivity analysis with respect to economic growth, innovation and costs, and world oil and gas prices. Full accounts are provided in DTI (2003b) and in an updated review in Leach *et al.* (2005, forthcoming). There are three main findings:

First, deep cuts in carbon emissions are technically and economically feasible over the long term. The engineering challenges facing the industry will be significant: to develop the technologies further and reduce costs; to transform the energy supply infrastructure, as it is twice renewed over the next two generations, in ways compatible with the use of new carbon-neutral technologies; to develop R&D capacity and the policies for the demonstration and commercialisation of new options; and to invest in the education and training of engineers and skilled labour. However, the options are available and capable of being developed further, including a range of energy-efficient technologies and practices, renewable energy technologies, nuclear power, carbon capture and storage, hydrogen production, and perhaps a move to new more decentralised energy supply and demand management systems than we have today. Box 1 summarises a selection of results for the electricity supply sector.

Second, the costs of a *measured* transition (an important qualification) to a low carbon economy over the next 50 years may or may not be high in *absolute* terms, depending on how far innovation succeeds in reducing the costs of the alternatives. But *relative* to total GDP and its growth the costs to the UK are unlikely to be high, around 0.5%–2.0%—or around one year's growth or less—of GDP, which can be expected to expand two- to three-fold over the next half century. As shown below, this range is within that of many other studies in other countries and internationally.

The *third* concerns the importance of, and supporting policies for, innovation. Presently the costs of the alternatives—renewable energy, nuclear power, carbon capture and storage, fuel cells, hydrogen production, for example—are appreciably higher than those using conventional fossil fuel options. However, in all areas there is appreciable scope for reducing costs through innovation. The history of energy supply, conversion and use is replete with examples of costs being reduced with innovation, in some cases by orders of magnitude. There is no evidence that this process has come to an end.

3. Global CO_2 mitigation cost modelling

3.1 Technologies and practices

Engineering studies have consistently drawn attention to the large number of low-carbon options available.[1] The recent analysis in *Science* by Pacala and Socolow (2004) provides an overview. Starting from a baseline scenario in which fossil fuels remain the major energy source, they consider the possibilities for reducing world carbon emissions by 7 gigatons (GtC) per year by 2050, to bring the emissions trajectory to "a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500ppm by 2125." For expository reasons they break the 7 GtC reduction down into seven 'wedges', each rising linearly from 0.0 (GtC) of abatement in 2004 to 1.0 GtC in 2050. They argue that there are at least *fifteen* technologically plausible ways for producing a wedge based on options "that are already deployed on an industrial scale and that could be scaled up further to produce at least one wedge. [Furthermore,] several options could be scaled up to at least two or more wedges…" The calculations allow for interactions: "emissions cannot be reduced twice… The more the electricity system becomes decarbonised, for example, the less available savings from greater efficiency in electricity uses, and vice versa."

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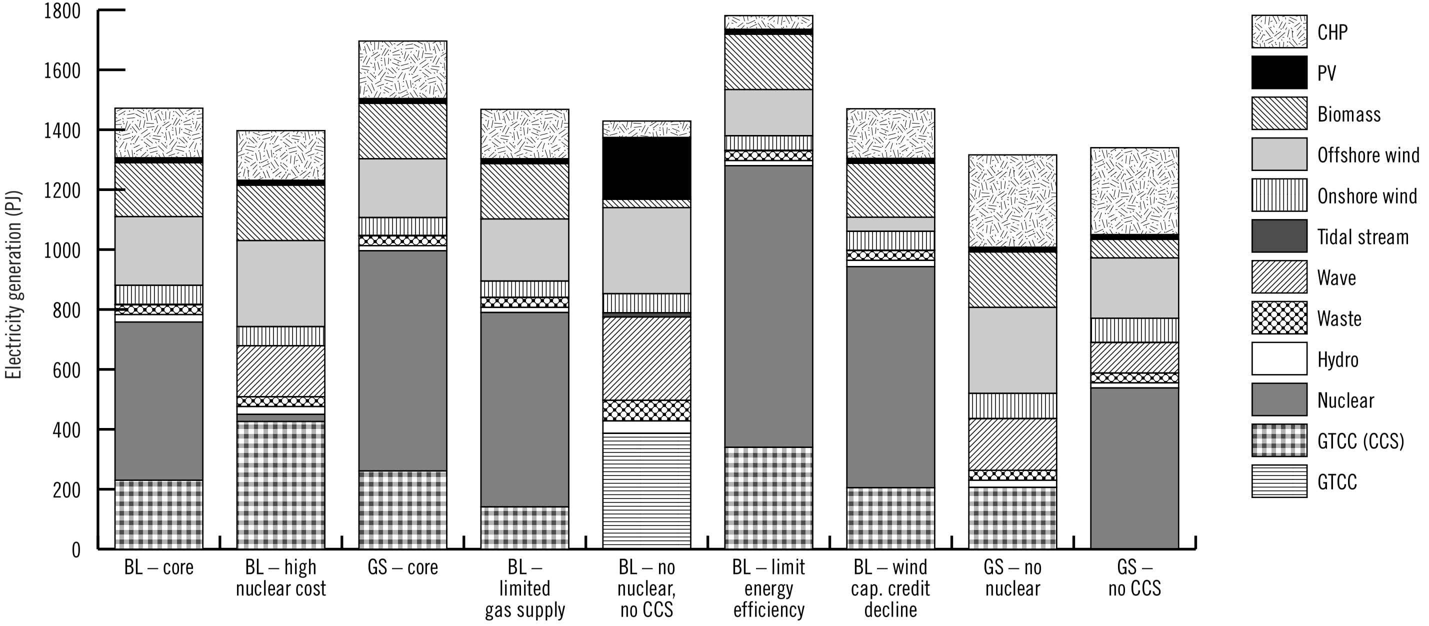
[1] See, for example, the *World Energy Assessment* of the UNDP and World Energy Council (2000), ICEPT (2003) for the Prime Minister's Strategy Unit provides a further assessment of technology options and costs, the scenarios of the Royal Dutch Shell Group (1996 and 2002) and the IPCC's Assessment Reports and Technical Papers (for example, Watson, Zonyowera and Moss, 1996).

BOX 1: A DIVERSITY OF TECHNOLOGICAL OPTIONS AT COMPARABLE COST: SIMULATION RESULTS FOR THE UK

There are five broad families of options for a low-carbon future: energy efficiency, renewable energy, carbon capture and storage, nuclear power and hydrogen derived in a carbon neutral way from fossil fuels or renewable or nuclear energy. Figure 1 shows the results from nine model runs with differing assumptions and constraints, which include a 60% emissions reduction target. The effects of differing possibilities for efficient end use technologies and practices are reflected in the differing levels of energy use. Results change kaleidoscopically with input assumptions about costs and other factors. However, they all have three things in common: they are consistent with the achievement of a low-carbon future; the effects on economic output and its growth are relatively small; and the estimated costs of meeting emission constraints are robust with respect to changes in assumptions about availability or performance for any one option.

Figure 1: Electricity generation in 2050 under a 60% carbon constraint



BL ('baseline') and GS ('global sustainability') are two scenario sets defined by the DTI. They have the same economic growth rates of 2.25%.

The following are some of the options they discuss, each being shown to be capable of reducing emissions by at least 1GtC per year in fifty years time:

(i) *Improved vehicle fuel economy*. Assuming that in 2054, 2 billion cars are on the road (roughly four times as many as today) and they average 10,000 miles per year (as they do today), one wedge would be achieved if fuel efficiency increased from 30 mpg to 60 mpg. Hybrid vehicles are a step in this direction, to name only one possibility.

(ii) *Energy efficiency in buildings*. Buildings account for about one-third of energy consumption. "Known and established approaches to energy-efficient space heating and cooling, water heating, lighting, and refrigeration in residential and commercial buildings" are capable of producing another wedge, with about "half of potential savings [being] in buildings in developing countries".

(iii) *Substitution of natural gas for coal in power generation*. The authors calculate that a fourfold increase in the use of gas for power generation over the next fifty years if substituted for coal would add up to another wedge.

(iv) *Carbon capture and storage from fossil power plants*. There are several possible routes, the main one being the pre-combustion production of hydrogen and CO_2 (through steam reforming of natural gas and of gas derived from the gasification of coal), separation of the two gases, geological storage of the CO_2, and the use of hydrogen for electricity generation. The CO_2 could be used for enhanced oil or coal bed methane recovery on a low-carbon cycle, an option that has been mooted in the UK for depleted oil fields in the North Sea.

(v) *Carbon capture and storage from hydrogen plants*. A similar process to (iv), with the hydrogen produced being used directly in buildings, industry and for transport fuels instead of large-scale electricity-generating plant.

(vi) *Carbon capture and storage from synfuels plants*. The production of liquid fuels (synfuels) from coal on a large scale is a well-known practice.

(vii) *Nuclear fission to replace fossil power generation*. This is a much discussed option for one or more further wedges.

(viii) *Renewable energy from wind and photovoltaics to replace fossil power generation*—which is capable of at least two more wedges.

(ix) *Biofuels to replace fossil fuels for transport.* The authors estimate that 34 million barrels per day could be produced in an area equal to about 15% of the world's cropland.

(x) *Hydrogen from renewable energy to replace fossil fuels in transport.*

The above studies are what are sometimes termed 'bottom up', in that they rest on detailed engineering analysis of options and what they might contribute to energy supplies and emissions reductions. But 'top down' studies based on macro-economic resource allocation point to similar conclusions.

The Stanford Energy Modelling Forum (Weyant, 2004), for example, has recently led a comparative analysis drawing on the models of eight international modelling groups. The study compares the global energy supply structures projected by the models for the year 2100. Each group was invited to consider (a) a case with no carbon-reduction policies in place; (b) a case in which the object was to limit CO_2 accumulations to 550ppmv. The following options were considered: (1) energy supply technologies including oil, gas, coal, solar, wind, advanced nuclear, hydrogen, biomass and other; (2) demand management technologies for raising energy efficiency; (3) technologies for carbon capture and geological storage from fossil fuels; and (4) biological sequestration. The differences in demand projections were appreciable, ranging from 400 to 1600 Exajoules (EJ) by 2100 as compared with today's demand of 400 EJ. Supply structures were found in all runs that would be capable of meeting the CO_2 accumulations objective. But once again, estimated supply patterns varied kaleidoscopically with assumptions: the estimated contribution of oil to total supply ranged from 3% to 40%; of gas from 6% to 40%; of coal (with carbon capture and storage), from 2% to 28%; of hydro from 1% to 3%; of nuclear power from 0% to 55%; of solar from 1% to 30%; of wind from 1% to 3%; and of biomass from 4% to 25%.

That some studies put more emphasis on nuclear power and others on a range of renewable energy technologies and carbon capture and storage is almost certainly due to differing assumptions as to relative costs and prices over time.[2] Even small differences in cost assumptions switch results markedly in favour of one technology to another. Since the

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[2] Estimates of comparative costs are to be found in ICEPT (2003), DTI (2003b), the World Energy Assessment of the UNDP and World Energy Council (2000), and Anderson (2005).

technologies all are close substitutes for the supply of electricity, heat and power, substitution effects become very large when prices converge.

3.2 Costs: aggregate effect on GDP

Economic output by the energy industries in the UK accounts for approximately 4.1% of GDP, of which 1.6% is from electricity and 2.5% from oil, gas and coal. The share of the energy industries in world product is similarly around 4%, though the figure differs greatly between countries depending on the contribution of the extractive industries to their national products. The share is rising in developing countries, where the per capita income elasticities of demand are still high (around 1.5), and falling in the industrial countries where energy markets are maturing and the per capita income elasticities are low (around 0.5).

These figures suggest why the costs of reducing CO_2 emissions by around 60% by 2050 are mostly in the range <0.0% to 4.5% of GDP, as summarised in Figure 2, having a mean value of 2½%. *First*, while the costs of carbon-neutral energy forms are higher than those of fossil fuels, they are not inordinately higher, and the share of energy costs in GDP is likely to remain low.[3] *Second*, there is appreciable scope for costs to decline with innovation and scale economies as the levels of use of the alternatives expand. *Third*, all studies point to the merits of a gradual transition to carbon-neutral energy forms; among other things this would provide time for the infrastructure to be developed as it is renewed over the coming decades and for the innovations to take root. Under this policy, the unit costs of the alternatives would be high when their contribution to energy supplies is still small, such that the effects on the aggregate costs of energy would also be small, but low when their contribution is large.

In their analysis of why results differ between models, Barker *et al.* (2002) find that important assumptions influencing the results are "the type of model (general equilibrium or econometric); whether a backstop technology is included; whether and how carbon tax revenues are recycled; whether environmental benefits are included; and whether some form of international joint implementation is allowed. The treatment of these assumptions can lead to the mitigation being associated with *increases* in GDP rather than decreases" [our emphasis].

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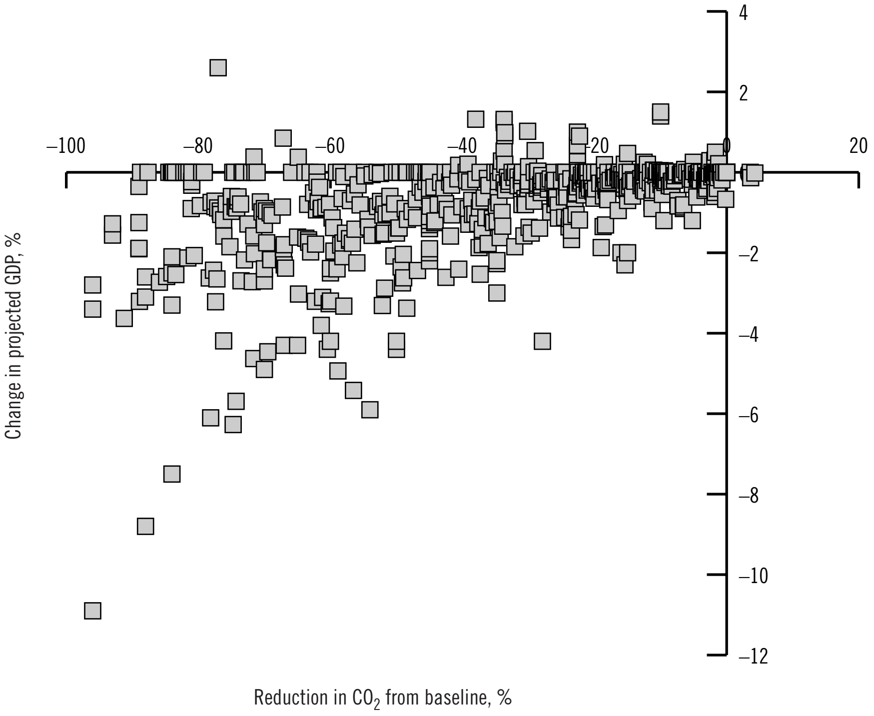
[3] Ibid.

Figure 2: Estimated costs (as % GDP) of reducing CO_2 emissions



Source: Barker *et al.* (2002). The baseline varies between studies in the models surveyed.

But overall, the effect on GDP and its growth of a long-term transition to a low-carbon economy seem likely to be small. The same conclusion was arrived at nearly 15 years ago in the survey by Grubb *et al.* (1993), the results of which are summarised in Table 1 and compared with those reported in the survey by Barker *et al.*

In absolute terms a year's growth is an appreciable commitment of resources. However, with 2% growth, per capita incomes would reach the same level just twelve months later. Such estimates do not allow for other factors such as energy price shocks or for a more sanguine view of the possibilities for innovation, both of which would reduce the estimated net costs of a transition to a low-carbon economy.

Table 1: Estimated % global GDP losses for a 50%–70% long-term reduction of CO_2 emissions: number of studies with estimates in the ranges shown

% Global GDP losses (range)	≤0.0–1.0	1.0–2.0	2.0–3.0	3.0–4.0	4.0–≥5.0	Total	Mean value of losses, % GDP
Barker *et al.* (2002)	3	7	8	3	7	28	2.6
Grubb *et al.* (1993)	3	1	6	1	0	11	2.0
Totals	6	8	14	4	7	39	2.4
US studies reviewed by Grubb *et al.* (1993)	3	2	7	1	2	14	2.5

Note: There are 28 studies in the survey by Barker *et al.* and 11 in that by Grubb *et al.* reporting estimates for the ranges shown. In most studies, the 50%–70% reduction occurs in 50 years' time, and is consistent with larger reductions and the stabilisation of accumulations beyond then.

3.3 Costs: effects on GDP—an exception

There is one exception to the conclusion that the effects on GDP are small. It is that, *if* the transition to a low-carbon economy were to be pushed to extremes over a very short period, then costs would indeed be high. A study by the US EIA (cited by the Administration as a reason for withdrawing from Kyoto) estimated that a 7% cut in CO_2 emissions (relative to 1990) by 2010 implemented over the 4 years 2005 to 2008, would lead to a loss of 4.2% of GDP by 2010, or around $400billion. The key assumptions were:

- a reference case in which US carbon emissions from energy use would rise by 33%, from 1346 million tonnes in 1990 to 1791 million tonnes in 2010 (Emissions have actually risen at 0.9% per year since 1990.)
- a "Kyoto targets" case in which emissions would be reduced by 7% relative to 1990 levels, to 1243 million tonnes in 2010.

Meeting the Kyoto targets would now require the US to cut emissions by 25% relative to what is now projected for 2010, a rate of reduction of 6%–7% per year over the four-year period assumed for the study. This would be five to ten times greater than the UK's already ambitious targets for the period 1997–2010. It would require the premature closing of coalmines and coal-fired stations and many other extraordinary changes in the energy system; and it would allow no time for innovation to reduce costs. No other study so far as we know has considered such an extreme policy when estimating the effects of carbon abatement on economic growth.

The conclusion is that adjustments to a low-carbon economy require a phased approach, in which existing technologies and infrastructures are gradually replaced by low carbon options as they come to the end of their working lifetimes, and in which innovations are not ‘forced through’ to excess when costs are high, but are allowed to develop with research and operating experience.[4]

3.4 Innovation and costs—and the need for a new generation of models

Surveys of energy-supply technologies have shown that costs decline appreciably with innovation. The effects are non-linear, being steepest when technologies are in their early phases of development and use. Estimates of the amount by which costs decline with each doubling of the cumulative volume of production and use (‘learning rates’) are, for example, in the ranges 8%–32% for wind, 18%–30% for solar photovoltaics, 20% for ethanol production, 6% for nuclear power, 35% for electricity production in the OECD from 1926–1970, and 25% for offshore gas pipelines (McDonald and Schrattenholzer, 2001). Technologies with 20% learning rates and whose market shares expand, say, from around 0.05% to 5%, would typically experience a four- to five-fold drop in costs, while mature technologies with the same learning rate would see only a 20% drop if their share doubled from, say, 30% to 60%. From 1900 to 1970, for instance, the costs of electricity supply in the US fell twenty-fold with innovation and scale economies—the thermal efficiencies of power stations alone having increased from under 5% to over 30% in the period, and are currently around 50%–55% for gas-fired power plant. While diminishing returns must eventually limit future cost reductions for the mature technologies based on fossil fuels and nuclear power, engineering studies suggest that significant further cost reductions of, perhaps, up to a factor of two are feasible (Williams, 2000); for the new carbon-neutral technologies,

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[4] Toman *et al.* (1999). Manne and Richels (1995) likewise pointed to the benefits of a flexible approach.

which still occupy very small shares of the market, much larger reductions are feasible, albeit from a higher base.

The attention—or in many cases the lack of it—to innovation in models of the energy system helps to explain some of the dispersion in the estimates of the effects of reducing carbon emissions on economic growth. In their survey, Barker *et al.* (2002) point to three classes of models on which estimates are based:

1. Engineering-based models, which consider a wide range of technologies and practices for energy supply, conversion and use. These models better reflect the possibilities for innovation and generally arrive at the lowest estimates of the costs of mitigation.

2. Econometric models, which have the advantage of representing more realistically the wider economic impact of technical change and of policies—for example, the effects of taxes and prices on technical choice, on public finances, employment, trade, macro-economic stability, and so forth. They also enable alternative instruments of policy to be explored, such as tradable permits versus taxes, the recycling of revenues from environmental taxes, the effects of 'perverse' subsidies on the environment and economic growth. Their two main limitations are that (a) the technological options are represented in a highly simplified and aggregate way, and (b) by being fitted to past data make limited or no use of evidence on the emerging technologies. These models generally arrive at the highest estimates of the costs of mitigation.

3. Computable General Equilibrium models seek to model a least-cost equilibrium allocation of resources in an economy, for a given set of assumptions about resources, technologies and constraints. They generally start from an assumption that current levels of energy consumption reflect optimum behaviour. Because they model equilibria, they do not capture transitional costs, but can be used for very long-term analysis; generally, innovation processes (such as learning-by-doing) are not captured, and long-term technology costs have to be externally specified by assumption.

The direction of research is now to embody the technological insights from engineering-based models into econometric models, to give more economic content to engineering analysis and more engineering content to economic analysis (see Grubler, Nakicenovic and Victor, 1999).

4. New evidence from other national studies

There is presently much national-level activity in emission-abatement modelling, both coordinated under the auspices of international bodies, and undertaken by individual research groups. The present paper does not review all available studies, but looks at a sample to illustrate the range of approaches and findings.

4.1 Western Europe

As part of the EMF–19 model comparison process (Weyant, 2004), ECN Policy Studies in The Netherlands have undertaken analysis of carbon emission abatement using the Western Europe MARKAL[5] model developed by the International Energy Agency (Smekens-Ramirez Morales, 2004). The EU–15 plus Norway, Switzerland and Iceland are modelled, treated as a single region. The simulation is for 2000 to 2100, in 10-year time steps. The model has a database of over 850 technologies and 70 energy demand categories. Carbon storage, both geological and biological (through forestry), is included. The study analysed a number of scenarios, including reference, climate stabilisation (e.g. at 550ppmv), several levels of carbon tax, and sensitivities to restrictions on availability of carbon storage.

In the reference case the share of non-fossil energy declines from an initial share of 25% to 20% in 2050 (nuclear phase out) and then increases to 30% by 2100 (through growth in renewables). For the 550ppmv case, the share increases to 35% by 2050 and 45% by 2100. From 2020 to 2050, use of solid fuels increases (with high efficiency technologies), fossil liquid fuels remain constant, gas use and biomass increase a little, nuclear power, wind and hydro increase, and solar PV enters the mix as a minor component. Over the following 50 years nuclear declines again, fossil liquids decline (as biofuels and hydrogen take over), whilst solids and the full range of renewables increase further.[6]

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[5] MARKAL is an abbreviation for a 'market allocation model'.

[6] A study for France, in contrast, places more emphasis on nuclear power and carbon sequestration. The estimated net costs are not presented but described as low. MIES (2004).

The estimated average welfare costs (economic costs as a % of GDP) of the scenarios range from reductions of 0.19% to 0.8%. The highest figure represents a sensitivity run for the 550ppmv case with 50% higher carbon capture and storage costs assumed. This compares to an estimated 0.7% loss for the standard 550ppmv case.

4.2 China

Chen (in press) has analysed the development of China's carbon emissions to 2050 using a linkage between MARKAL and the macroeconomic model, MACRO. The study is rich in technological detail, with a good representation of advanced fossil technologies (though carbon capture and storage is a noticeable omission), renewable energy, nuclear power and energy efficiency measures.

Since 1980, China's annual economic growth has been around 9.6%, whilst annual growth in energy consumption and carbon emissions has been just 3.8% and 3.6% respectively, due to structural adjustment and energy efficiency gains. The study's reference scenario to 2050 assumes "continuous great efforts on structural adjustment, energy efficiency and energy substitution" which limits emissions growth significantly, with the carbon intensity of GDP decreasing by 3% per year over the period. This reference scenario includes almost all of the 'no-regrets' energy efficiency measures identified for the economy.

The study investigated the costs of a gradual tightening of emissions constraints. For 45% reduction, the estimated GDP is reduced in 2050 by around 1.25% compared to the reference case. The abatement scenario results suggest that nuclear capacity could more than double; without additional nuclear power, the GDP impact is around 70% higher. Five earlier studies for China (see the survey of Grubb *et al.*, 1993) estimated that the reduction in GDP for a 45% reduction in emissions would be in the range 1.1% to 2.5%, and for a 70% reduction 1.3% to 4.5%.

4.3 The US: analyses of the Climate Stewardship Act

The Climate Stewardship Act 2003 was introduced as Senate Bill 139 in January 2003 by Senators McCain and Lieberman. It would require the Administrator of the US Environmental Protection Agency to promulgate regulations to limit greenhouse gas emissions. This Bill has stimulated much debate and lobbying in the US, with several parallel modelling efforts. Some of the results have apparently been influential in the Government's position on Kyoto and climate change generally. The time horizons of the Bill—and thus of the variety of modelling studies of it—are much shorter than for most of the studies discussed in earlier sections of this paper. The Bill is focused on targets for 2015 and 2020, and, as such, comparisons with other analyses looking at 2050 cannot be made directly. However, there is evidence within the various analyses of S.139 which is of value to the broader emissions abatement discussion.

Key features of the bill are:

- a research programme on climate change and related activities
- a national greenhouse gas database and registry of reductions, including the mandatory reporting of emissions by covered entities in the commercial, industrial, and electricity sectors with annual greenhouse gas emissions greater than a threshold level of 10,000 metric tons carbon dioxide equivalent. All petroleum use for transport is covered, with refiners having the responsibility to obtain allowances for emissions related to petroleum sold for transportation use. The residential and agriculture sectors are exempt
- a system of tradable allowances to reduce greenhouse gas emissions among the commercial, industrial, electric power, and transportation sectors.

The programme would go into effect in 2010. In Phase I—2010 through 2015—the number of allowances issued annually is based on the aggregated emissions of the covered sectors in 2000. In Phase II, beginning in 2016, the number of allowances issued is based on 1990 emission levels (and reduced by emissions of non-covered entities in 1990). Little is said about the period post-2020. The Energy Information Administration (EIA) was asked to perform a comprehensive analysis of the bill, for which it used its National Energy Modelling System (NEMS) to analyse US energy markets to 2025 (EIA, 2003).

The study examined several cases: a *Reference Case*, without the Bill; the "S.139 Case", which simulates enactment of the bill; and a series of sensitivity cases, to alternative cost assumptions, no new nuclear stations, no carbon capture and storage, and alternative trading arrangements. Under the S. 139 Case:

- total GHG emissions are at 2000 levels, around one-third below reference scenario levels
- end-use prices typically increase by 27% for gasoline and 46% for electricity by 2025. The average household energy bill (including vehicle fuel) is only 13% higher
- the reduction in GDP compared to the reference case in 2025 is 0.6% (3.02% annual growth from 2001, compared to 3.04%). The impact on GDP, however, depends on auctioning and revenue recycling methods, though is small. As the EIA (2003) conclude: *"This suggests that the uncertainty in growth patterns related to other factors that drive the U.S. economy, such as labor force and productivity growth, are likely to play a larger role than decisions regarding the enactment of S.139 in determining the size of the U.S. economy in 2025."*

This result—which in terms of the estimated effect on economic growth rates, is at the lower end of those summarised in Table 1 above, and similar to the results reported above for the UK—is in stark contrast to that discussed above regarding the estimated costs to the US of implementing the Kyoto Accords, and once again points to the importance of a flexible and phased approach to policy.

Critics of the EIA's analysis[7] are agreed that the details of policy design would have a large effect on costs—e.g., with respect to the possibilities for 'banking' tradable permits, the timing of the emissions constraint, the recycling of revenues from auctions, and the extension of credits for abatement outside the covered sectors, etc. However, they differ in their assessment of costs, since their models vary in their treatment of abatement technology and options, and probably also on the parameters used (they were rather poor in reporting on their assumptions and data). None of the models reviewed could be classed as bottom-up engineering models, and thus the assumptions about abatement options and costs are generally less sanguine about innovation than if a more detailed treatment of technologies were included.

Nevertheless, the estimated impacts on GDP are small: the US EPA have the lowest estimate (0.01% of GDP by 2025), with the sensitivity runs of other models being as high as 1%; the majority of estimates lie in

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[7] ACCF (2004); Charles River Associates (2003); the Pew Centre (2003); and others.

the 0.2% to 0.7% range, which implies very small reductions in the rate of growth of the economy.

5. Summing up and implications for policy

For more than a decade, studies have consistently found that the costs of mitigating climate change would be small in relation to the level of GDP and would not be disruptive to economic growth. The average estimate is around 2½%, or around one year's growth, over a 50-year period when GDP is likely to grow by two or three hundred percent in any economy enjoying economic success. The explanation is that there is already a range of technologies and practices available for reducing greenhouse gas emissions and which are capable of significant further development, both to improve efficiency and reduce costs. It follows that policies to simulate innovation directly will be central to addressing the problems posed by climate change.

The importance of innovation raises new questions for policies at the national and international levels. The case has been made several times:[8]

- by reducing uncertainties about the performance of a technology before it is turned to on a large scale, it generates options for policy
- by reducing costs to future investors and consumers, and by enabling environmental problems to be solved sooner, it has appreciable positive external benefits
- some of the technologies are likely to be beneficial in their own right, even ignoring the climate change problem, as the technology structures identified in the 'reference scenarios' of many studies have shown.

A new focus on innovation would mark a significant departure from the recommendations of economic analysis based on the textbook approach to the cost–benefit analysis of environmental problems. For some years there has been a tension between economists arguing for an almost exclusive focus on carbon taxes, or the alternatives of tradable permits, and a broader body of professional opinion that has argued for incentives to support innovation directly, *as a complement* to carbon taxes or tradable permits. The argument is not simply theoretical. All OECD countries now have

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[8] ICEPT (2001, 2003); Grubler *et al.* (1999); Alic *et al.* (2003); Goulder (2004).

innovation policies of one form or another, as do the rapidly developing regions of China, India and Brazil. At the international level, however, the role of innovation is barely discussed, with most attention focussed on abatement targets. An international initiative to encourage innovation and the adoption of new energy technologies and practices, as the UK Prime Minister himself has recognised,[9] would offer new opportunities for international co-operation based on already strong national policies in many countries.

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