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Submission to the Stern Review on the Economics of Climate Change

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Executive Summary

This submission identifies key findings from recent research undertaken by our two Centres at the University of Cambridge and Imperial College London, both separately and in collaboration, focussing on the importance of technological change for the economics and policy of climate change. Further details of the research and full references to the literature can be found in the papers referred to here.

The main findings may be summarised as follows:

- Any assessment of the costs and benefits of mitigating climate change needs to incorporate technological change as an endogenous part of the global economic system.
- Much technological change is driven by industry in response to energy market conditions and expectations, through knowledge investment and learning by doing.
- These ideas are being incorporated into the latest generation of energy-economy-environment models, through knowledge capital and learning curves in the energy sector.
- Increasing returns to the adoption of technologies through scale, learning, adaptive and network effects (increasing international trade and investment) lead to more general cost reductions and improvements in performance.
- This modelling suggests that additional technological change towards low-carbon technologies induced by market-based policy instruments (permit trading and carbon taxes) reduces the cost of mitigating carbon emissions towards atmospheric stabilisation.
- However, the carbon prices associated with these policies may be high, especially for more stringent stabilisation targets, implying substantial public-sector revenues from auctioned permits and carbon taxes. The welfare and GDP costs can be further reduced if these revenues are used to reduce the tax burden or in some other beneficial way.
- Energy systems modelling incorporating these effects suggests that lowest cost energy futures group around two alternatives: the high-carbon future, based on coal and carbon-intensive resources (including oil shales and tar sands) or the low-carbon future, based on low- and zero-carbon resources. Significant levels of investment will be required to realise either path.
- Meta-analysis of a large number of international modelling studies finds that most models estimate the costs of global GHG mitigation (reducing CO_2 emissions by up to 80% by 2100 relative to baseline) to be in range 0.5 to 4.5% of GDP, with a mean value of 2.5%, or around one year's GDP growth.
- Taken together, these analyses provide strong evidence for policy measures to support the innovation and adoption of low-carbon technologies to facilitate a gradual transition to a low-carbon economy.

1. Introduction

As academic researchers involved in both the UK Energy Research Centre and the Tyndall Centre for Climate Change Research, we welcome both the setting up of this Review on the economics of climate change, and this opportunity to submit written evidence, in addition to other inputs to the Review. The Review comes at an important time in the climate change debate: with the Fourth Assessment Report of the Inter-government Panel on Climate Change (IPCC 4AR), due in 2007, likely to report increasing evidence of the impacts of human-induced climate change; and with political thinking about potential agreements for a post-2012 climate policy regime stimulated by the G8 Gleneagles Summit in 2005.

Nevertheless, in contrast to the increasing scientific consensus, there is still heated debate about the economics of climate change, often reflecting entrenched positions grounded in radically different theoretical bases.[1] In this paper, we provide several lines of argument for the proposition that any assessment of the costs and benefits of mitigating climate change needs to incorporate technological change as an endogenous part of the global economic system. We further argue that many current assessments of the costs and benefits of mitigation must be treated with extreme caution because they either fail to endogenise technological change or do so in a very limited and stylised way.

From an economic and policy perspective, climate change is complex because it is a long-term global social choice problem with two interacting market failures (the carbon externality, where the social costs of carbon emissions are not borne by the polluters, and the innovation externality, where the full benefits from investment and learning-by-doing are not captured by the innovator), in which both the impacts and the mitigation options are uncertain. Nevertheless, over the past 7 years, progress has been made in the literature on endogenous and induced technological change and climate policies. In this paper, we set out recent economic thinking on assessing the implications of endogenous technological change for the costs of climate change mitigation and on clarifying the resulting policy implications.

Although we argue that technological change is fundamental to addressing climate change mitigation, this is not to deny that there may also be a need for radical behavioural changes, such as reducing the growth in air travel, and for adaptation measures, which are addressed in detail in a submission by Neil Adger and other colleagues from the Tyndall Centre.

Section 2 of the paper explains why endogenous technological change (ETC) matters in assessing the costs and benefits of mitigating climate change. Section 3 sets out the evidence of the impacts of ETC on mitigation costs and economic growth from macro-economic modelling. Section 4 sets out the evidence of the impacts of ETC on mitigation costs and economic growth from energy systems modelling. Section 5 examines long-term technological change and its implications for economic growth. Section 6 looks at arguments suggesting that increasing returns to the adoption of technologies and supporting institutions have led to the 'lock-in' of global carbon-based energy systems. In the final section, we address the policy implications of our arguments.

[1] See DeCanio (2003) for a critique of the assumptions employed in most economic models of climate change.

2. The importance of endogenous technological change

Most assessments of the costs and benefits of mitigating climate change use one of a number of types of energy, economy and environment (E3) models. Until very recently, most such models made exogenous assumptions about the rate of technological change. This may be reasonable for short to medium term projections, as in the effects of Kyoto to 2012, when the effects of such change, especially changes involving whole systems, are likely to be small. However, it is highly questionable when models are used for very long term projections that run 100 years and sometimes 400 years into the future. Drawing on Grubb, Köhler and Anderson (2002) and Alic *et al*. (2003), we argue that this represents an incomplete economic analysis and is a fundamental weakness of such long-term models. In the following sections, we present evidence from more recent macroeconomic and energy systems modelling which incorporates endogenous technological change (ETC) and so produces radically different estimates of costs and benefits of mitigation.

As described by Grubb et al. (2002)[2], the wide and extensive literature on technological change recognises that it is not an autonomous process, but occurs as a result of identifiable economic processes, such as public and private research and development, corporate technology investment and increasing returns effects (see Foxon (2003) for a review of the innovation literature, applied to low-carbon technologies). Much technical[3] change is led by the private sector, in response to government policies, market conditions, investment, and expectations. Hence, the rate and direction of technological change is endogenous to economic systems, and its representation in E3 modelling is likely to have important implications for preferred environmental and innovation policy recommendations for mitigating climate change. As pointed out by Pearce (2002), this also has important implications for economic growth. Growth models incorporating endogenous technological change imply that "deliberate policy enters the picture – long-run growth rates would appear to be able to be influenced by public policy. It is this policy implication that is perhaps the most important differentiating factor between exogenous and endogenous growth models" (Pearce, 2002, p.20).

The importance of technological progress in contributing to significant levels of abatement for a range of air and water pollutants, and to dramatically reducing the costs of such pollution abatement has been well documented (see Anderson and Cavendish (2001) for a review). The range of technological options available to address climate change, including renewable energy technologies, nuclear power, carbon capture and storage, energy efficiency measures for buildings, appliances and vehicles, and hydrogen and fuel cell technologies, and an assessment of their current status and potential was provided in a recent ICEPT report to the Prime Minister's Strategy Unit (ICEPT, 2002). A similar identification of a range of technological options that could each reduce global carbon emissions by 1 GtC over the next 50 years – so-called 'stabilization wedges' – is provided by Pacala and Socolow (2005). The point we wish to make here is that there is no 'magic bullet' and a number of different technological options are likely to be required to meet demands for energy and transport

[2] Note that the paper by Grubb et al. (2002) refers to 'induced technical change' as that influenced over time by energy market conditions and expectations, and 'endogenous technical change' when such change is incorporated into economic modelling. More recent literature, e.g. Goulder (2004); Kohler et al. (2006), uses 'induced technical change' to refer specifically to technical change induced by policy. In order to avoid confusion, we follow the latter definition of 'induced technical change', and take 'endogenous technical change' to refer to that influenced over time by energy market conditions and expectations.
[3] The terms "technical" and "technological" are often used interchangeably in the literature.

(mobility) services, depending on local conditions. Hence, a representation of the economic forces underlying their innovation and diffusion is essential for any estimation of mitigation costs and benefits.

An academic review for the U.S. Pew Center on Global Climate Change (Alic *et al.*, 2003) also emphasises the importance of technology and innovation policies for addressing climate change. Drawing on a large body of literature in economics and other fields concerning the innovation process, they conclude:

- *Technological innovation is a complex process involving invention, development, adoption, learning and diffusion of technology into the marketplace*. The process is highly iterative, and different policies influence outcomes at different stages.
- *Gains from new technologies are realised only with widespread adoption, a process that takes considerable time and typically depends on a lengthy sequence of incremental improvements that enhance performance and costs.*
- *Technological learning is the essential step that paces adoption and diffusion*, through 'learning-by-doing' and 'learning-by-using'.
- *Technological innovation is a highly uncertain process*.

Alic *et al*. (2003) conclude that these factors have special salience because of the long time horizon of the climate change issue, and that technology policies and regulatory policies should leave 'space' for continuing technological improvements based on future learning. (We discuss policy implications of these ideas in more detail in Section 6 of this paper.)

Grubb *et al.* (2002) show that the key characteristic of endogenous technological change in climate-policy analysis is that it occurs in response to energy market conditions and expectations. Hence, technological development is primarily influenced by demand side factors – principally, prices and markets, and expectations of these, in response to varied factors including government policies. This emphasises ongoing innovation and development of applied technologies undertaken largely by the private sector, in addition to earlier stage research and development (R&D), which is often publicly supported for well-known economic reasons. (Private firms tend to under-invest in R&D because they can not appropriate the full benefits of that investment, since advances in knowledge 'spill over' to other firms and consumers.) Hence, commercial technologies do not appear as 'manna from heaven', but require considerable development effort, much of it by industry and dependent on market conditions and expectations. This usually comprises two factors:

- *Knowledge investment* – activities such as research, development, demonstration and testing that are directed primarily at generating options and improving technologies;
- *Learning by doing* – performance improvements and cost reductions which occur as result of market investment in the commercialisation of a technology (Arrow, 1962).

However, until very recently, most energy-environment-economy (E3) modelling has treated technological change as exogenous to the economic system, typically through the assumption of an autonomous energy efficiency improvement (AEEI) factor. Such models, e.g. DICE (Nordhaus, 1994), typically conclude that it is more cost effective to wait for technological improvements to occur rather than create incentives for early investment. This ignores the fact that such investment depends on market conditions and expectations, including those induced by policy. Indeed, for most emerging low-carbon technologies, policy is currently the principal driver of market growth.

In the following sections, we discuss how macro-economic and energy systems modelling that incorporates endogenous technological change reach radically different conclusions regarding the costs of climate change mitigation compared to the ‘traditional’ exogenous approaches.

3. Evidence from macro-economic modelling incorporating endogenous technological change

This Section draws on findings from the International Model Comparison Project (IMCP), which investigated the implications of the incorporation of endogenous technological change (ETC) and consequent (policy-) induced technological change (ITC) on estimates of climate change mitigation. These findings are reported in a Special Issue of the Energy Journal to appear in 2006 (Köhler *et al*., 2006; Edenhofer *et al*., 2006).

The IMCP compared the results of running the same set of scenarios (as far as possible) on a range of different economy-energy-environment models incorporating ETC, including:

(1) General equilibrium (CGE) market models which balance demand and supply among multiple actors;
(2) Endogenous Growth Integrated Assessment Models maximising social welfare in an inter-temporal optimisation;
(3) Simulation and Econometric models which solve initial value or boundary condition problems;
(4) Energy System Models that minimise costs in the energy sector.

A major feature of the latest generation of models, compared with previous generations, is that they incorporate increasing returns through one or both of two main concepts: knowledge capital and learning curves. These incorporate a common theme: technological change, both technical progress and the diffusion of new technologies, is driven by the development of knowledge capital and its particular economic characteristics of being partly non-rival and partly non-excludable (Köhler *et al*., 2006).

The models were all run for scenarios stabilising atmospheric CO_2 concentrations at levels of 450 ppm, 500 ppm and 550 ppm, respectively, both with and without additional policy-induced technological change. Findings from this comparison between 'with' and 'without' induced technological change (ITC) concluded that climate policy does induce additional technological change, in some models to a substantial extent. Its effect is a reduction of costs of abatement for stabilisation, unanimously in all participating models. However, the size of the cost reduction depends on the flexibility of investment decisions and the range of relevant mitigation options incorporated in the models. All models indicate that real carbon prices for stabilisation targets rise with time in the early years, with some models showing a decline in the carbon price after 2050 due to accumulated effects of learning-by-doing and positive spillovers on economic growth.

Edenhofer at al (2006) conclude that the results for effects of ITC depend on:

1) baseline effects: assumptions about the role of technology can lead to relatively low costs of mitigation;
2) the assumption of full employment of resources: if the economy is already assumed to be at an optimum, mitigation policies must be costly; any policy-induced change, such as more low-carbon R&D or more investment in low-carbon energy, must be at the expense of other R&D or other investment;
3) how the investment decision is modeled: leading to significant effects in growth and energy-system models;
4) the modeling of the backstop technology: this can substantially affect the results, e.g. if investment in the technology is endogenous and exhibits learning by doing, then costs can fall dramatically.

They also assess the relation between model type and estimated costs of mitigation. They find that CGE models tend to calculate higher costs than energy-system or growth models, but the reason is not necessarily the model type, but the assumptions each group of modelers tend to make e.g. about foresight. Energy-system models include energy costs; but they usually omit macroeconomic feedback and hence macroeconomic costs and benefits. They omit most rebound effects and any crowding out of investment. CGE models often reduce the flexibility of investment substantially compared to growth-model treatments.

One of the model results included in the project was that of the Cambridge E3MG model (coupled to the simple climate model MAGICC), which was also presented at the 2005 Exeter Conference and in the resulting Proceedings (Barker et al., 2005). This is a macro-economic model in which economic growth is demand-led and supply-constrained, and incorporates panel-data analysis of the global energy systems 1970-2001 using formal econometric techniques. In this model, climate policies lead to higher productive investment, which leads to higher output and growth in the short-term, which, in turn, leads to higher long-term growth by raising the productive potential of the global economy. As an illustrative and stylised exercise, this model was used to investigate the costs of meeting the above CO_2 stabilisation targets, with emissions modelled to 2100, and applied two global policy instruments from 2011: emission trading permits for the energy industries and carbon taxes for the rest of the economy, with the revenues recycled to maintain fiscal neutrality. Extra investment is induced by the permit schemes and taxes since they lead to substantial increases in the real cost of burning fossil fuels, according to their carbon content. The ensuing world-wide wave of extra investment in low-carbon technologies to 2100 raises the rate of economic growth. This gives rise to a small net economic benefit for climate stabilisation.

Some U.S. economists have also recently accepted the importance of induced technological change (ITC) for the effective design of climate policy. Goulder (2004) reviewed the literature and concluded that climate policy can alter the future by influencing the rate and direction of technological change. Specifically, he found that:

(1) *The presence of ITC lowers the costs of achieving emissions reductions*. Models that disregard policy-induced technological advances will tend to overestimate costs.
(2) *The presence of ITC justifies more extensive reductions in GHGs than would otherwise be called for*. The net benefits from climate policy are larger.
(3) *The presence of ITC alters the optimal timing of emissions abatement*. Analysis by Goulder and Mathai (2000) suggests that, insofar as technological change results from R&D, the presence of ITC justifies somewhat less abatement in the near-term and more abatement in the future, whereas, if technological change primarily results from learning-by-doing, greater abatement may be justified in the short-term, since early abatement efforts accelerate the learning process and can thereby lower costs.
(4) *In the presence of ITC, announcing climate policies in advance can reduce policy costs.*
(5) *Economic analysis offers a justification for public policies to induce technological change, even when the returns are highly uncertain*. A strong rationale for public policy to stimulate ITC is provided by the interaction of innovation and environmental market failures: (1) the “spillover benefits” to society as a result of R&D investments by individual firms and (2) the presence of negative externalities – adverse impacts that are not accounted for in the market price of carbon based fuels.
(6) *To promote ITC and reduce GHG emissions most cost-effectively, two types of policies are required: policies to reduce emissions (such as carbon caps or carbon taxes) and incentives for technological innovation*.

4. Evidence from energy systems modelling incorporating endogenous technological change

This Section discusses evidence from bottom-up energy systems modelling, which typically explicitly incorporate a wider range of technology options, and endogenise technological change through the incorporation of learning curves for the reduction of costs of technology with adoption of that technology (IEA, 2000; Macdonald and Schrattenholzer, 2003).

An important early study was undertaken by Gritsevskyi and Nakicenovic (2000), building on several years of work at the International Institute for Applied Systems Analysis (IIASA) in Austria. They used a version of the MESSAGE energy systems-engineering model, incorporating a very wide range of energy technologies and resources, coupled with learning-by-doing, and learning spillover effects due to technology clusters. The model was run stochastically under widely defined uncertainties in the inputs to generate 130,000 scenarios (with 520 clusters of technological dynamics) for global energy systems to 2100, which spanned a huge range of CO_2 emissions and costs. They then selected the over 13,000 least-cost scenarios (with 53 clusters of dynamics) (see Fig. 1). These were found to be grouped around a set of low-carbon scenarios (global emissions of 8-13 GtC/yr in 2100) and a set of high carbon scenarios (global emissions of 15-26 GtC/yr in 2100).

Hence there may be two possible broad directions for innovation in global energy systems, for which the costs are indistinguishable within the range of uncertainties, and either of which might prove to be the least cost path as conventional hydrocarbon resources become scarce:

- the high-carbon future based mostly around coal-based and carbon-intensive resources (including oil shales and tar sands). or
- the low-carbon future, based on low- and zero-carbon resources (methane and hydrogen utilised with distributed technologies including fuel cells, and with major roles for renewable energy and/or nuclear as primary sources for electricity generation, together with carbon capture and storage for fossil fuel sources).

Grubb (2001) shows that significant levels of investment will be required to realise *either* path: the high-carbon scenarios involve extensive investment and learning in the high-carbon frontier of unconventional heavy carbon deposits and conversion technologies; the low-carbon scenarios contrast this by investing and learning primarily in developing the range of low-carbon technologies.

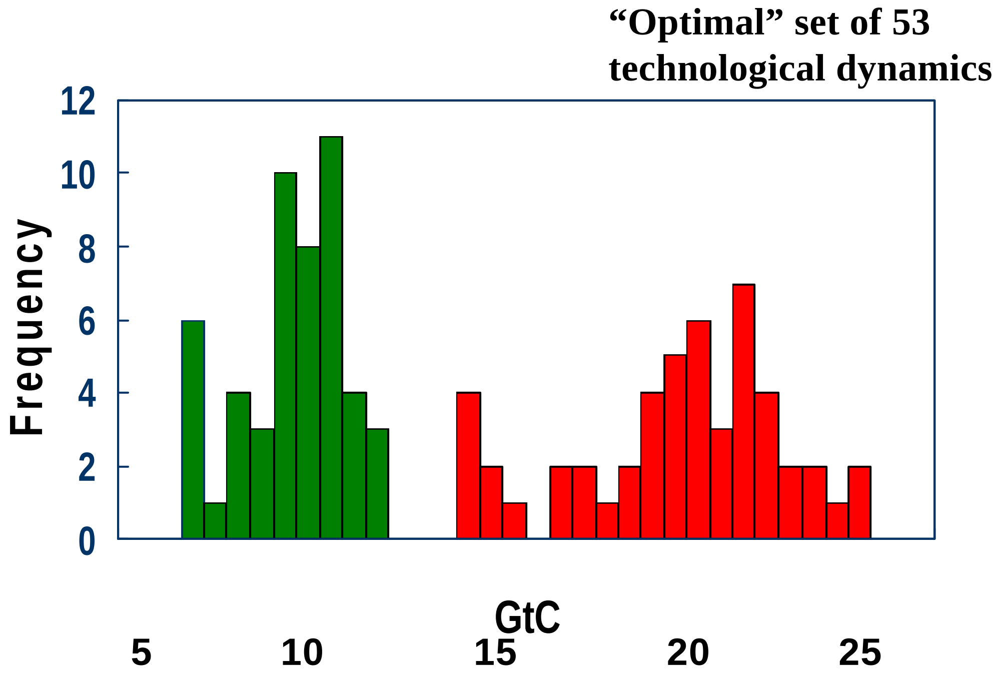


Fig.1. CO2 emissions in 2100 for set of least-cost technology mixes (Source: Gritsevskyi and Nakicenovic, 2000)
Note: Each bar represents the percentage frequency in ranges covering over 13,000 'optimal' scenarios from 53 different technological dynamics, in yielding the 2100 outcome for emissions. All the bars add to 100%.

Modelling undertaken[4] for the 2003 UK Energy White Paper used a bottom-up energy systems model, MARKAL, to analyse scenarios for the UK achieving a 60% reduction in CO_2 emissions by 2050 (DTI, 2003). This uses a linear programming algorithm to identify the 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. 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 technologies, hydrogen and end-use energy efficiency. Sensitivity analysis was performed in relation to costs, uptake and availability of different options.

The modelling showed that deep cuts in carbon emissions are technically and economically feasible over the long term, including in scenarios with and without nuclear generation and with and without carbon capture and storage. When both these options were constrained to be unavailable, the discounted system costs rose significantly (by 250%). The results indicate

[4] This was undertaken by Future Energy Solutions and Imperial College Centre for Energy Policy and Technology (ICEPT)

that energy efficiency will be a cornerstone of cost effective emissions abatement, and that there will also be a key role for low-carbon electricity generation and (towards the end of the 50 year period) hydrogen vehicles. The challenges to achieve this will be significant: to develop the technologies further and reduce costs; to transform the energy supply infrastructure in ways compatible with the use of low-carbon technologies; to develop R&D capacity and the policies for demonstration and commercialisation of new technologies; and to invest in the education and training of engineers and skilled labour.

The model was also used to estimate the costs of achieving the 60% abatement target, through a *measured* transition to a low-carbon economy in the UK over the next 50 years. Annual abatement costs by 2050 were found to range from £7 bn to £42 bn per year, equivalent to 0.3% to 2% of projected GDP in 2050, or less than one year's GDP growth over the 50 year period (Leach et al., 2005; Anderson and Leach, 2005).

A meta-analysis of a large number of international modelling studies was undertaken by Barker et al. (2002), including the post-SRES scenarios for different levels of stabilization of atmospheric CO_2 concentrations using models involved in the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al.*, 2000; Morita *et al.*, 2000). The distribution of estimated costs (as % GDP) for these stabilization scenarios against the reduction in CO_2 emissions from baseline is shown in Figure 2.

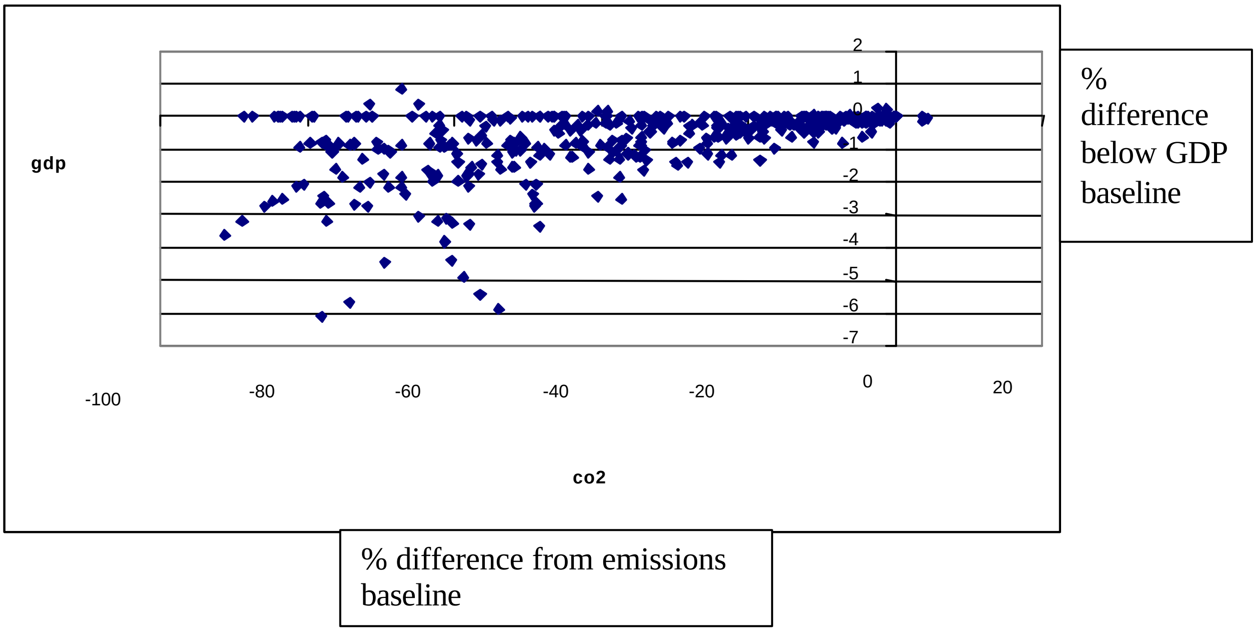


Fig. 2. Cost against emissions reduction for stabilization scenarios based on 6 SRES baseline scenarios (Source: Barker *et al.*, 2002)

The meta-analysis concluded that most of the variation between the model findings could be explained in terms of the different theoretical and structural assumptions incorporated into the models and the assumptions about policy and technology scenarios. Specifically, the results regarding GDP costs of mitigating climate change depend on: the type of model (computable general equilibrium or macroeconomic); whether a non-carbon backstop technology is included; whether and how carbon tax revenues are recycled; whether ancillary environmental benefits are included; and whether some form of international joint implementation (JI) is allowed. The treatment of these assumptions could lead to the mitigation being associated with increases in GDP rather than decreases (Barker *et al*., 2002).

Fig. 2 shows that costs of mitigation towards stabilising atmospheric CO_2 concentrations (reducing CO_2 emissions by up to 80% by 2100 relative to baseline) are mostly in the range 0.5 to 4.5% of GDP, with a mean value of 2.5%. It is argued that the costs of even such a significant transition in global energy systems remain a relatively small proportion of GDP due to three main factors (Leach et al., 2005; Anderson and Leach, 2005). Firstly, while the costs of low-carbon energy forms are higher than those of fossil fuels, they are not inordinately higher. Secondly, there is appreciable scope for costs to decline with innovation and scale economies as the levels of use of the alternatives expand. Thirdly, all studies point to the merits of a *gradual transition* to low or zero carbon energy forms, to provide time for infrastructure to be developed and for the innovations to take root.

In addition, as Barker and Ekins (2004) point out, most modelling studies to date have not included ancillary benefits of climate change policies, such as reduction of other forms of pollution, health benefits and achievement of more secure energy supplies. They argue that if ancillary benefits, revenue recycling and the use of the Kyoto flexible mechanisms (emissions tradings, JI and CDM) are included, then the macroeconomic costs of achieving greenhouse gas mitigation targets of the scale in the Kyoto Protocol are likely to be small for the U.S. and other Annex 1 countries - provided that the policies are expected to continue indefinitely, are long-term (to allow time for adjustment) and well-designed. However, there may be large transition costs for some industrial sectors, such as coal, which will hence be likely to resist change.

The current generation of macro-economic and energy systems modelling provides important insights, but further work is needed. It would be beneficial to undertake a meta-analysis of the estimates of the costs of mitigation in the latest generation of models which incorporate endogenous and induced technological change. The next generation of models should seek to bring together the macro-economic analysis of top-down energy-environment-economy models with the technological richness of bottom-up energy systems modelling. Work in this direction will be undertaken over the next four years under the UK Energy Research Centre's Energy Systems and Modelling Theme.

5. Understanding long-term technological change and its implications for economic growth

It is clear from the study of economic growth over past centuries that technological change is closely associated with growth. Looking back over the last 200 years, the global economic system has been transformed by industrialization, a process that appears to be at its most dynamic in the current generation. World GDP began growing as the industrial revolution based on coal, iron and water transport developed in the 18th century (Maddison, 2001). As technologies diffused and the extent of the markets widened through trade, the world economy began a period of sustained but uneven long-term growth, which accelerated in the mid- and then the late 20th century. The system is being transformed at a rate unprecedented in the historical record, led and enabled by the exploitation of technology, migration of labour from traditional to modern sectors in developing countries, and international trade. The global economy seems to be characterized by ongoing fundamental change, rather than convergence to any steady state.

Long-run growth and structural change through socio-technical systems are described by Freeman and Louçã (2001). They argue that we are currently near the beginning of a new wave of change characterised by information, bio- and nano- technologies. Development and adoption of these technologies will have major impacts on input structure and resource efficiency throughout the global economy, and will be characterised by significant levels of investment.

Maddison (2001) finds growth rates to be very different across groups of countries and over time, and ascribes the comparatively high rates of growth to technological progress and diffusion. He argues that the increase in growth rates that emerged in Europe since 1500, and that became endemic from 1820, were founded on innovations in banking and accounting, transport and military equipment, scientific thinking and engineering. He also finds that inequalities between nations in per capita GDP have increased (in particular since WW2), not diminished over time. Technological progress associated with investment is intimately related to Denison's (1967, 1985) causal factors (capital, economies of scale and knowledge) accounting for 57% of growth. More recently, Wolff (1994a, 1994b) has found strong correlations between investment embodying technological change and growth in OECD economies.

Tooze (2006) has linked Maddison's GDP data with WRI (2005) CO2 emissions data as shown in Figures 3 and.4. The burning of fossil fuels in all their forms - coal, oil, gas - has been since the 17th century a major technological driver and facilitator of economic growth in industry, transport and agriculture (through the use of artificial fertilizers). The combustion generates both local pollution and increasing concentrations of CO2 in the global atmosphere. Figure 3 shows how the trends in the carbon intensity of GDP have changed dramatically in the 20th century, as economic growth is increasingly separated from CO2 emissions through the switch in supply to low-carbon energy, especially natural gas, and the switch in demand to low-carbon services. The two notable breaks in the series are associated with the rising in oil prices in the 1970s and the collapse of the Soviet Union in 1989-90. In the long-term context, the question is whether this falling trend will continue through the next century. Figure 4 shows CO2 emissions in relation to global GDP.

The evolution of energy use and its influences in the United Kingdom over the very long run (several centuries) has also been analysed (Fouquet and Pearson, 1998, 2003, 2006). They argue that the provision of energy services, mainly heat and power, is bound by the tensions between a changing growth rate and structure of economic activity and the constraints of energetic resources. After periods of tension, energy price differentials, as well as the diffusion of technological innovation and the development of new fuels, led to new mixes of energy sources to supply heat and power. Three major changes that characterise the history of United Kingdom energy use have been identified: first, the dramatic increase in per capita energy use; second, the shift in methods of supplying energy services, from biomass sources to fossil fuels, from coal to petroleum to natural gas, and from raw forms to more value-added energy sources; and, third, the replacing of direct methods of generating power, from animate sources, wind and water, by the use of mechanical and electrical methods, which have so far depended mainly on fossil fuels. These changes were instrumental in influencing the relationship between GDP and energy use, and also the levels of environmental pollution.

Evidence also suggests that major energy system transitions can take considerable time, often decades, to mature. For example, in the UK it took about 40 years from the invention of incandescent lighting in the late 1870s for it to become economically competitive with gas lighting (Pearson and Fouquet, 2006).[5] Such time lags suggest the value of early stimulation of innovation and of creating the conditions in which innovations can more easily penetrate and grow. Work on energy services also illustrates the extraordinary reductions in their costs – and corresponding increases in economic welfare – that can result from innovation in energy technologies: e.g. by the year 2000, the marginal cost of lighting services in the UK fell to less than one three-thousandth of what it had been in 1800, mainly through advances in the conversion of energy into light (Pearson and Fouquet, 2006).

[5] See also Crafts (2004) on the impact of steam on British productivity growth in the second half of the 19th century and after.

Figure 3*: Carbon Intensity of the Global Economy: Units of CO2 per $ Global GDP*
Source: Tooze (2006)

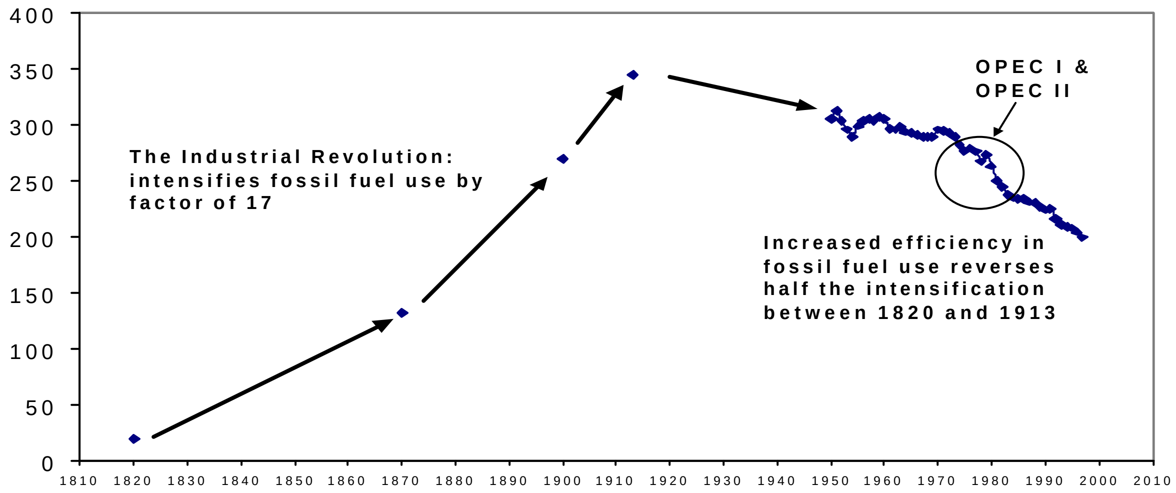
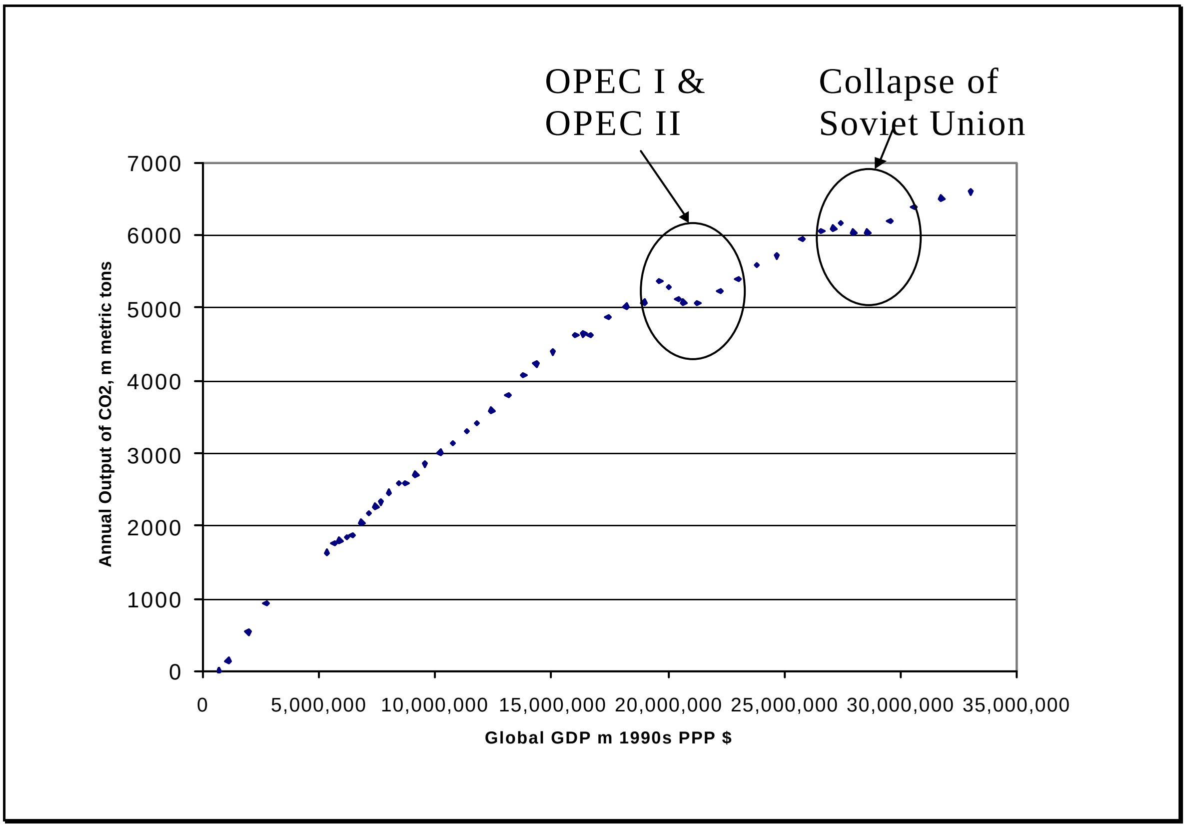


Figure 11.3.4*: CO2 emisions and GDP*
Source: Tooze (2006)



6. Increasing returns and technological lock-in

The above findings from the incorporation of endogenous technological change into energy-environment-economics modeling are supported by other analyses of the implications of increasing returns on technological change and innovation (see Foxon, 2003, 2006). These argue that the successful innovation and take up of a new technology depends on the path of its development - so-called 'path dependency' (David, 1985), including the particular characteristics of initial markets, the institutional and regulatory factors governing its introduction and the expectations of consumers. Arthur (1989) modelled increasing returns to adoption, i.e. positive feedbacks which mean that the more a technology is adopted, the more likely it is to be further adopted, and showed that these can lead to 'lock-in' of incumbent technologies, preventing the take up of potentially superior alternatives.

Arthur (1994) identified four major classes of increasing returns: *scale economies*, *learning effects*, *adaptive expectations* and *network economies*. The first of these, *scale economies*, occurs when unit costs decline with increasing output. For example, when a technology has large set-up or fixed costs because of indivisibilities, unit production costs decline as they are spread over increasing production volume. Thus, an existing technology often has significant 'sunk costs' from earlier investments, and so, if these are still yielding benefits, incentives to invest in alternative technologies to garner these benefits will be diminished. *Learning effects* act to improve products or reduce their cost as specialised skills and knowledge accumulate through production and market experience. This idea was first formulated as 'learning-by-doing' (Arrow, 1962), and learning curves have been empirically demonstrated for a number of technologies, showing unit costs declining with cumulative production (IEA, 2000). *Adaptive expectations* arise as increasing adoption reduces uncertainty and both users and producers become increasingly confident about quality, performance and longevity of the current technology. This means that there may a lack of 'market pull' for alternatives. *Network* or *co-ordination effects* occur when advantages accrue to agents adopting the same technologies as others. Similarly, infrastructures develop based on the attributes of existing technologies, creating a barrier to the adoption of alternative technologies with different attributes.

North (1990) argued that all the features identified by Arthur as creating increasing returns to the adoption of technologies can also be applied to institutions, i.e. social rule systems. New institutions often entail *high set-up or fixed costs*. There are significant *learning effects* for organisations that arise because of the opportunities provided by the institutional framework. There are *co-ordination effects*, directly via contracts with other organisations and indirectly by induced investment, and through the informal constraints generated. *Adaptive expectations* occur because increased prevalence of contracting based on a specific institutional framework reduces uncertainty about the continuation of that framework. In summary, he argued that "the interdependent web of an institutional matrix produces massive increasing returns" (North, 1990, p. 95).

Unruh (2000, 2002) has argued that the global carbon-based energy system has undergone a process of technological and institutional co-evolution, driven by path-dependent increasing returns to adoption, leading to a state of 'carbon lock-in' of fossil fuel based technologies and supporting institutions. This creates technological and institutional barriers preventing the development and take-up of alternative technologies, such as low-carbon energy sources.

7. Policy implications

The evidence summarised above indicates that the costs of achieving even high levels of greenhouse gas mitigation and ultimately stabilisation of atmospheric GHG concentrations may be modest in terms of percentage of GDP (and could even give rise to net benefits) when the effects of technological change are taken into account. However, the findings also suggest that projections of 'business-as-usual' frameworks or even the incremental policy measures currently being employed are unlikely to create the necessary incentives to achieve significant mitigation and atmospheric stabilisation. In a briefing paper for policy-makers summarising the findings of our joint Tyndall Centre project (Köhler et al., 2005), we argue that there is a need for policies for innovation and investment to initiate a transition to a low-carbon global economy and society, in addition to the economic instruments of taxation and emissions trading systems or regulations and standards.

As the analysis by Grubb (2001) showed, based on the IIASA model findings, significant levels of investment in energy systems will be needed to meet growing global energy demands under any plausible scenario. Currently, high levels of investment are going in to the continuation of the existing high carbon fossil fuel dominated energy path, including the development of new carbon-intensive resources, such as oil shales and tar sands. However, the findings suggest that the alternative low-carbon energy path could be achieved at little or no higher cost to the global economy, provided that significant levels of investment are diverted towards the range of low-carbon technologies which are available. Hence, the key policy question is how to incentivise such a switch towards investment in low-carbon technologies, in ways that will stimulate innovation and reduce costs through the wider deployment of these technologies.

Global energy systems are characterised by large stocks of assets, so large scale changes will require large investments in new assets over a long period of time – in infrastructures, supply technologies and end-use technologies and systems. In particular, building stocks and transport systems both have long lifetimes. Hence, there is a role for policy to provide a long-term orientation and clear signals to facilitate a gradual transition towards low-carbon energy and transport systems. One example of how this may be done in practice is the 'energy transition' programme currently being implemented in the Netherlands by the Ministry of Economic Affairs (2004). This involves public and private actors working together to agree long and medium-term priorities and strategic goals, together with transition paths setting out broad directions for change, and initial demonstration projects or experiments along these paths, with learning by doing as to which are successful and practical. Thus, the government is not choosing specific options, but supporting clusters of options, whilst giving market players the opportunity to develop their own products based on their own market analysis, ambitions and entrepreneurship. Some guiding principles for policy frameworks, strategies and processes that support technological and institutional innovation in ways that promote economic, environmental and social sustainability, drawing on these transition ideas and wider innovation systems thinking are set out in a recent report for policy-makers (Foxon *et al*., 2005).

This type of macro-level argument is supported by more micro-economic arguments for innovation policies (Anderson *et al.*, 2001; Gross and Foxon, 2003; Alic *et al.*, 2003, Anderson and Leach, 2005). This case has three main elements:

- Creating options or bringing them forward in time improves the flexibility of policy, which studies agree is key both to reducing costs and to winning public acceptance.

- Reducing uncertainties about the performance of a technology before it is implemented on a large scale increases the *option value* of a policy, i.e. there is a positive economic value to creating options when faced with radical uncertainties;
- Reducing costs to future investors and consumers, and enabling environmental problems to be solved sooner has appreciable positive external benefits.

This focus on environmental innovation policies recognises that there is an interaction between the environmental externality (that the negative social costs of carbon emissions are not borne by the polluters) and the innovation externality (the positive spillover benefits from investment and learning-by-doing), which is neglected in traditional economic cost-benefit analyses. This suggests that incentives are needed to support low-carbon innovation directly, as a complement to carbon taxes or emissions trading schemes, which aim to internalise the carbon externality.

However, both analytical and modelling studies (Anderson and Winne, 2004) suggest that these policies need to be long-term and persistent to generate the clear signals and expectation levels for significant investment. Only relatively small amounts of public expenditure are likely to be needed, though, to support innovation at the early R&D and demonstration stages (to get over the so-called ‘valley of death’ at which many promising technologies fail to make the leap to successful commercialisation). How these ideas may applied to overcoming barriers and ‘systems failures’ to promote innovation in long term renewable energy technology options is discussed in Foxon et al. (2003).

All OECD countries now have innovation policies of one form or another, as do the rapidly developing regions of China, India and Brazil. An international incentive to encourage innovation and adoption of new energy technologies and practices[6] would offer new opportunities for international co-operation based on already strong national policies in many countries (Anderson and Leach, 2005).

[6] As suggested in the Prime Minister’s speech of 14 September 2004.

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