# Technology Policy and the Environment

SUSTAINABLE DEVELOPMENT

OECD

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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# FOREWORD

A Workshop on Technology Policy and the Environment was held in Paris on 21 June 2001 as part of the OECD Horizontal Programme on Sustainable Development. Its aim was to explore the role of technology and technology policy in addressing environmental concerns and to develop proposals for future OECD analytical and policy work in this area. It was chaired by OECD Deputy Secretary-General Thorvald Moe, who is also responsible for the co-ordination of the OECD Horizontal Programme on Sustainable Development.

This brochure contains a summary of the workshop discussions, which focused on the contributions of economic theory and modelling to understanding technology/environment relationships. Participants debated the role and design of technology policy in addressing environmental problems and developed a list of recommendations for future OECD work. Two technical papers prepared as background material are also included. The workshop agenda is attached as an annex. The insights gained at the workshop will contribute to furthering OECD work on sustainable development and to the formulation of proposals for future work.

This brochure is published on the responsibility of the Secretary-General of the OECD.

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# WORKSHOP SUMMARY

## Introduction

In opening the workshop, OECD Deputy Secretary-General Thorvald Moe explained the goals of the OECD Horizontal Programme on Sustainable Development and the relevance of the technology-related issues to be discussed. In May 1998, OECD Ministers agreed "that the achievement of sustainable development is a key priority for OECD countries. They encouraged the elaboration of a strategy … in the areas of climate change, technological development, sustainability indicators, and the environmental impact of subsidies." A report, including policy recommendations, was issued in 2001. That report, based on work completed by the OECD and its affiliated organisations over a three-year period, contains the following recommendations with regard to technology (OECD, 2001a):

> "Scientific progress and technological development are major forces underlying improvements in productivity and living standards. New technologies offer considerable promise for decoupling economic growth from long-term environmental degradation. But there is no guarantee that innovations will appear when and where they are most needed, or at a price that reflects all environmental and social externalities associated with their deployment. Governments need to create a policy environment that provides the right signals to innovators and users of technology processes, both domestically and internationally; to fund basic research; and to support private initiatives in an appropriate manner:

- "Provide permanent incentives to innovate and diffuse technologies that support sustainable development objectives by expanding the use of market-based approaches in environmental policy. When market-based instruments are not appropriate, use performance standards in preference to measures that prescribe and support specific technologies.

- "Support long-term basic research through funding and efforts to build capacity (*e.g.* development of centres of excellence). Increase research on ecosystems, the value of the services they provide, the long-term impact of human activity on the environment and the employment effects of new technologies.

- "Address unintended environmental and social consequences of technology by separating technology promotion responsibilities from those on health, safety and environmental protection within governments.

- "Support applied research activities when they are clearly in the public interest (*e.g.* protection of public health and environment) and unlikely to be provided by the private sector by:

    - "Co-operating with the private sector to develop and diffuse new technologies.

- "Facilitating public-private and inter-firm collaboration with the innovators of cleaner technologies and practices.
- "Seeking out opportunities for greater international collaboration on research, especially on issues critical for sustainable development.
- "Allowing competition among technologies that can meet the same policy objective, and equal access to 'learning opportunities' (*e.g.* protected niche markets and similar schemes) by foreign as well as domestic investors."

These precepts are generally accepted, but there remains some disagreement over the role of new technologies in achieving sustainable development goals and their costs and benefits. The role of technology policy in addressing environmental concerns and the level of government intervention in designing science, technology and innovation policies and programmes for the environment are also subject to debate. Workshop discussions focused on these issues.

### Technology and the environment: how economic theory informs policy

The role of technology in addressing environmental concerns and its place in various economic constructs was the subject of the opening presentation by David Pearce, University College London. In most traditional theories and models of economic growth, new technology is an exogenous variable which simply appears at the right time and the right price. In reality, however, market failure, owing to information deficiencies and inappropriate pricing, risks suffocating rather than stimulating the adoption of technologies able to enhance sustainable development. Producers and consumers may lack knowledge about the environmental impact of different products and activities. Moreover, prices of many goods and services do not reflect resource use or environmental and social externalities and new technologies tend to be more expensive than conventional ones. The costs of developing new, clean technologies and integrated approaches are often high and the time frames long. Where the benefits are more public than private, the result is insufficient industrial investment and inadequate technological innovation.

Endogenous growth theories, on the other hand, acknowledge that technological change occurs as a result of identifiable processes, including corporate investment and public policy. In this view, governments have an important role to play in getting prices right and in providing a climate for environment-related innovation. The economic, legal and physical infrastructure is an important determinant of levels and patterns of research and development (R&D), institutional interaction, education and training, investment and finance, communications, etc. Market factors, such as consumption trends, and government regulation affect the innovation climate. Therefore, governments can play a more direct role in developing and diffusing technology for sustainable development and in financing the basic research that underlies innovation.

However, as Dr. Pearce explained, raising resource productivity to reduce use of natural resources may be inconsistent with raising labour productivity, and thus bad for multifactor productivity (MFP) growth. To address the environmental dimension of sustainability may affect the growth component of sustainability. However, improved resource productivity may lower waste and pollution and thus help to improve human health. Therefore, improvements to the environment may help to improve human health and thus to augment labour productivity. The economic justification for technology policy may lie in achieving non-market well-being and indirect benefits for economic growth and productivity in the longer term.

Discussion focused on the failure of mainstream economics to explain adequately the role of technology in sustainable development or to help to advance the cause of technology policy in the context of other government policies. According to Alan Sanstad, Lawrence Berkeley National Laboratory, economic instruments that would stimulate investment in new environment-related technologies have been insufficiently used. Carbon taxes, for example, could provide economic incentives for research on climate change technologies, but they have not been implemented at appropriate levels or rates or on a sufficiently broad scale.

It was pointed out that economists tend to look at environmental problems from the top down, while scientists and engineers view them from the bottom up and feel that good technology policy is generally good environmental policy. However, proper price signals are essential if environmental alternatives are not to be significantly more expensive than existing products and processes. Moreover, if subsidies that may allow environmental damage are reduced, government intervention to lower the costs of new and more ecological technologies will have positive market outcomes.

Many felt it important to look at infrastructures, rather than single products and processes, when considering the potential role of technology. In this regard, information and communications technologies (ICT) may hold the greatest possibilities for reducing economy-wide environmental impacts. Governments should fund the development of broad technologies – *e.g.* information technologies, biotechnologies, nanotechnologies – that could have substantial positive spillovers in terms of environmental improvements. Rather than targeting specific environmental technologies, governments should provide support for all types of technology development. Still, certain technological areas, such as ICT, are identified as generally beneficial and as deserving more support.

More attention should also be given to firm behaviour and organisational economics in order to understand why firms make environmental investments or adopt particular technologies. Endogenous growth theory is still evolving and more information is needed on enterprise decision-making processes.

It was noted that technology can increase productivity without having any beneficial environmental impact. Government technology policy should be more integrated with environmental policy to ensure that firms have the right incentives to invest in technologies and processes that also contribute to environmental goals. Workshop participants generally agreed that there is an important role for technology policy in providing incentives for research and reducing the costs of beneficial technologies, and that S&T policy should be integrated with a wide range of economic and environmental policy approaches to achieve sustainable development goals.

## Technology and environmental modelling: lessons for policy

Economic modelling can also inform technology and technology policy for sustainable development, as Michael Grubb, Imperial College, London, demonstrated. Current models make a distinction between autonomous technical change, which depends on autonomous trends and government R&D, and induced technical change, which depends mostly upon corporate investment in R&D in response to market conditions and government policies. Incorporating induced technical change into economic models is a complex task. It makes the modelling inherently non-linear, with path dependencies and the potential for multiple equilibria. This is beyond the scope of the major E3 models currently used, where technical change is incorporated through exogenous assumptions. This remains an important weakness.

Newer models devoted to investigating induced technical change show that technology can alter results in many ways. Models that draw upon the empirical engineering literature tend to show that technology has very large impacts. Models in which innovation is a constrained resource that may shift from one sector to another show fewer effects. Efforts are now being made to incorporate technical change into mainstream E3 models. Other approaches are also being taken but do not undermine the importance of modelling induced technical change, which can have important economic and policy implications.

For example, some models that incorporate induced technical change indicate that addressing climate change – including atmospheric stabilisation – could be quite cheap in the long run owing to learning by doing, whereby technology costs are reduced by cumulative investment and knowledge diffusion. Induced technical change usually increases the benefits of early action by accelerating the development of cheaper technologies. Models using autonomous technical change, instead, imply that benefits are to be gained by waiting for superior technologies to be developed. Models based on induced technical change offer an economic formalisation of the "Porter hypothesis", *i.e.* that environmental regulation can improve economic competitiveness by stimulating the development of better technologies.

Modelling indicates that, with regard to energy, the environment and climate change, government policies should give more attention to technical change. Efficient response may involve a wide mix of instruments, targeted to spur market-based innovation in relevant sectors, and broader mitigation policies, including economic instruments. It may not be optimal to equalise marginal costs in each period, because the returns to learning by doing will differ between sectors and technologies. In addition, if efforts to mitigate climate change induce better technologies in industrialised nations, these technologies are likely to diffuse globally. The positive spillovers will offset the "negative spillovers" usually expected to result from the migration of polluting industries. Empirical data and analysis are still extremely weak in this area, although preliminary studies suggest that this effect may prevail over time, resulting overall in negative leakage (*i.e.* emissions reductions in industrialised countries may also result in reduced emissions in the rest of the world), because of the enormous leverage potentially exerted by global technology diffusion over time.

According to Patrick Criqui, IEPE-CNRS, Grenoble, technical change is the result of: *i)* exogenous events such as scientific discoveries; *ii)* inducement factors, such as government R&D and market prices; and *iii)* endogenous mechanisms such as learning by doing. Government policies can influence the environmental orientation of all three variables, but it is difficult to incorporate these factors into economic models. However, models can include the possible effects of learning by doing (experience effects) and of public and private research, including possible decreasing returns to both over time.

The improvement of current environment and energy models to better incorporate the technology element was discussed. Proposals included exploring the gap between growth models and engineering models, making better use of systemic modelling approaches, incorporating induced technical change in macroeconomic models, and including technology transfer and diffusion processes in regional models. It was generally agreed that models can be useful when presenting scenarios to policy makers and laying out policy choices. For example, models show that achieving low carbon outcomes may require radical policy changes in both economic instruments and R&D policies. Models also highlight the importance of information diffusion programmes, because of the vast spillovers resulting from the use of environmental technologies and learning effects. Models indicate that a range of policy instruments is needed to achieve environmentally beneficial pricing, disseminate information and stimulate technology investments. They also indicate that investment in environmental technologies now can lead to important cost savings in the future.

## Role of technology policy in addressing environmental concerns

The debate concerning the role and design of technology policy in the context of sustainable development was introduced by Risaburo Nezu, Director, OECD Directorate for Science, Technology and Industry. Some believe that the evolution of technology is one part of an economic and social framework which, if market conditions are right, will be economically, environmentally and socially sustainable. They believe that many government technology policies – beyond some basic R&D funding – amount to "picking winners" and are excessively interventionist. They further maintain that science and technology policies should be neutral and should not be targeted to environmental concerns. They believe that if externalities are properly internalised, there is no need for special help to ensure that technology is pointed in the right direction. However, there is some doubt as to whether environmental externalities will ever be fully internalised for a number of reasons:

- First, environmental issues on the policy agenda change constantly. Consequently, what it means to "internalise externalities" also changes. For example, 20 years ago, $CO_2$ emissions were not viewed as an environmental externality that had to be internalised as they are now. There is a mismatch between the long time horizons of R&D and innovation and the urgency of certain problems.

- Second, the long-term, high-risk nature of technology development, coupled with the strong presence of externalities, make it impossible for the market to ensure optimum allocation of resources over time unless there is backing by appropriate government policies.

- Third, publicly funded research should deal with "public good" issues, such as human health and the environment, areas in which the private sector will undoubtedly under-invest.

Most agree that technology can provide solutions to environmental problems without sacrificing economic growth and job creation. Technology policy tools are essential as well. This is a less than perfect world when it comes to internalisation of externalities. Science and technology policies are needed which are enlightened by an environmental perspective, and which are directed, to the extent possible, towards the goals of sustainable growth and sustainable development.

This does not mean that governments should engage in "picking winners". However, governments can explicitly take environmental objectives into account when setting priorities and funding public science and technology support programmes, including funding of university research and government laboratory research, research grants to the private sector, public-private R&D partnerships, technology diffusion programmes and other schemes. Many technology policy approaches – partnerships, technology foresight, clusters – can focus research efforts not by picking winners but by engaging diverse stakeholders in the identification of technology development paths.

Governments have determined the path of technology development far more than most will admit. Sometimes this has not been helpful. However, certain US companies, backed by massive government investments, gave us jet engines, radar, antibiotics and an understanding of electronic processes. Nobody could predict just how government-funded research would lead to computers, the Internet and all the other technical advances that now fuel growth. Nonetheless, the government and the private sector knew that certain electronic pathways were worth in-depth investigation. Research in OECD universities and national laboratories – supported by OECD governments – has propelled economic growth and productivity gains.

Technology development can now be more directed towards environmental and sustainable development goals. Governments are already doing so. They have partnerships with the private sector to develop clean cars. They are funding a great deal of research on biotechnologies for cleaner production. They have programmes to diffuse environmental technologies to small firms. Some have R&D tax credits specifically for environment-related research. Others have investment tax credits for purchases of clean technology. The OECD should help governments to evaluate the effectiveness of these programmes and to share their experience so that all can learn more about what stimulates firms to innovate for the environment and how to better design these policies.

Subsequent discussion centred on the role of governments and of markets in steering technology development. According to Nicholas Vanston, OECD Economics Department, technology investment should be largely left to market signals, and governments should refrain from subsidising the development of particular techniques or approaches in the name of the environment. Public R&D may crowd out private research efforts or provide windfall gains to private actors who would have undertaken certain research projects in the absence of government incentives. Policies should focus on getting prices right and internalising externalities – *e.g.* by removing subsidies and making greater use of economic instruments such as environmental taxes and charges, tradeable permits – rather than intervening unnecessarily in private-sector decisions regarding technology development.

According to Ken Ruffing, Deputy Director, OECD Environment Directorate, induced technical change could be the answer to a wide range of environmental problems, but technology policy needs to be closely integrated with environmental policies. While the role of government policies in technological development is vital, radical and continuous technological change can only be achieved by co-ordinating environmental policy and technological/innovation policy and exploiting their complementarity (OECD, 2001b). A range of tools should be used to steer technology development towards greater sustainability, including public support to basic research, green government procurement, maintaining appropriate intellectual property right regimes, getting prices right by removing government subsidies and using economic instruments, and improving regulatory regimes through use of approaches such as best available technologies (BAT).

Jonathan Pershing, Head of the Energy and Environment Division, International Energy Agency (IEA), pointed out that the use of economic instruments to address problems such as climate change is limited by countries' internal politics and competitiveness concerns. Therefore, a package of policies is needed, as in the climate-specific programmes of IEA Member countries. These programmes include: fiscal policies such as taxes, subsidies and subsidy removal; market mechanisms including cap-and-trade programmes and the Clean Development Mechanism; regulatory policies; public/private partnerships and voluntary agreements; R&D and innovation policies; and outreach programmes; and consultative processes with civil society (IEA, 2000). This "portfolio approach" in energy policy development is supplemented by a focus on particular sectors: residential/commercial, transport, industry and manufacturing, electricity generation, etc. Countries need to understand the implications of both policy instruments and sectoral targets when designing technology programmes to address environmental and energy concerns.

## Future directions for OECD analysis

The workshop concluded with a discussion of the best avenues for future OECD analysis at the crossroads of technology and environment. The following recommendations were made:

- ***Technology/environment modelling.*** Development of approaches for incorporating induced technical change and related aspects (regionalisation, technology costs) into OECD energy/environment models, including further integration of top-down and bottom-up modelling approaches.

- ***Environmental R&D indicators***. Development of improved indicators of public and private R&D expenditures related to the environment and sustainable development; analysis of environment-related research initiatives at public laboratories and institutions.

- ***Environment/growth relations***. Analysis of the implications of environmental technology investments for economic growth, with a focus on interaction between increases in resource productivity and labour productivity.

- ***Environmental technology portfolio.*** Analysis of the potential of a range of technologies (*e.g.* biotechnologies, information technologies, materials and energy technologies) to contribute to pollution prevention and necessary infrastructure investments.

- ***Integrated policy approaches.*** Analysis of the integration of environmental and technology policies in order to stimulate technical change; identification of an optimal policy mix. This could be based on country/sector studies of best practice policy integration, with a focus on climate change and reduction of greenhouse gas emissions.

- ***Firm-level responses***. Analysis of firm-level decision-making processes on environmental/ energy technology investments. This would help to improve understanding of business and organisational behaviour and choices of environmental management strategies, including how they may differ by industrial sector and firm size.

- ***Technology policy***. Analysis of the effects of government technology programmes directed towards environmental goals (*e.g.* generic research, advanced technology programmes, public/private partnerships, technology diffusion programmes, fiscal incentives, innovative clusters) with a view to identifying best practices. The relative roles of public and private R&D and supply-push and demand-pull policies would be examined.

- ***Environmental impacts of information technology***:

    - Updating input-output models to examine the link between structural change in the economy (towards ICT-based services) and trends in resource efficiency, energy consumption and pollution.

    - Analysis of the effects of electronic commerce on transport patterns and resource consumption (*e.g.* paper, energy).

    - Analysis of the role of information technology in cleaner production processes, the effects on business performance and government programmes for ICT diffusion.

    - Analysis of the use of ICT for implementing environmental policy, including monitoring compliance, disseminating information and implementing economic instruments (*e.g.* tradeable permit systems).

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# TECHNOLOGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT: WHAT ROLE FOR TECHNOLOGY POLICY?

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## The issue

OECD governments are committed to sustainable development. Sustainable development involves ensuring that per capita well-being rises through time on a (fairly) continuous basis. It is also widely regarded as involving a bias in development policy towards the less well-off in society. Sustainable development differs from sustainable growth in that the former embraces non-market gains in human well-being, as well as the market gains that appear in growth indicators such as rates of change in GDP per capita.

The problem is that growth and development may be incompatible if the growth process brings about losses in non-market well-being, *e.g.* through loss of natural environments. The attraction of sustainable development is that it offers the potential for securing positive growth while protecting non-market social and environmental well-being. That attraction is also the challenge. “Win-win” outcomes are politically very attractive: they create the illusion that one can avoid trade-offs between market and non-market well-being.

In fact, only certain policies hold out a realistic promise of securing sustainable development. Absolutely crucial to those policies is the role played by technological change. The role of technological change was fairly explicit in traditional “neo-classical” models of economic growth and is fundamental to modern “endogenous” growth models. As endogenous growth models appear to be more in tune with the way in which modern economies grow, they appear to be more relevant. Hence, the role of technological progress is fundamental to economic growth. Few of these models have an environmental dimension, and none appears to deal with the social dimension. However, technological change is just as relevant to models seeking to secure sustainable development, as opposed to sustainable growth. The basic rationale is that technological change is needed to raise the productivity or efficiency of environmental and natural resources (hereafter grouped together as natural resources).

If technology is central to prospects for sustainable development, the issue is what must be done to secure technological progress. Viewpoints vary substantially and range from a belief that the “market” will induce the “right” amount of technological change, to the belief that government should play a central role in inducing that change. The following discussion looks at this issue in the context of so-called exogenous and endogenous technological change and the modern theory of sustainable development.

## Resource productivity

A fundamental aim of governments is to raise levels of labour productivity, *i.e.* output per unit of employment, a traditional measure of economic achievement. More recently, there has been an additional focus on the productivity of natural resources. This new focus has three goals:

- To raise the productivity of resources to help raise labour productivity and help competitiveness both between firms and industries, and internationally.
- To raise resource productivity to lower absolute use of natural resources in any given time period, thus conserving what may be supply-scarce natural resources.
- To raise resource productivity to lower the resource throughput in the economy, which means disposing of fewer waste products to receiving environments per unit of output.

Making natural resources more productive thus appears to serve both the goals of sustainable growth (higher labour productivity) and sustainable development (improved environmental quality). However, it is debatable how far resource productivity is consistent with sustainable growth, not least because very little seems to be known about links between resource productivity and labour productivity.

If resource productivity is a goal, how is it best achieved? Three broad options seem relevant. First, resource productivity may simply rise through time "naturally" as economies develop. Second, resource productivity might be secured by behavioural and attitudinal change: individuals and firms may simply decide to become less wasteful and use fewer resources per unit of economic activity. Third, induced technological change may improve resource productivity, *i.e.* technological change occurs as a direct result of policy.

Rising resource productivity appears to come about "naturally" as economies move through phases. The ratio of primary energy use to GDP, for example, has a well-known "inverse U" shape when looked at from the perspective of time series (IEA, 1999). Energy intensity at first rises as industrialisation takes place and then falls on a fairly consistent basis. Typically, then, developing countries will have rising energy intensities and developed economies will have falling energy intensities.[1] These changes reflect a number of different factors: structural economic change tends to reduce the role played by energy-intensive industry, fuel mixes change towards thermally more efficient fuels and to electricity, which has considerable economies of location and convenience, and technological changes occur that make energy use more efficient. By and large, the technological changes can be attributed to price changes but perhaps also to some "autonomous" or "exogenous" change. The notion of exogenous technological change is fundamental to neo-classical growth models and to most integrated assessment models of energy use. Whether or not the changes are truly exogenous is discussed below.

The role for behavioural change that is independent of policy measures such as price changes is open to debate, but appears to be limited. IEA (1997) concludes that behavioural change through "energy consciousness" has played a role in the manufacturing and household sectors. The roles played by prices and deliberate policy measures (*e.g.* efficiency standards) are perhaps more important.

## Exogenous growth

Exogenous growth models embody a production function of the general form:

$$Y(t) = T(t).f(K(t), L(t), R(t)) \qquad [1]$$

where $Y$ is output, $K$ is capital, $L$ is labour, $R$ is "natural resources", $t$ is time, and $f$ is a function to be specified. $T$ is total factor productivity (TFP) and refers to the increase in output that is secured independently of the growth of factor inputs, *i.e.* independently of changes in $K$, $L$ and $R$. Equation [1] is specified in such a way that technology is exogenous, *i.e.* $T$ is not a function of other factors in the equation. TFP was traditionally equated with the notion of exogenous technological change, but it is perhaps better characterised as a "don't know" factor. Essentially, all kinds of growth-determining factors are included in $T$, so that defining technological change as anything that raises factor productivity is somewhat misleading.

Equation [1] can be made more precise by specifying the form of the function embracing $K$, $L$ and $R$. A common form is Cobb-Douglas, which would convert equation [1] into:

$$Y(t) = T(t).K(t)^{\alpha} L(t)^{\beta} R(t)^{\gamma} \qquad [2]$$

The parameters $\alpha$, $\beta$ and $\gamma$ are the elasticity of output with respect to capital, labour and natural resources, respectively. Taking logarithms and differentiating with respect to time, $t$, gives:

$$\frac{\partial \ln Y}{\partial t} = \frac{\partial \ln T}{\partial t} + \frac{\alpha.\partial \ln K}{\partial K} + \frac{\beta.\partial \ln L}{\partial L} + \frac{\gamma.\partial \ln R}{\partial R} \qquad [3]$$

which can be expressed in the form of rates of change as:

$$r_Y = r_T + \alpha.r_K + \beta.r_L + \gamma.r_R \qquad [4]$$

The change in TFP is given by $r_T$, so this rate of change can be estimated by rearranging [4] as:

$$r_T = r_Y - \alpha.r_K - \beta.r_L - \gamma.r_R \qquad [5]$$

The change in TFP is therefore estimated as a residual. Rates of change in GDP are estimated and rates of change in other inputs are deducted, with the appropriate "weights", $\alpha$, $\beta$ and $\gamma$, being applied.

The next issue is to find the weights of $\alpha$, $\beta$ and $\gamma$. Provided factor and product markets are competitive, marginal factor products should be equal to factor prices. If this condition holds, the relevant weights are equal to the share of factor payments in total GDP. Thus $\alpha$ would be given by the share of capital in GDP, $\beta$ would be given by the share of labour in GDP and $\gamma$ would be given by the share of natural resources in GDP. If there are constant returns to scale, $\alpha + \beta + \gamma = 1$.

Equation [5] is expressed in terms of conventional measures of output, *i.e.* GDP or GDP per capita (it is shown below how it can be modified for GDP per unit employment – *i.e.* labour productivity). As such, it relates to the notion of growth rather than development. A procedure for re-expressing the relationships in terms of development rather than growth is given in Appendix 1.

"Growth accounting" exercises show that the change in TFP is an important contributor to past economic growth. Table 1 reports selected results from Barro and Sala I Martin (1995) and Maddison (1995).

Table 1. **Percentage contribution of TFP to observed growth rates**

| Region | Period | Barro and Sala I Martin | Maddison |
|---|---|---|---|
| OECD | 1947-73 | 33-64% | |
| G7 | 1960-90 | 11-52% | |
| Latin America | 1940-80 | 0-40% | |
| East Asia | 1966-90 | -5-30% | |
| United States | 1950-73 | | 44% |
| United States | 1973-92 | | 8% |
| United Kingdom | 1950-73 | | 49% |
| United Kingdom | 1973-92 | | 43% |
| Japan | 1950-73 | | 55% |
| Japan | 1973-92 | | 28% |

*Source*: Barro and Sala I Martin (1995); Maddison (1995).

The role played by TFP suggests that if technological change dominates the definition of TFP, then technological change is a prime determinant of modern economic growth. Some growth accounting exercises have modified the procedures to allow for R&D as an explanatory factor in TFP. Essentially, TFP is estimated as a residual and the residual is then broken down into the contribution of R&D and a time trend to capture "truly" exogenous technological change. These approaches suggest very high social rates of return to R&D, perhaps of the order of 20-40% a year (Barro and Sala I Martin, 1995).

It is easy to see how the notion of breaking down the TFP residual can be extended to generalised regression approaches. In other words, why not regress economic growth rates on whatever factors may be relevant to explaining growth? This has produced, and is still producing, a substantial empirical literature. Determinants have included proxies for education, life expectancy as a proxy for human health, population change, economic variables such as the openness of the economy and many "political economy" factors such as political stability and freedom. Traditional capital investment tends to be important in these exercises, although other factors may explain capital investment and growth together. However, the results do not suggest contributions that differ from the share of capital in GDP ($\alpha$ in the above equations). Human capital also appears to contribute to the share of labour ($\beta$). After that, studies seem to vary in the importance attached to trade variables, inequality, democracy, etc. (for an overview, see Durlauf and Quah, 1998). Barro and Sala I Martin (1995) find that market distortions affect growth negatively, as does the size of government and political instability.

## Endogenous growth

Endogenous growth theory is the growth theory context for the "general framework" of the resource productivity exercise. The rationale is that neo-classical growth theory fails to provide an explanation of the growth process. Capital accumulation experiences diminishing returns, and economic growth ceases when the ratio of capital to labour reaches a certain level. Growth "ends" but for the influence of $T(t)$, the determinants of which were not investigated in detail in the neo-classical models. If the world was characterised by production functions like [1], we could not explain continued economic growth except by reference to a somewhat mysterious "T" factor. Even then, one could not explain changes in growth rates. A second problem is that neo-classical theory predicts convergence of growth rates in different economies: those with lower capital/labour ratios will have high marginal products of capital, leading to more investment. Eventually, they should catch up to economies with high capital/labour ratios. Since convergence is not observed, the neo-classical model appears to lack explanatory power (Barro and Sala I Martin, 1995).

Endogenous growth theory is a response to the neo-classical model's lack of explanatory power. The basic idea is that growth is determined by factors inherent in the model: the mystery of technological progress is resolved by endogenising it, *i.e.* technological change is "embodied" in $K$ and $L$ (and $R$, although few models incorporate natural resources). $L$ is redefined to be conventional labour (hours worked) and quality-adjusted labour (human capital). As $K$ and $L$ expand, innovation occurs, producing "learning by investing" and "learning by doing". This basic connection allows policy to influence growth, something that the neo-classical model did not, in essence, permit.

However, there are quite a few variants of endogenous growth models, so that the precise mechanisms that determine growth are the subject of some speculation. The normal process of "testing" models would be to see if they explain growth historically or cross-sectionally, but this is fraught with difficulty owing to the nature of the linkages involved and the difficulty of specifying them econometrically. The basic elements involve knowledge. As investment takes place – whether in man-made or human capital, or both – learning occurs, expanding the stock of knowledge. This stock of knowledge is usually assumed to be a public good, so once created by one firm or agent, it is available to others. There are "knowledge spillovers" or "knowledge externalities".

The essence of endogenous models can be captured as follows. Rewriting [2] to exclude natural resources and allowing for constant returns to scale gives:

$$Y = T.K^{\alpha}.L^{1-\alpha} \qquad [6]$$

Dividing through by $L$ gives:

$$\frac{Y}{L} = T.\left(\frac{K}{L}\right)^{\alpha}$$

or:

$$y = T.k^{\alpha} \qquad [7]$$

so that the production function is now expressed in terms of labour productivity. Taking logarithms:

$$\ln y = \ln T + \alpha \ln k$$

which in turn can be written as:

$$\ln y = \ln T + (1-\beta)\ln k \qquad [8]$$

where $\beta$ is simply the share of labour in the economy.

Let technological change be "embodied" in $K$ so that:

$$\ln A = \gamma . \ln k \qquad [9]$$

*i.e.* technological change depends on the growth of the capital-labour ratio. Then [8] becomes:

$$\ln y = \ln T + (1 - \beta + \gamma) \ln k \qquad [10]$$

Note that, after accounting for embodied technological change, "*T*" is a residual. Equation [10] says that investment will raise the capital-labour ratio, and this will raise output by (1 – *β*). There is an additional "spillover" effect shown by *γ*. Social rates of return to investment are higher than normal "private" returns because of the technological externality.

**How useful are endogenous growth models?**

The usefulness of endogenous growth models is debated. Some neo-classicists argue that the original "*T*" can be broken down into many factors that determine growth. The attraction of endogenous growth theory is that it at least provides a rationale for sustained and changing growth, and it does so by focusing attention on how knowledge spills over from investment in man-made and human capital. In turn, the various transmission mechanisms become important, as do obstacles that may inhibit the adoption of new technology. Market structure thus becomes central to the endogenous growth approach.

Moreover, deliberate policy enters the picture – long-run growth rates would appear to be able to be influenced by public policy.[2] It is this policy implication that is perhaps the most important differentiating factor between exogenous and endogenous growth models. In the neo-classical models, policy appears to be impotent. In endogenous models, its role is quite explicit since government can both remove or reduce obstacles to knowledge spillovers and take positive action to induce technological change.

However, there are at least two problems. First, nearly all of the endogenous growth literature is theoretical, so that the numerical scale of the various interactions is not easy to gauge. Second, nearly all of the models exclude natural resources. Yet natural resources must be accounted for when the interest is in sustainable development rather than sustainable growth (see Appendix 1). A clue to the role that could be played by natural resources is given in the treatment of R&D in the endogenous growth literature. R&D essentially creates positive externalities, as explained above. Changes in resource productivity can be thought of as doing the same through the effects on environmental quality and hence on human capital.

In other words, natural resource productivity plays two roles. First, it improves environmental quality and hence non-market well-being. Second, it has indirect effects on labour productivity, and at least two mechanisms are involved. As environmental quality improves, human health improves. Human health can be thought of as a constituent part of human capital, but it is also relevant to improvements in labour productivity. It is fair to say that there are only limited studies that show what these linkages are in empirical terms.

However, those that exist find very significant effects. Bhargava *et al.* (2000) give a general review of the link between health and economic growth. They find a clear link between health and growth in low-income countries. Hansen and Selte (2000) find that an increase of 1 microgram/cubic metre in particulate matter in Oslo leads to a 0.6% increase in the number of sick leaves. A focus on externalities and productivity, however, does not take into account other social policy concerns. It is well known, for example, that air pollution affects mainly those in the "non-productive" age groups (asthma is a potentially serious exception). Excessive focus on "conventional" productivity concerns ($r_T$ rather than $r_T^*$) may produce an unjustified social bias. Nonetheless, if policy makers are motivated mainly by conventional labour productivity concerns, it is essential to identify and measure the positive spillovers from environmental improvement to labour productivity gains. It becomes even more important when the links between resource productivity and labour productivity are explored in the context of endogenous growth models (see below).

A search of the empirical literature reveals comparatively few studies in which some form of endogenous growth model is estimated. den Butter and Wollmer (1996) construct a model for the Netherlands which: *i)* has significant endogenous growth model features, with "technology capital" interacting with human and man-made capital; and *ii)* includes energy as part of efficiency-adjusted capital stocks. Capital and energy are complements, with an elasticity of substitution of 0.2. Various policies are simulated, including a 10% increase in investment and a 10% increase in R&D expenditures. Since energy is a complement, its use rises. The effect on labour productivity is fairly dramatic, but the cost is very high increases in unemployment. The model does not simulate energy productivity changes.

In the same spirit, Hofkes (1996; see also den Butter and Hofkes, 2001) constructs a two-sector endogenous growth model with a pollution abatement sector. The model has abatement expenditures and pollution-saving technological change which, in the current context, could be thought of as an improvement in resource productivity. Perhaps most importantly, the model allows the environment to generate well-being directly *and* to influence labour productivity via the health route suggested earlier. One analytical result is that growth is achievable with a non-declining value for the (single) environmental variable, *i.e.* a kind of "strong sustainability" is secured as the growth in technology and in abatement activities compensate for the effects of growth on increased use of the environment.

Mabey *et al*. (1997) estimate an "endogenous technical progress model" in which the growth rate of fossil fuel energy use is dependent on the share of energy in GDP (energy intensity), fossil fuel energy prices and an endogenised time trend. The aim is to secure an outcome in which energy prices rise to finite levels while inducing energy efficiency in a context of continuing economic growth. Raising energy prices, *e.g.* by a tax, has two broad effects – a demand effect and an inducement to technological progress. The latter effect reflects the spirit of endogenous growth models, *i.e.* technological progress producing resource productivity in the energy sector is the outcome of policy measures. Moreover, since the study finds low price elasticity for the response of energy intensity to price, it is technological change that "delivers" energy efficiency, shifting the focus of policy to the means of securing that technological change. In the full model, rising energy prices induce energy efficiency but lower labour productivity, raising a concern that resource productivity could harm the goal of raising labour productivity, at least in the short to medium term. How does this potential negative interaction come about?

The "standard" policy for inducing resource-saving technological change is to raise the price of resources. In so doing, substitution between the various factors of production is encouraged. If the "input" of natural resources is reduced because of resource price increases, there should be increases in the inputs of labour and capital, lowering their marginal productivity. While resource productivity increases, labour productivity, for example, may decrease. den Butter and Hofkes (2001) suggest a second mechanism whereby labour productivity might decline. Financial resources could be diverted away from investments in improving labour productivity and towards investments in resource saving. Effectively, the rate of return to resource saving increases and this alters the relative attractiveness of different investment opportunities. Hence, labour productivity might suffer further.

If this very provisional result from endogenous growth models that include an environmental component is correct, there is a possible negative link between resource productivity and labour productivity. Since improving resource productivity is essential to environmental policy in a sustainable development context, a dilemma arises. Addressing the environmental dimension of sustainability may be detrimental to the growth component of sustainable development. However, this somewhat gloomy finding can be offset by the previous finding that resource productivity affects human capital via the health route, and hence also labour productivity. If other research findings are correct, there may be several indirect routes. For example, the US Environmental Protection Agency (EPA, 1997) finds close links between air pollution and impairment of children's IQ.

What appears to be important, then, is to establish the relative sizes of two potentially countervailing forces: the effects on labour productivity of factor substitution owing to resource productivity policy and labour productivity enhancement owing to improved human capital arising from resource productivity. In all honesty, little is known about the importance of these two effects.

## Conclusions

Endogenous growth theory provides a platform for those who wish to argue for an interventionist technology policy. Technological change and human capital appear to be fundamental to the process of sustainable growth and, by implication, sustainable development. However, technological change is affected by many factors, and policy can influence directly at least some of the more important ones. It is well known that R&D has many of the characteristics of a public good, so that free market systems are likely to under-invest in R&D.

The public sector has a role here, possibly in terms of direct provision of R&D but more probably in the area of incentive systems for improving R&D, knowledge and technological change. Many of these incentive systems are familiar: differential wage and salary payments to different scientific disciplines, profit-sharing schemes, the "networking" of facilities, centres of excellence, student support, better directed university research, etc. If market structures are an obstacle, industrial policies to secure more competitiveness become relevant, as do procedures for guaranteeing intellectual property rights. No one, it seems, is sure of the cost-effectiveness of each of these policy interventions, but all need close monitoring and appraisal.

How does the environment fit into this kind of technology policy? Perhaps one observation of relevance is the fact that the environmental technology market is huge, globally of the order of hundreds of billions of dollars a year. A substantial market for environmental technology needs to be harnessed. To a considerable extent, the future scale of these markets will depend on what the world's nations do about global warming. If American intransigence remains, perhaps the rest of the world can "go it alone". If the United States eventually comes on board, the demand for innovative technological solutions to global warming will be immense. It is clear that without low-carbon and non-carbon technologies, global warming cannot be addressed in more than cosmetic fashion. Technology is crucial, and it is obvious that renewable energy technologies are extremely important.

Anderson (2000) sets out the case for a far more radical renewable technology policy than is currently in place in OECD countries. First, he argues that investment now expands the menu of energy options now rather than later. This expanded menu operates like a form of option value – the value of having a wider portfolio to choose from rather than the narrower one that would be available if investment did not occur. Second, investment now lowers the costs of future developments, a spillover effect very much in line with the suggestions of endogenous growth theory.

Will the market secure these changes so that the “switchover” between carbon-based economies and renewables-based economies is optimal? This seems unlikely, not least because the full environmental costs of carbon technologies are probably still not reflected in carbon energy prices. One route to acceleration of a renewable energy world would be to tax fossil fuel energy for its externalities. Anderson suggests that such policies need to be supplemented by the idea of investing directly in renewable R&D. The value of the benefit from such investment would be the present value of all the future cost reductions secured, which would not occur in the absence of such investment.

This reflects Arrow’s notion of positive externalities to investment (Arrow, 1962), which is embodied in most endogenous growth theory. Anderson’s argument is that uncertainty over climate change science – an uncertainty that has perhaps played some part in US opposition to the Kyoto Protocol – makes investing in renewables more risky. If the investments are undertaken and the climate issue proves less serious, investors will have invested large sums in technologies that are currently more expensive than fossil fuel counterpart technologies. However, if the investments lower costs, the potential for “regret” is much less. It would seem that if investors know this, they would invest anyway, since their investments would lower the costs of renewable energy by moving down learning curves. One fairly obvious reason that they do not is that they are in a game theory context. No one wants to risk being the first mover, since only collective investment by all agents, *e.g.* all oil companies, will bring about the cost reductions.

This is perhaps the true role for technology policy. First, environmental policy and technology policy have to be seen as closely complementary: a dominant justification for technology policy is the environmental gains it will bring and thus the gain in human well-being. The justification for technology policy would be less the conventional productivity effects than the maximising of human well-being. In turn, the justification of environmental policy is the same achievement of non-market well-being, but also the longer-run indirect effects of environmental improvement on health and intelligence, and hence productivity generally. Second, technology policy has to overcome the problems of “atomised” decision making. Cost reductions are essential if renewable technology is to compete, but cost reductions require concerted action. The decentralised market is unlikely to provide that.

### *Appendix 1*

# GROWTH ACCOUNTING FOR SUSTAINABLE DEVELOPMENT

The links between conventional and welfare-oriented productivity measures can be analysed as follows using a growth accounting procedure (following Repetto *et al*., 1996). The conventional approach to measuring changes in total factor productivity (TFP) is captured (for exogenous technical change) in equation [A1] below, which comes from posing a typical neo-classical production function, taking logarithms, differentiating and rearranging to give:

$$r_T = r_Y - \alpha.r_K - \beta.r_L - \gamma.r_R \qquad [A1.1]$$

where $r_T$ is the rate of change in the residual ("technological change" or the "don't know" factor), $r_K$ is the rate of change in (man-made) capital stock, $r_L$ is the rate of change in labour, $r_R$ is the rate of change in natural resource stocks, and $\alpha$, $\beta$ and $\gamma$ are the shares of capital, labour and natural resources in GDP.

For convenience, let:

$$[\alpha.r_K + \beta.r_L + \gamma.r_R] = x \qquad [A1.2]$$

so that [A1.1] becomes:

$$r_T = r_Y - x \qquad [A1.3]$$

True output (well-being) in the economy is given by the sum of GDP (*Y*) and non-marketed damage (*N*), so that:

$$U = Y + N \qquad [A1.4]$$

The rate of growth *U* is given by:

$$\frac{\dot{U}}{U} = s_Y.\frac{\dot{Y}}{Y} + s_N.\frac{\dot{N}}{N} \qquad [A1.5]$$

where $\dot{U}$ denotes $\frac{\partial U}{\partial t}$ and so on, $s_Y$ is the share of marketed output in total output and $s_N$ is the share of non-marketed output in total output. Also $\frac{\dot{Y}}{Y} = r_Y$ and $\frac{\dot{N}}{N} = r_N$ .

The modified rate of change in total factor productivity ($r_T^*$) is given by:

$$r_T^* = s_Y.r_Y + s_N.r_N - x \qquad [A1.6]$$

Subtracting $r_T$ from $r_T^*$ and noting that $s_Y = 1 - s_N$ we have:

$$r_T^* = r_T + s_N [r_N - r_Y] \qquad [A1.7]$$

Note that $s_N < 0$ since $N$ refers to damage.[3] As long as damage grows less fast than output, the modified TFP will grow faster than the conventional TFP measure.

Equations [A1.1]-[A1.7] show how externalities can be incorporated in a growth accounting framework. One argument that appears to favour the conventional TFP measure rather than the externality-modified one is that non-market effects are irrelevant to international competitiveness or to competitiveness between firms. In other words, it would appear that the productivity of market activity alone determines competitiveness. This is a somewhat old-fashioned view, since it ignores the linkages from the externalities to productivity discussed above.

## NOTES

1. There are some interesting exceptions. China, for example, has halved its energy intensity since 1975. See UNDP (2000), p. 180.

2. Arguably, one could derive these conclusions from neo-classical models. “Technology” is also important in the sense that TFP “explains” growth. TFP can be broken down and would reveal factors that can be quite explicitly addressed in policy terms. However, the debate between neo-classicists and endogenous growth theorists is not of central concern here.

3. Repetto *et al.* (1996) do not allow for the creation of external benefits that would be relevant for agriculture at least. For such estimates, see Hartridge and Pearce (2001).

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# TECHNICAL CHANGE AND ENERGY/ENVIRONMENTAL MODELLING

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## Introduction

Technical change is generally acknowledged to be an important factor in addressing major environmental issues, particularly large-scale, long-term problems like climate change (IPCC, 1996; Weitzman, 1997). This has been highlighted in work by the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC) and many others. Recent work also highlights how more rapid development of clean energy technology can reduce risks in the face of uncertain long-term environmental threats. However, in economic modelling of policy questions in this area, relatively little attention has been paid to how technical change occurs. In many economic models, technical change is incorporated as an exogenous variable: it is reflected in specific assumptions entered as data about improved efficiency and declining costs of certain kinds of technologies over time. This reflects an idea of technical change as a mainly autonomous process: it happens in ways that do not depend upon other policy or economic variables.

The wider literature on technical change, however, acknowledges that technical change is not an autonomous process: it occurs as a result of identifiable processes, such as government research and development (R&D), corporate technology investment, and economy of scale effects. In reality, a great deal of technical change is led by the private sector and is induced in response to government policies, market conditions, investment and expectations. In modelling terms, therefore, technical change really should be endogenous, *i.e*. dependent upon other parameters reflected in the model.

Recent studies have tried to address specific elements of induced technical change in limited ways and suggest that the implications may be far-reaching. For example, induced technical change may affect the optimal degree, nature, timing and distribution of abatement efforts. It may also affect international aspects with respect to estimates of leakage and international policy with respect to technology transfer. The main results suggest that the modelling of technical change is important for deriving policy conclusions: the means by which technical change occurs may have implications for optimal environmental and innovation policies. Indeed, incorrect modelling of technical change can lead not only to wrong conclusions about the capacity to solve environmental problems, but to policy recommendations that may be counterproductive.

This pilot study seeks to clarify the economic issues relating to induced technical change, reviews the modelling of technical change and what has been learned from studies carried out during the 1990s, and discusses the nature of the policy implications. It addresses the following questions:

- ***Role of technical change.*** How important is it in the wider context?

- ***Sources of technical change.*** What is the evidence for induced *vs.* autonomous technical change?

- ***Technology modelling.*** How do the mainstream models account for technical change?

- ***Induced technical change.*** What studies have been carried out and what do they tell us?

- ***Future modelling.*** What approaches are being explored and what is the state of the art?

- ***Government policies.*** What are the implications for governments?

## Importance of technical change

In the course of economic growth, technical progress holds the key to pollution abatement and to reducing its costs. For pollutants like particulate matter (PM), lead in fuels, volatile organic compounds (VOCs) and more recently $SO_2$ and NOx, technologies and fuels have been developed that can reduce pollution per unit of energy use by factors of ten to several thousand or more. Even with rising energy consumption, emission levels have been reduced dramatically in countries that have introduced policies to encourage pollution abatement. Moreover, the costs have often been far less than anticipated and are sometimes lower than those of the fuels they displaced – the substitution of gas for coal in electricity generation and as a domestic and industrial fuel is a well-known example – or have been offset by efficiency gains elsewhere in the activity in question. In short, technology is making it possible to reconcile energy use with a better environment with relatively little effect on energy costs.

*Will finding alternatives to fossil fuels to address climate change be an exception?* Probably not, although considerable effort is still required to develop the alternative technologies – especially given the continuing difficulties with nuclear power. We know that a wide range of options is emerging, thanks to recent research, demonstration and market stimulation programmes in a range of renewable energy technologies, such as photovoltaics, wind (onshore and offshore), solar thermal, ocean-based systems, geothermal, biomass gasification and combustion for power generation, hydrogen derived from renewable resources and fuel cells. Possibilities for extracting hydrogen from gas and coal, with the carbon (in the form of $CO_2$) being used for enhanced oil and coal-bed methane recovery on closed, non-net-$CO_2$-emitting cycles are also much discussed. The IPCC, and notably the recent report of the team working on the *Special Report on Emissions Scenarios*, and many others have consistently suggested that a low-carbon future can be reconciled with high and rising levels of world energy use in the long term through a shift to alternative technologies.

Table 2 provides relevant evidence by showing the emissions intensities of technologies and practices for reducing emissions and environmental damage relative to the (polluting) alternatives they displace. Also shown are some indicators of the effects on costs, which are generally small, and sometimes, in retrospect, negative. For each source and individual pollutant, the percentage of emissions from available low-polluting practices/technologies compared to the current average levels is shown in the second column. The third column shows marginal costs of low-polluting options as a percentage of the marginal cost of supply. Cost uncertainties related to renewable energy technologies and addressing climate change will be discussed shortly.

Table 2. **Pollution intensities/costs for selected energy-related activities and pollutants**

| Source and pollutant | Emissions ratio of low-polluting to polluting practices[1] | Net private MC of low-polluting option as % of MC of supply[2] | Nature of low-polluting alternatives |
|---|---|---|---|
| *Electricity generation from coal* | | | |
| PM emissions | <0.1 | < 0 to ≈ 2 | Natural gas; ESP, BHF, FGD, IGCC and FBC (for coal); "low NOx" combustion and catalytic methods.[3] |
| $SO_2$ | 0 to 0.5 | 5 | |
| $NO_x$ | 5 to 10 | 5 | |
| *Gasoline engines* | | | |
| Lead | 0 | Combined costs of 4-5% of vehicle and fuel used | Unleaded/reformulated fuels; catalytic converters. |
| CO | 5 | | |
| Nox | 20 | | |
| VOCs | 5 | | |
| *Marine pollution from oil* | | | |
| Wastes | 10 | n.a.[4] | Improved ballasting & discharge reduction, improved operating, navigation and safety practices since the 1970s. |
| Spills | <10 | | |
| *Traditional household fuels (wood and charcoal) in low-income countries* | | | |
| Smoke (PM, CO and sulphur) | <0.01 | < 0[5] | Gas and kerosene. |
| *Soil erosion* | | | |
| Sediment yield | -5 to 5[6] | ≈ -20 | Agroforestry; contouring, terracing, vetiver grasses, mulching, and other. Indirectly: substitution of modern energy forms for dung and firewood as cooking fuels. |
| *$CO_2$ emissions from burning fossil fuels* | | | |
| Electricity (LDCs) | 0 | ≈ 0[7] | Advanced solar energy, wind and other renewable energy technologies for power generation; biomass for liquid fuels and power generation; hydrogen from renewable energy sources and fuel cells for power generation and vehicles; decarbonisation of fossil fuels for hydrogen production with carbon sequestration. |
| Electricity (industrial countries) | 0 | ≈ 20[7] | |
| Liquid fuel substitutes | 0 | ≈ 30-50 | |

PM = particulate matter.

1. The practices displaced can be inferred from the note on technologies and practices in the last column and the descriptions to be found in the sources. See Anderson and Chua (1999) for a non-technical summary.
2. Net private marginal costs (MC) are used since several technologies and practices have economic justifications that go beyond their environmental benefits, for example water supplies, the use of gas as a domestic and industrial fuel, and soil erosion control. These investments are justified solely in terms of their private costs and benefits, without reference to their environmental benefits, important as these may be. Thus if MEB denotes the marginal environmental benefits, MPB the marginal private benefits, defined as what people are willing to pay for the technologies or practices, and MPC the gross private marginal cost of using them, then the social benefit-cost criterion for investment is MEB – (MPC – MPB) ≥ 0. The estimates shown in this column are for the term (MPC –MPB)/MPC.
3. Acronyms are for electrostatic precipitators, bag-house filters, flue gas desulphurisation, and integrated coal gasification combined-cycle technologies. The negative cost figure arises if gas is available for power generation as a substitute for coal.
4. Major reductions have been achieved through improved management, navigation and accident prevention, the net costs of which as a percentage of shipping costs are likely to have been small. The introduction of double hulled tankers to minimise the effects of spills was estimated to raise average shipping costs from roughly USD 3 to USD 4 per barrel in the early 1990s.
5. The negative figure refers to the costs of turning in urban areas from wood and charcoal to gas, LPG and kerosene for cooking. The latter, "modern" fuels are five to ten times more efficient than the use of wood and charcoal for cooking, and in regions where free access to forests and woodlands is precluded by distance or law, are generally cheaper. Their savings in household labour also make their private costs lower than those of traditional fuels.
6. Soil regeneration and land reclamation are feasible in many areas, and are commonly discussed in connection with abatement policies for global warming. The estimate is based on the effects of such practices on crop yields. See Anderson (1999). The estimate is included here since land degradation is a widespread consequence of the use of fuelwood and dung for household fuels in developing countries. See World Bank (1996) for a review.
7. The cost estimates for developing countries are lower than for the northern industrial countries because incident solar energy is two to three times greater in the former regions and its seasonal fluctuation is less than one-third.

*Source*: Anderson and Cavendish (forthcoming). The background paper is on the Web site of the Imperial College Centre for Energy Policy and Technology. See Anderson and Chua (1999) for a review of the engineering-economic literature and Kiely (1997) for an introductory text on technologies. Aside from $CO_2$ emissions, all estimates are based on technologies and practices in widespread use. The $CO_2$ emissions reduction technologies have been well demonstrated; the cost estimates are based on best projections found in engineering studies, reviewed in Johansson *et al*. (1993) and Ahmed (1994).

If we consider the identity *Emissions = Energy Use x Emissions/Energy Use*, it is clear from Table 2 that very high levels of energy consumption can be sustained with greatly reduced emissions, once low-polluting technologies and practices are in place, notwithstanding the point that national energy intensity is not simply the inverse of energy technology (Birol and Keppler, 2000). As noted, with the possible exception of climate change, effects on costs are generally small. Many economic modelling studies have confirmed the sensitivity of long-term cost results to long-term assumptions about technology costs. Edmonds (1998) have perhaps done most to explore the sensitivity of model results to technology cost assumptions and called for a major international programme to develop cleaner technologies to address climate change. However, the focus of this study is not on whether technology development is important – which now seems beyond question – but on how technology development occurs, how it is represented in models, and the nature of the economic and policy conclusions that flow from this.

## Sources of technical change: classification and evidence

The process of genuine, original innovation is not understood – it has been characterised as "the triumph of action over analysis". However, viable commercial technologies do not appear as "manna from heaven". They require considerable developmental effort, much of it by industry, as well as by laboratories that carry out basic research. This is evident in the development of non-carbon technologies such as photovoltaics, off-shore wind, fuel cells and so forth. It was also true in the development of technologies to address local and regional pollution, such as scrubbers to reduce $SO_2$, the various mechanical and electrical methods to remove particulate matter (PM), the reduction of vehicle exhaust emissions, on which research continues. The R&D and demonstration effort often extends over several decades and requires a mix of private and public initiatives and funding.

Various technology diffusion studies emphasise the complexity of the factors that determine whether or not technological ideas are developed and adopted. It is clear that this depends heavily upon external conditions (Freeman, 1990). Studies of emerging energy technologies that seem likely to have significant market impact have concluded that "most of the technologies considered reflect primarily a process of demand pull rather than supply push" (Grubb and Walker, 1992); and that "the commercial opportunities of new technologies (the market pull) provide a stronger driver than what is technically possible (the technology push)" (POST, 2000). Specific examples, at successively greater levels of aggregation, illustrate the extent to which developments in technologies and energy systems are not autonomous, but reflect market and other external pressures and the role of government policies and incentives. First, consider the evidence of various technologies:

- ***Oil platforms***. When oil companies started operating in the deeper waters of the North Sea, it was on the basis of projections of oil prices rising to levels of USD 50/bbl or more. In the early 1980s, it was estimated that the cost of oil from new deep water platforms would be around USD 25/bbl. Yet as oil prices declined, companies responded with strenuous attempts to cut costs, leading to radical innovations in platform design and project management. Today, deep-water fields are being developed by companies that believe that oil prices may not rise above USD 20/bbl for many years, probably with production costs on the order of USD 10/bbl. Such developments required extensive efforts and investment in new techniques and would not have occurred to anything like the same degree without the need to survive in response to declining oil prices. This is an example of learning by doing.

- ***Wind energy***. A similar story – this time stimulated deliberately by market incentives – can be told of the development of wind energy. Massive incentives in California induced quick market development, in which Danish technology – which had been backed for years in

Denmark – assumed a leading edge. Costs declined and cheaper, more reliable technologies developed on the back of the California incentives have led to rapid growth, particularly in Europe (and India), where capacity grew by about 25% a year throughout the 1990s. The costs have declined accordingly.

- ***Photovoltaic (PV) cells***. Watanabe and Griffy-Brown (1999) provide a detailed empirical and modelling study of the development of the photovoltaic solar cell in Japan. They highlight the central importance of technology learning and cost reductions through a combination of R&D and increased production volumes, applications in a range of interrelated technologies and knowledge spillovers between firms. They emphasise the need for investment as part of the creation of a "virtuous circle" between technology improvement, learning and spillovers.

At a more aggregate level, the history of energy efficiency analysis suggests similar conclusions. In 1980, the UK Department of Energy carried out an assessment of the potential for energy efficiency improvements in UK industry. They concluded that industrial energy intensities could be reduced by about 20% over the following ten years with cost-effective investments. In 1990, a new assessment concluded that most of the potential identified had in fact already been exploited, but that, despite lower energy prices, almost a further 20% of cost-effective efficiency improvements could be identified. The greater interest and investment in energy-efficient techniques in the United Kingdom and elsewhere had apparently helped to generate the development of more efficient techniques. Assessments by the IPCC continue to identify a similar scope for efficiency improvements. The process of developing new options continues. It is hard to judge how much is driven by energy price changes and greater investment in energy-efficient techniques, but it is notable that the assessment of remaining potential is not much lower in economies that are already much more efficient. The persistence of such results suggests that, in itself, investing in greater energy efficiency helps to stimulate and identify options previously overlooked. This is an example of the "ratchet effect", where price-induced technology improvements do not reverse, and better techniques, once developed and applied, are not forgotten or abandoned.

In terms of the macroeconomic response to the energy price shock and subsequent decline in energy prices, traditional econometric models based upon price elasticity would suggest that response to the price rise – a sharp decline in the trend of energy consumption – should have been mirrored by an equivalent rise after the price fall (after allowing for autonomous trends). This was not observed. Walker and Wirl (1993) found that "Energy demand since 1986 seems inconsistent with the notion of constant income and price elasticity reported in the literature." Gately (1993) concluded that "the response to price cuts in the 1980s was perhaps only one-fifth of that for price increases in the 1970s". Dargay (1993) pinpointed the reason: "high energy prices induced the development and application of considerably more energy-efficient technologies in all sectors of the economy, many of which will remain economically optimal despite falling prices".

Dowlatabadi (1998) has proposed that classical energy elasticity needs to be supplemented with an "energy efficiency response model" (EERM) of (demand-side) induced technical change, which responds to energy prices with a response "half life" of about ten years. He estimates that in 1960-75, the period of declining energy prices, the energy efficiency response was about -1.6% per year, and that in 1975-90, following the price rises, it averaged +1% per year.

In the 1990s, technology studies provided clearer quantification of some aspects of technology development processes. A strong empirical engineering literature has quantified progress ratios of cost reduction as a function of capacity and investment. These tend to place cost reductions at between 10% and 20% for a doubling of production volumes of most manufactured goods. There are exceptions that fall outside this range, and progress ratios greater than 20% are not uncommon in nascent technologies and new industries. For a review, see Grübler and Messner (1998); a more condensed analysis of the long-term evolution of energy technologies can be found in Grübler *et al*. (1999).

## Technology modelling

This section surveys the various approaches to modelling technical change in the main literature on the modelling of energy policy and the economics of climate change (Table 3). A later section will consider the ways in which technological modelling has recently been improved. Three categories of models can be identified: *i)* macroeconomic models, which are based on modelling economic systems and include E3 models (energy-environment-economy models); *ii)* energy sector models, which specifically focus on the energy sector and/or climate change policy; and *iii)* integrated assessment models, which combine highly aggregated models of climate change, economic activity and energy systems and emissions.

### *Macroeconomic models*

All these models produce a price response due to substitution between different inputs to production given changes in relative prices. This is a choice among available technology options. Technological change is different in that it changes the production function itself. In most macroeconomic models, the most common method of modelling technological change in the energy sector has been to assume that there exists an autonomous energy efficiency improvement (AEEI). This means that technological change, at least that part related to energy-consuming technologies, is exogenous to the model. There is simply an energy efficiency improvement that is applied to industrial production or energy demand (a number of models incorporate explicit representation of energy supply technologies and for these, technical change tends to be represented in terms of exogenous assumptions about how the costs of different classes of technology decline over time).

There are several serious problems with the AEEI, although it is better than a constant technology. First, because the models cover long time periods – up to 100 years – even small differences in the number chosen for the AEEI dramatically change the results with regard to economic growth, energy demand, costs of emissions reductions, etc. However, there is no consensus on the AEEI that should be used. As Mabey *et al*., 1997) observe, any change in the AEEI over time is arbitrary and unrelated to the policy variables that are modelled. Next, the AEEI can be expected to be different in different sectors and regions of the economies, so different levels of aggregation require different AEEIs. A disaggregated AEEI is needed, although this is not always considered. As Grübler and Messner (1998) point out, models with an AEEI typically result in a deferral of investment decisions until the technology has become cheap enough to be competitive. The problem with this is that such models ignore the problem of how the initial R&D and investment take place, and models with endogenous technical change do not support a strategy for investment in new technology.

The most fundamental problem with the AEEI is that it is not a reasonable approximation of observed technical change. Technological progress does not just happen but is a result of inventions, application of the inventions to production processes and products followed by the spread (or not) of the technology through the domestic and international economies. Dowlatabadi (1998) has demonstrated clearly that the AEEI is not really autonomous at all: he suggests it should be replaced by an "energy efficiency response model" of induced technical change that responds to energy prices with a response "half life" of about ten years, and he shows that this index has been strongly influenced by energy price changes. This is far more consistent with the observations of Dargay and others on asymmetric elasticity noted above.

Table 3. **Technical change in large-scale models**

| **Model** | **Type** | **Representation of technological change** |
|---|---|---|
| DICE (Nordhaus, 1994) | Macroeconomic computable general equilibrium model | Decaying AEEI |
| E3ME (Barker and Köhler, 1998) | Macroeconometric model | Semi-endogenous |
| EGEM (Mabey *et al*., 1997) | Macroeconometric model | Endogenous |
| G-cubed (McKibbin and Wilcoxen, 1993) | Macroeconomic computable general equilibrium model | AEEI |
| GEM-E3 (Capros *et al*., 1996) | Macroeconomic computable general equilibrium model | AEEI |
| GREEN (Burniaux *et al*., 1992b) | Macroeconomic computable general equilibrium model | AEEI |
| WARM (Carraro and Galeotti, 1997) | Macroeconomic computable general equilibrium model | Endogenous |
| IEA model (Vouyoukas, 1992) | Econometric energy sector | Hicks neutral change |
| MARKAL (Goldstein, 1991) | Energy engineering optimisation | Assumed reductions in production costs |
| MESSAGE (Grübler and Messner, 1998) | Energy engineering optimisation | Learning by doing |
| PAGE95 (Plambeck *et al*., 1997) | Energy policy simulation | No technology modelling |
| POLES (Bourgeois *et al*., 1999) | Energy engineering optimisation | Various, including learning by doing |
| FUND (Tol, 1999) | Integrated assessment model | Scenarios for technological development |
| ICAM3 (Dowlatabadi, 1998) | Integrated assessment model | Learning by doing and priced induced technical change |
| IMAGE (Alcamo *et al*., 1998) | Integrated assessment model | AEEI and priced induced technical change |
| Pizer (1999) | Integrated assessment model | AEEI |
| Prinn *et al*. (1999) | Integrated assessment model | Declining AEEI |
| den Butter and Wollmer (1996) | Macroeconomic computable general equilibrium model | Endogenous |
| MESEMET (Van Bergeijk *et al*., 1997) | Macroeconomic computable general equilibrium model | Endogenous |

The other main way in which technological change is considered in modelling is through explicit assumptions about the characteristics of available technologies, which are not necessarily currently fully exploited or developed. In particular, for the "bottom-up" or energy sector engineering models, many alternative energy technologies may be specified, all of which can be used for energy production if necessary, depending upon the required characteristics of the technology. The MARKAL energy sector models are a good example. This implies that the structure of energy production and the technology employed can change dramatically from the starting technology mix, but there is no new technological development as such.

Many of the macroeconomic models assume that a non-carbon "backstop technology" exists. This means that there is a form of energy production which is not currently commercially viable because production costs are significantly higher than for the currently deployed carbon technologies. If the price of energy increases significantly, through greater demand, taxation, exhaustion of new oil discoveries, etc., this backstop technology will become commercially viable and will take a significant role. Furthermore, it is assumed that this source effectively offers an infinite supply. A typical example is solar energy such as photovoltaics or perhaps fuel cells, which are expensive but use abundantly available natural resources. This assumption implies that there is a definite limit to the amount by which energy prices can increase (fixed by assumption in most models).

Energy-environment-economy (E3) models are a type of macroeconomic model which treats energy consumption and emissions in a consistent way with economic activity. This is particularly important in the long run, where the energy sector may change significantly in response to changes in energy prices, output, technological change, etc. They are usually economic models of regions of the world, such as the European Union or the United States, but also the world as a whole.

The DICE model has an exponential slowdown in productivity growth ($1-e^{dt}$), starting from a base of 1.41% per year in 1965 with the constant $d$ set at 0.11 per decade. Other macroeconomic environmental models such as GREEN, GEM-E3 and G-cubed have a constant AEEI, typically in a range of 0.5-2.5% a year. The OECD GREEN model (Burniaux *et al.*, 1992a) is a computable general equilibrium (CGE) model which divides the world into 12 regions (EU, United States, Japan, etc.) and 12 industrial sectors. The model has been run with various assumptions concerning the AEEI (initially 1% and subsequently with sensitivity studies, including a link to labour productivity). The limitations of the AEEI approach to technological change have been recognised by the modelling community, but "endogenising" efficiency improvements more realistically has proven difficult.

### *Energy sector models*

These are models designed to consider in detail the energy sector and emissions from energy production and consumption. They do not incorporate a complete model of economic activity and can be thought of as partial equilibrium models. They may have a detailed model of the energy sector and different energy sources and a much simpler model of the economy than that of the macroeconomic models. They often take overall economic activity as exogenous. With their more limited treatment of economics, these models tend to take simple approaches to incorporating technical change. However, their more detailed modelling of the energy sector often means that they allow specifically for the different characteristics of different energy technologies. If they are run with scenarios that incorporate or assume switches between energy technologies, these characteristics will affect energy costs and emissions from production.

The International Energy Agency (IEA) developed an econometric model of the energy sector that takes the macroeconomy as exogenous (Vouyoukas, 1992). This model does not calculate the overall cost of carbon taxation, for example, but predicts energy demand through to 2005. It was deliberately designed as a short- to medium-term model and has Hicks-neutral technical progress in all sectors, so that (exogenous or assumed) GDP growth is a result of implied technological progress. The PAGE95 model of energy policy has an assumed growth rate for each region, and technological development is an implicit assumption within the growth rate.

One of the most commonly used energy sector models is MARKAL (Goldstein, 1991), which has been used for several single-country analyses by the IEA (*e.g.* Kram and Hill, 1996). This is a dynamic linear programming model of the energy sector. It is a single region model, which optimises a choice between different energy technologies, abatement cost and $CO_2$ emissions targets. A database of different supply, conversion and demand technologies is used, with information on physical inputs, outputs and cost data (Gielen, 1995). Once the data have been entered, there is no change in the technology, *i.e.* there is no modelling of any process of technological development but only adoption of different, currently available (and costed) technologies. The model has been combined with a macroeconomic model (MARKAL-MACRO) to provide economic data for the energy system (Bueler, 1997).

### *Integrated assessment models*

The newer integrated assessment models combine macroeconomic approaches with energy sector models and specific consideration of the physical process of climate change. These models have the advantage of modelling the feedback between socio-economic and physical processes in a consistent way. The disadvantage is that, to have a tractable model that can be used for policy analysis, relatively simple sub-models for the energy, climate change and economic components are used. They also have simple treatments of technology, consistent with their very general nature. Some of these models use previously developed macroeconomic models such as GREEN (Prinn *et al.*, 1999) or DICE (the IMAGE model) for their macroeconomic component.

One way around the problem of modelling technological development is to run different scenarios with a wide range of different assumptions about technological progress. The FUND model takes this approach, using the IPCC scenarios and the IMAGE database scenarios. IMAGE itself incorporates energy-economy and industrial production sub-models. These model technical change using a combination of an AEEI and price-induced energy efficiency improvements. The latter depend on the lagged variable, costs of improving energy efficiency, energy prices, output and the scrapping rate of old equipment. Prinn *et al*. base their economic module on GREEN, implying a constant AEEI. Pizer, following the DICE model, has labour productivity as a random walk with exponentially decaying drift.

### *Technology sensitivity*

A significant problem in assessing the modelling of technology is the fact that technological development is a small part of these models and little effort has been devoted to studying the implications for the results of parameter values and different approaches to technological change.

A sensitivity study of the implications of model structure for macroeconomic models and integrated assessment models is currently in progress. This is a development and expansion of WRI (1997), which surveys macroeconomic modelling of $CO_2$ abatement for the United States. They use the meta-analysis methodology, which performs a regression on the combined results of the different models. GDP change is the dependent variable, with the characteristics of the models and the scenario assumptions, including a correction for the assumed level of $CO_2$ abatement. One of the variables of the models is whether or not they include a non-carbon backstop technology. If the price of the backstop technology is not set much higher than the fossil fuel technology, the costs of significant $CO_2$ abatement are much lower than for models that assume a high backstop energy price, *e.g.* six times the current average fossil fuel price. Their regression analysis finds that the incorporation of a backstop technology has a significant and positive influence on GDP (WRI, 1997).

OECD (1999) reports the results for a wide range of energy technology options for western Europe (EU and EFTA) using the MARKAL model. Although the focus is on materials rather than technology options, they give results for the application of alternative energy technologies. Note, however, that they model GHG reductions of 50% by 2030. Given such a large reduction over a medium time frame, the lack of economic modelling is a significant limitation. With this caveat, they find a total cost aggregated over the time frame of the analysis of EUR 280-380 billion, with an imposed constraint of 24% of primary energy use in 2030 from renewables. Burniaux *et al*. (1992a) report some sensitivity studies with the OECD GREEN model on the costs of reducing $CO_2$ emissions, with a baseline incorporating an AEEI of 1% a year. If the AEEI is reduced to 0.5% a year for all regions, global emissions in 2050 are 11% higher than the baseline of 19 billion tonnes of carbon in 2050.

The point to be taken from this brief overview is that most of these models suffer from the limitations of basing technological advances on an AEEI. Given the importance of technology and structural change for climate change, this is a serious weakness. The adoption of scenarios using more detailed models would be a more realistic approach.

### Induced technical change

Although the costs of many energy technology options have been declining for several years, the evidence shows that, once investment begins, there is a dynamic process of invention and innovation that, in the more promising cases, reduces costs further and opens up new opportunities for development. In other words, there is learning by doing. This is not a new suggestion and, as reflected in the discussion above, neither is the relevant evidence, which was already accumulated by the mid-1990s. Incorporation into economic modelling has, however, been slow. Nevertheless, the empirical evidence, together with developments in growth theory and other disciplines, including mathematical and computational techniques for analysing non-linear systems, have resurrected interest in induced technical change as a topic of economic modelling research. Since the early 1990s, studies relating this to energy systems and climate change have begun to appear.

The literature focused directly on the question takes two main approaches: *i)* incorporation of learning by doing, in which technology costs are a function of cumulative investment, recently extended to include learning interactions between different technology clusters; and *ii)* direct modelling of investment in knowledge/innovation. In addition, two simpler approaches, less dependent on complex modelling, have been brought to bear, and these are also considered.

#### *Learning by doing*

The most direct and empirically grounded category of approaches is explicitly to model learning by doing in technologies or systems. In a classic paper, Arrow (1962) identified learning by doing as an important source of technological advance. He hypothesised that “it is the very activity of production which gives rise ... to favourable responses over time”, and he demonstrated that “the presence of learning means that an act of investment benefits future investors, but this benefit is not paid for by the market ... the aggregate amount of investment will fall short of the socially optimum level”. In that sense, induced technical change can be considered as an external benefit. E3 modelling has begun to try and quantify this for some energy-environment models.

In the microeconomic situation, technology costs are modelled explicitly as a function of cumulative investment (or of installed capacity) in that technology. This approach was first applied to energy system scenarios by Anderson and Bird (1992), and Anderson (1999) has recently presented a more general formulation. Anderson and Bird found that by including learning by doing, scenarios could readily be developed in which renewable energy technologies became competitive and penetrated the global energy system on a large scale by the middle of the 21st century, leading to stabilisation of global atmospheric concentrations at around 500 ppm $CO_2$. This work was particularly influential for Shell’s thinking and development of global energy scenarios.

The potential for innovation increases uncertainties and possibilities. Recent simulation studies have explored possibilities with alternative values of the learning curve parameter applied to low-carbon energy technologies. They suggest that the long-run costs of substituting renewable energy forms (including linked technologies such as hydrogen and fuel cells) for fossil fuels range from being significantly more than those of the latter (although not unaffordably more) to significantly less, an economic surprise cannot be ruled out.

This is borne out by two sets of studies. Gritsevskyi and Nakicenovic (1999) present numerical results of a model which incorporates a very wide range of energy technologies and resources, coupled with learning by doing and learning spillover effects in technology clusters. The model itself was run stochastically under widely defined uncertainties in the input scenarios, generating hundreds of thousands of energy system scenarios for the next century. The resulting scenarios span a huge range of $CO_2$ emissions by the end of the next century. When the 53 least-cost scenarios were selected, the range of results narrows very little; instead, the central scenarios tended to disappear (Figure 1).

The importance of this result is not in the specific numbers and assumptions, but in the extraordinary range of possible least-cost outcomes and their bimodal distribution. It indicates that there are two broad directions for innovation in global energy systems: one based mostly on coal-based and carbon-intensive resources (including shale conversions, liquefaction, etc.), the other based on low- and zero-carbon resources (methane and hydrogen utilised with dispersed technologies including fuel cells, and with major roles for renewable energy and/or nuclear as primary sources alongside methane). The costs were indistinguishable within the range of uncertainties.

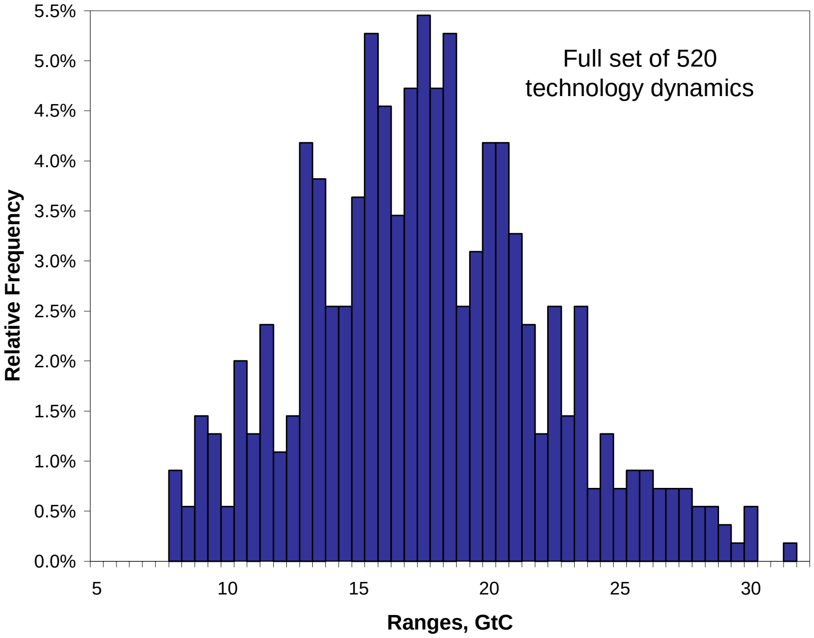
A study by Papathanasiou and Anderson (2000) represents the costs of the renewable energy alternative by an elementary learning curve, the key parameter of which was uncertainty. (Other uncertainties were also modelled, including uncertainties for the costs of climate change and the energy efficiency parameter in the energy demand equations.) The costs were discounted to present worth over the century. Figure 2 shows the distribution of the difference in costs between a future in which renewables take over a large part of energy production (Cr50) and a fossil fuel scenario (Crf). The important point is that the range of "abatement" costs is very wide, and seems as likely to be negative as to be positive in the long term, depending on assumptions about technical progress.

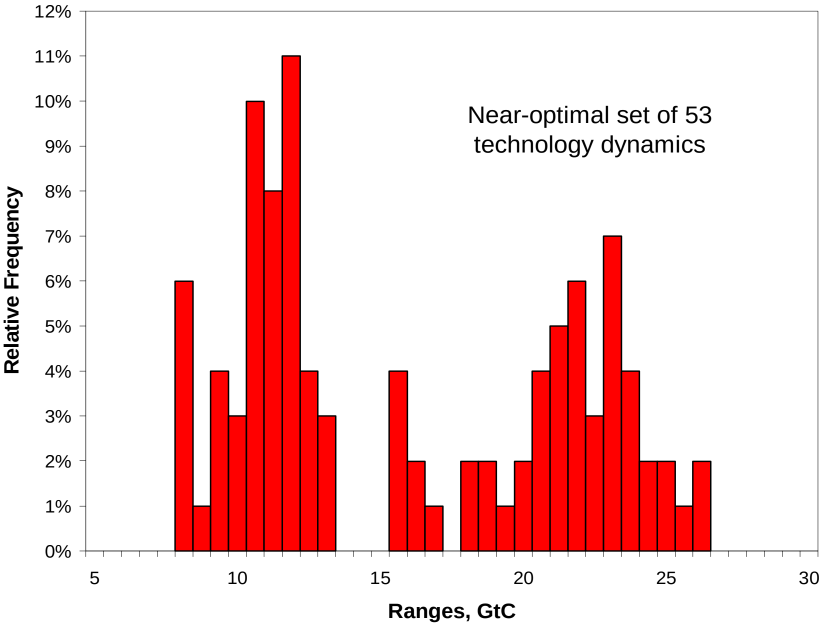
A similar conclusion, not based upon formal modelling, was argued by some of the energy literature surveyed in the IPCC Second Assessment Report, in particular in the context of the "low emitting supply scenarios" of the IPCC's Working Group II. One chapter attempted to integrate technology information elsewhere in the report by developing "low emitting supply scenarios" with global emissions down from 6 billion tonnes of carbon (GtC) in 1990 to 4 GtC in 2050 and 2 GtC by 2100, and argued that this might not involve costs additional to the "reference" scenarios, given the cost reductions that could be expected as production scales increased.

Anderson's work also has important implications for the technological developments of developing countries. Now that the technologies exist to address a large number of local and regional pollution problems in the industrial countries, developing countries can hope to address their problems at a much earlier phase of their development. Figure 3 shows the results of this learning by doing. It summarises some recent simulations of acid deposition in Asia, which consider by how much pollution could be reduced, and how soon, if the South and East Asian countries introduced gas and "clean coal" technologies earlier, rather than wait until their per capita incomes approached those of the industrial countries in the 1970s – as proponents of the now discredited environmental Kuznets curve hypothesis assume will happen (Anderson and Cavendish, forthcoming). Similar simulations for other pollutants, including $CO_2$, suggest that developing countries are in fact generally in a position to reduce pollution earlier in their development than the industrial countries.

Figure 1. **Forecasts of global carbon dioxide emissions**

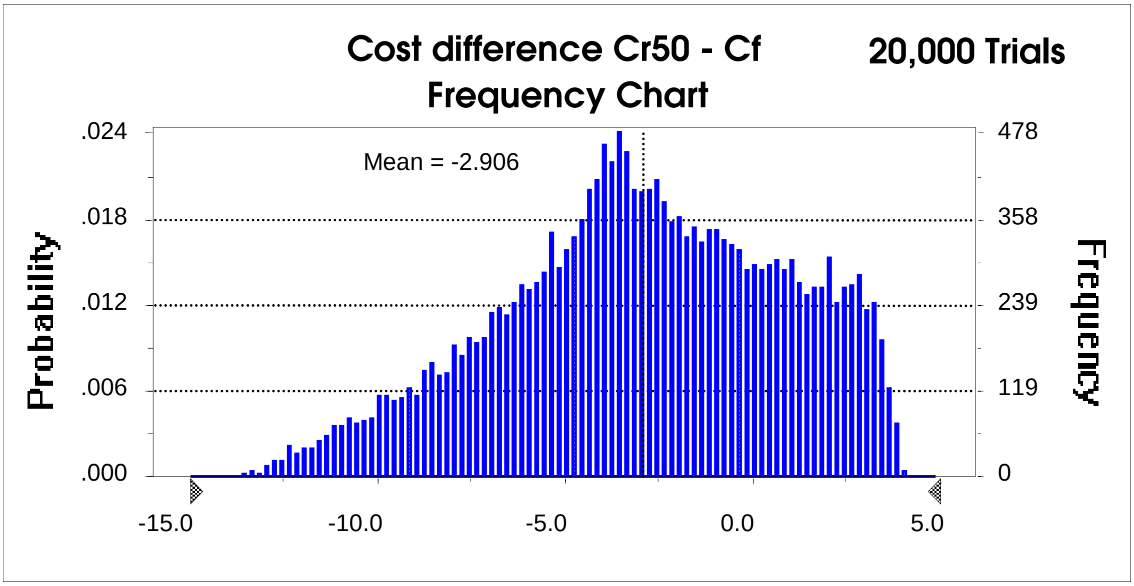
(with induced technical change under uncertainty: range of emissions by 2100)





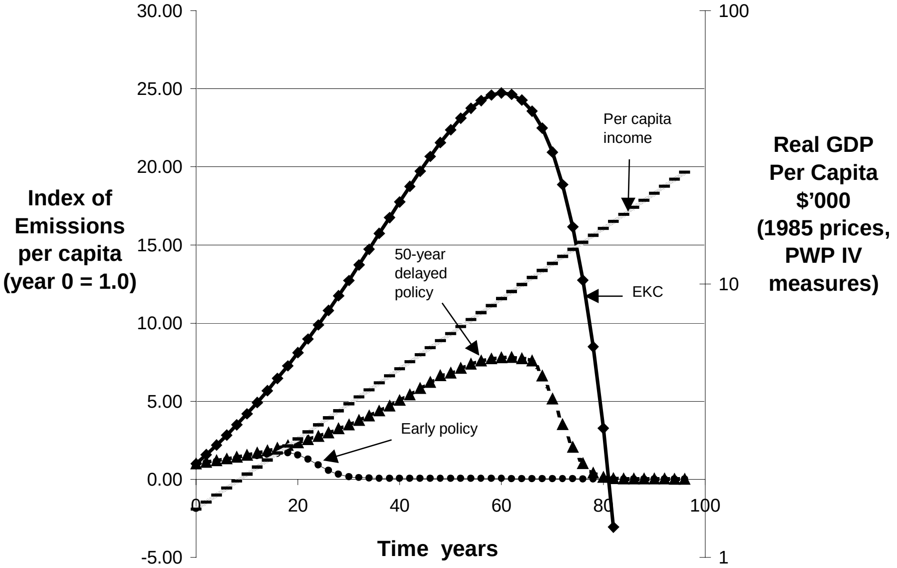
*Source*: Gritsevskyi and Nakicenovic (2000).

Figure 2. **Energy cost scenarios**[1]



1. The probability distribution of the difference in energy costs between a renewable energy scenario (Cr50) and a fossil fuel scenario (Cf).
*Source*: Papathansiou and Anderson (2000).

Figure 3. **Effects of environmental policy on emissions**[1]



1. Simulation results for $SO_2$ emissions contrasted with the EKC. Case: Initial real GDP per capita USD 1 500, growth rate: 3% a year.
*Source*: Anderson and Cavendish, forthcoming.

In general, therefore, induced technical change has a very large impact in these explicit technology-based models of learning by doing. Since addressing climate change involves such large-scale and long-term changes, the results suggest that the long-run economics of climate change policy cannot plausibly be considered without taking learning by doing fully into account. This contrasts strikingly with the aggregate economic models of investment in explicit knowledge sectors considered below.

Some strands of modelling produce less dramatic results. Goulder and Mathai’s (2000) aggregate macroeconomic model of learning by doing in carbon abatement appears to be somewhat at odds with the technology-based studies of innovation and to indicate that learning by doing has a far more modest influence. This could be due to various factors. Probably most important is the lack of sectoral disaggregation, and the corresponding reflection of the fact that marginal returns from learning by doing are likely to vary greatly for industries at different stages of development. Goulder and Schneider (1998) note that, in the real economy, the conventional energy industries “tend to be mature industries where learning-by-doing effects may be rather small”, in contrast for example to renewable energy industries. Another possible factor may be the specification of the way that knowledge accumulates and dissipates between time periods: their central case appears to involve 50% of the learning by doing gained in one period dissipating exponentially in each subsequent decade.

### ***Investment in knowledge/innovation***

The second class of modelling approaches treats innovation as a product of explicit investment in a knowledge sector. This is the most common approach in broader economic growth theory studies. In the field of climate change, it is represented by the work of Nordhaus (1994), Goulder and Schneider (1998), Carraro (1998) and the R&D-led study by Goulder and Mathai (2000). In principle, there are three main variants.

- One assumes that the economy operates with an optimal allocation of R&D resources in the absence of climate change, the disposition of which is affected by the existence of the climate change externality.
- One assumes that overall investment in innovation is constant but allows its disposition between sectors to change.
- One allows investment in innovation to reduce greenhouse gas emissions in an unconstrained way; “innovation resources” for reducing the cost of climate-friendly technologies could be drawn from any part of the economy.

In each case – but particularly the second – the sectoral disaggregation of the model may be a key aspect. For example, a likely response to $CO_2$ constraints would be for oil companies to shift R&D resources from R&D in frontier development of techniques for exploiting tar sands and shales – whose long-term future may be precluded – towards renewable energy sources. Even if overall investment in innovation is either optimal (a) or constrained (b), innovation responses to climate change do not necessarily withdraw “innovation resources” from the wider economy. Unfortunately, Nordhaus’s model, which is of type (b), has one aggregate energy-carbon sector with no opportunity for substitution towards non-carbon sources.

Goulder and Schneider (1998) model knowledge investment with separate representation of carbon-intensive and carbon-free sectors. Their results indicate that induced technical change may have a significant effect on the long-run costs of abatement, depending upon the assumptions adopted, but apparently to a much lesser degree than in the disaggregated models of learning by doing. Their rich analysis could be explored further, but its limitations are still the disaggregation of all technologies into just two sectors (carbon and non-carbon) and the absence of learning by doing. The Goulder and Mathai (2000) approach is to analyse investment in innovation with costs as a general function of abatement but without sectoral disaggregation. The impact is again relatively modest compared with the technology-disaggregated learning-by-doing models.

In general, the models so far applied in this category generate relatively weak responses to induced technical change, though, as Goulder emphasises, the long-run effect of addressing a problem like climate change on reducing costs may be substantial even in his model. The lack of sectoral disaggregation combined with other constraints may thus be one reason why these models generate weak responses to the incorporation of induced technical change. Given the striking discrepancy in their basic conclusions, the reasons for the differences between these two main classes of modelling approach require further exploration.

### *Simplified parameter models*

At least two other much simpler approaches have been brought to bear on the possible impact of induced technical change on energy-environment problems. One is that of Grubb *et al*. (1995), inspired in part by the modelling of Hourcade (1992) on the penetration of low-$CO_2$ technologies into the French energy system. This focuses on the potential of the overall system to adapt over time, subject to transition costs. It results in a relatively simple model formulation which is specified in terms of the degree of adaptivity (or malleability) of the energy system in the long run. The cost function is specified directly in terms of continuing and transition costs. The former correspond to classical equilibrium cost concepts, but it is argued that in fact a large part may be a reflection of the transition costs of innovation and infrastructure development as economic systems adapt to a new set of constraints and incentives. Under their high-adaptive/high-inertia case, these authors find that induced technical change is indeed extremely important: this case results in optimal scenarios that lead to stabilisation of atmospheric concentrations within a few decades, and the costs of deferred abatement are dominated by the lost opportunities of starting to adapt the energy system to $CO_2$ constraints.

The recent results of IIASA in particular, but also those of the wider energy technology literature, shed new light on this approach. The implication of the IIASA work (and the IPCC LESS scenarios) is that the identifiable range of possible least-cost energy systems in the long term is indeed extremely wide in terms of $CO_2$ emissions (and other characteristics). This lends strong weight to the hypothesis of long-term adaptivity of energy systems advanced by Grubb *et al.* (1995) and suggests that their highly adaptive case is perhaps more plausible even than they indicated.

More recently, Parry *et al.* (2000) address the question through an adaptation of classical supply curves. Within certain assumptions, they conclude that for many environmental problems the economic impact of induced technical change will be modest compared to the direct benefits of pollution abatement. If the problem is serious and urgent, major reductions in emissions should be made immediately and cost reductions from induced technical change should be a secondary consideration from an economic standpoint. Only if the initial optimal level of abatement is modest, and the problem is long-term, do they find that induced technical change may substantially affect the economics.

There are important limitations to this analysis. The major functional forms assumed are linear, and crucially, they assume no increasing returns or spillovers from innovation. By adopting an infinite time horizon, they are in effect making the total knowledge stock constant over time, which is of course quite unrealistic. Furthermore, it is striking that the conditions under which they admit that induced technical change may be very important – initially high abatement costs making initial abatement levels modest, but with a very long-term and ultimately potentially extremely damaging problem – are exactly the characteristics of climate change. These factors probably explain why the two sets of analysis are not as inconsistent as they first appear.

There is another way of viewing the results in terms of the long-term adaptability of the energy system. The future is uncertain. The further ahead we look, the more uncertain it is, and the more questionable become models that embody as a fundamental assumption an optimal “reference” future. The possibility for innovation in widely divergent directions further amplifies the uncertainties. Under such circumstances, one cannot credibly assume that there is a natural, knowable and well-defined least-cost optimum disposition of economic resources, including resources for innovation; uncertainty is intrinsic and the hypothesis of long-run malleability of energy systems – that innovation can be directed in various directions at costs that are not distinguishable – becomes more plausible.

It is important to understand this point. It is not that long-run uncertainty about the optimal system is exactly the same as malleability (the capacity to adapt). The former implies that the current (and historic) direction of innovation may be sub-optimal, or “distorted”, because governments and market actors do not know enough. The latter implies that the optimum is genuinely unknowable, in a quite fundamental sense. However, in terms of implications for current policy decisions, the two views are in important respects indistinguishable. They both amplify the returns to policies that induce innovation in directions that reduce identified externalities. Grubb *et al.* (1995) suggest that in the context of a long-term problem like climate change, this effect dominates the more direct benefits of externality reduction.

Indeed, most innovation over the last century has been in the direction of expanding fossil fuel activities and technologies, and neglecting the various environmental externalities associated with use of fossil fuels. Therefore, it would not be surprising if the returns to innovation in new energy technologies, which also help to reduce externalities that were previously not factored in, yield large returns on innovation that also cumulatively yield large reductions in the externality.

## Implications for modelling

This section surveys recent developments in modelling technological change within economy-wide E3 models. The mathematics are described in Appendix 2. The shortcomings of the current models are assessed and directions for future improvements are suggested.

First, it is worth clarifying why so few major economic models have incorporated induced technical change. The answer is simple: it is very difficult to do so. Specifically, the incorporation of induced technical change immediately implies non-linearity and the introduction of path dependence – the costs of an option depend upon what has happened before. This introduces a qualitative step and can introduce the phenomenon of multiple equilibria: there may be no optimum solution, or at least no mathematical technique can find the lowest of possible costs because many different directions are possible. These are general features of such non-linear systems, which have potentially increasing returns to scale (Arthur, 1994). This is clearly illustrated by the IIASA studies, which show a huge range of potential long-term $CO_2$ emissions for systems that differ very little in terms of costs. Introducing such complexities into models that are already complex in terms of the number of variables is not for the faint-hearted. Nevertheless, efforts are increasingly being made and are described below.

### *Macroeconomic models*

There are now various models in which technological change is treated as endogenous. The E3ME model can be seen as a first step in this direction. Developing Lee *et al.* (1990), technological progress in each industry and region $T_t$ follows a recursive relationship dependent on gross investment and R&D expenditure. While this approach has the merit of simplicity and the data on investment and R&D expenditures are mostly available, it is still simplistic. The theory assumes, following Kaldor, that technological progress is linear in terms of gross investment. This assumption has been questioned by Bairam (1999). Also, the theory has no microeconomic underpinning. However, the relationships are disaggregated by region and industry.

Recently, macroeconomic models have begun to consider endogenous technical change in a more sophisticated manner. In the EGEM model, technical progress is considered in the aggregate energy demand equations and in the production function of the representative firm. Aggregate fossil fuel consumption is dependent on fuel prices, lagged differences in consumption and a time trend. The time trend is dependent on lagged fuel prices and endogenous trend determinants: non-fossil fuel supply, manufacturing component of GDP, trade, investment. In the production function, when a variant with endogenous technical change is used, the CES-type production function has the energy equations factored out and includes an exogenous technical trend term and the proportion of labour productivity associated with technical change embodied in capital equipment. The equations and parameters are estimated separately for each country.

The WARM model also includes an endogenous variable of technical change. Changes in the polluting and non-polluting capital stock are dependent on other variables in the models, the parameters for the equations being econometrically estimated. Both approaches represent a considerable improvement in the modelling of technical change. As well as allowing technical progress in energy demand and/or productivity to depend on economic variables such as output and prices, they estimate equations that also allow for some dynamic adaptive effects. The limitation of the WARM model is that only two forms of capital are allowed; consideration of the actual technologies that are currently known is aggregated into the parameters estimated for a representative firm for each country as a whole. Thus it presents a very abstract analysis of technology.

### *Energy sector models*

Some of these models also incorporate ideas in the technology literature about the dynamics of technical change. The MESSAGE model incorporates learning-by-doing effects; for a new technology, in particular, the cost of the technology $C$ is a function of the number of installations $x$: $C(x) = b1x^{-b2}$ where $b1$ is the cost of the first unit and $b2$ is the learning index. It also takes account of uncertainty by employing a stochastic, rather than a deterministic, optimisation technique.

The POLES model incorporates both learning effects and the other main theme of the technology literature, the idea of the diffusion of a new technology through an economy as described by "diffusion curves". Different sectors have different treatments. The final demand sector has an AEEI. In the centralised electricity generating sector, technical improvement comes through investment in new plant, with market shares a function of existing capacity structure and relative costs. This brings an element of path dependence to the sector. For the primary energy production sector, coal, nuclear and hydroelectric have an AEEI. For the oil sub-sector, technological improvements in oil recovery are dependent on prices and an AEEI. New and renewable energy technologies have a more complex treatment of technological development, in three steps. In step 1, the costs of the technology are dependent on cumulative production (a learning effect) and an AEEI. Step 2 introduces a logistic curve for the share of technical potential that is realised as economic potential, dependent on the payback period. The final step is the diffusion of a technology, with a typical logistic diffusion curve. The speed of diffusion coefficient is endogenous, dependent on the payback period.

Grübler *et al*. (1999) contains an initial analysis of a combined modelling approach. They combine the stochastic MESSAGE model with a conventional global macroeconomic model – the MACRO model (Manne and Richels, 1992). The energy modelling incorporates learning curves that combine cumulative R&D expenditures and investment expenditures for three energy technologies. The competitive position of each of these technologies is characterised by its position on a diffusion curve, described as "radical", "incremental" and "mature".

### Integrated assessment models

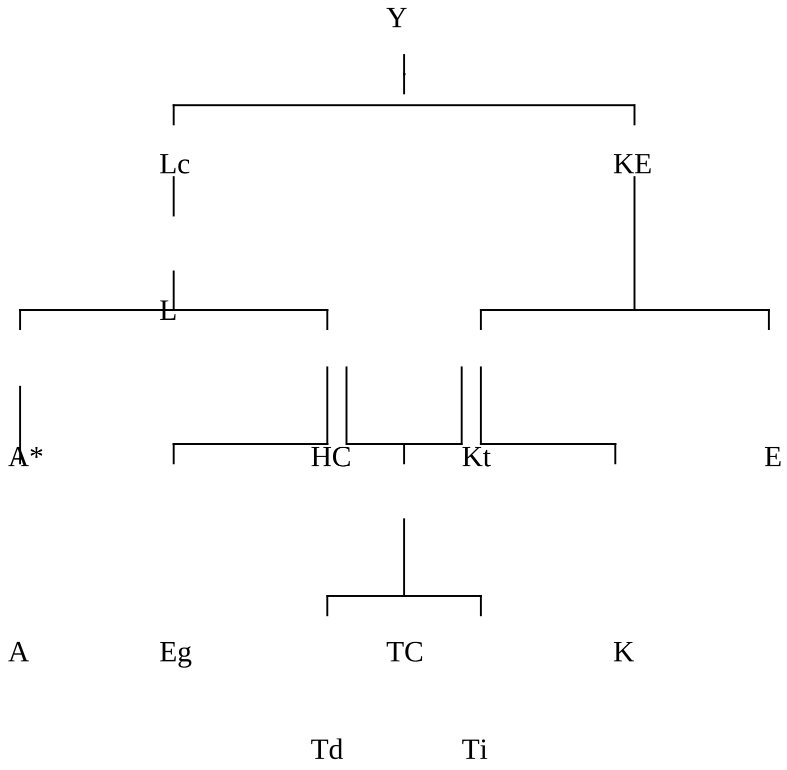
ICAM3 (Dowlatabadi, 1998) has a relatively complex structure for technological change, with three aspects. First, expectations of price increases may lead to technological innovation and diffusion. Next, given oil and gas prices above a certain threshold, new extraction activity is generated and the cost of non-fossil production decreases. Finally, the model has been run in a version incorporating reductions in the cost of non-fossil-fuel energy due to learning by doing. It is a sequential decision model, not an economic optimisation model, and for this reason has perhaps received less attention in the economics arena.

### General models

The literature on technology effects in macroeconomic models that do not emphasise energy indicates a way to incorporate insights from technology studies into macroeconomic models. The first example of such an approach is den Butter and Wollmer (1996), who use a disequilibrium macroeconometric model of the Dutch economy with a nested CES production structure incorporating technology capital with spillovers into human capital. The production structure is shown in Figure 4. The innovation in modelling here is that technology capital and human capital are explicitly considered. Also, there are spillovers from the stock of technology capital into human capital and hence labour productivity. The rationale is that the use of technology involves "learning by doing" or "learning by designing" when technology capital is employed.

The MESEMET model (van Bergeijk *et al*., 1997) develops these ideas further. Also using a macroeconometric model with nested CES production functions, they have a treatment of human capital with spillovers. Both investment and R&D expenditure have spillovers into human capital, which then affects labour productivity as in den Butter and Wollmer. Technology capital accumulates with $RD_p$ and $RD_g$, with the price of $RD_p$ determined by wages, capital costs and tax allowances for R&D. Furthermore, exports depend on the ratios of domestic to foreign technology capital and domestic to foreign human capital.

Figure 4. **Nested structure of production model**



Where:

Y is output
L is efficiency units of labour
Lc is L adjusted for changes in contractual working time
KE is composite inputs of capital and energy
A is labour demand, A* is full capacity labour demand
HC is human capital
K is physical capital, Kt is efficiency units of capital
E is energy inputs
Eg is government expenditure on education
TC is technology capital, Td domestic and Ti imported technology capital

### *Shortcomings of current approaches*

As can be seen, the importance of technology modelling has been recognised by modellers and many methods have been used. The literature has developed considerably in the last ten years. Given the fundamental importance of technology modelling for the results generated by these models, the inadequacy of the AEEI approach is now widely recognised. There is also an extensive microeconomic and engineering literature on technological development, both in industrial analysis and more specifically in the energy sector and for environmental technologies. At the global level, empirical analysis has been limited by a lack of reliable data. However, as Anderson (1999) argues, it is possible to use engineering cost estimates as a first step where economic data are inadequate.

The question then is, how should these large-scale models incorporate the insights of the microeconomic literature? It is important to stress that there is no single answer. Different models are designed to meet different objectives, with varying levels of aggregation, time spans, policy analysis, technology forecasting, etc. There is as yet no consensus on how to proceed. However, certain ideas have become widely accepted. Technological development is recognised as a dynamic process. There are different technologies and often different associated infrastructures, leading to clusters of technologies (Grübler *et al*., 1999). This means that it is necessary to study the dynamics of technological choice and regime switching, in addition to the dynamics of development of individual technologies.

At the highest level of aggregation, the approach of integrated assessment models in which differing scenarios are postulated is a valid one. This assumes that the scenarios are viewed as realistic or feasible and leads immediately to the question of how the scenarios are generated. If technological progress is to be modelled, the process must be endogenous. Time series econometric methodology enables a high level of aggregation to be employed, but its shortcoming is a backward-looking approach. This means that not only are reasonable time series data required, but significant departures from historical experience cannot be accounted for. Consequently, this form of modelling is only applicable to the short/medium term in which the technological regime does not change radically.

For models concerned with the long-term future, with possible radical changes in technology, a different approach is necessary. There are now many different energy and environmental technologies, some of whose characteristics are very different from those of the technologies currently in common use. For example, very low emissions technologies such as solar photovoltaics require no energy extraction, and a hydrogen-fuelled economy would require a new infrastructure (Grübler *et al*., 1999). The technological and economic characteristics of new technologies can be identified. The spread of technologies can be modelled through the use of diffusion curves, the Bass diffusion model or epidemic models (Kemp, 1997). Changes in the technology from learning effects and the consequent influence on firms' decisions can be incorporated in such models.

The models have to reflect a high degree of path dependence; once a technology and the associated infrastructure are established, a new technology requiring a different infrastructure will be at a considerable competitive disadvantage, even if it offers significantly improved performance. In contrast, new technologies that can use the existing infrastructure will be more readily adopted. This path dependence implies that many radically different futures are possible, with associated differences in technologies, emissions patterns over both time and geographical region, changes in industrial structure, etc. The study of which paths may occur will have to be based on a microeconomic analysis.

A further and also fundamental issue is the fact that radical technological changes will be accompanied by radical social and economic changes. It is necessary to imagine the different socio-economic environments and economic structures that accompany the alternative technological futures. An element that is absent from all the models surveyed here is the possibilities for energy conservation, with significant changes in the pattern of energy demand that may be independent of energy technologies. This is probably the most difficult task when attempting to propose long-term futures.

Such considerations underscore the problem of incorporating uncertainty in the modelling process. Use of a wide range of scenarios to cover alternative futures is helpful here; the models that are econometrically estimated only allow for uncertainty in a limited way. More generally, models that incorporate decision processes should allow for decision makers' attitudes to risk. Current technologies may become unsustainable, if climate changes require significantly less polluting technologies, or supply shortages (due to physical or political factors) may increase economic costs. Models that look at the medium to long term and take specific account of uncertainty will often generate hedging strategies, in which a range of possibly expensive alternative technologies is pursued to allow for possible future limits to supply.

The most satisfactory approach is probably that of Grübler *et al*. (1999), because they combine macroeconomic analysis with learning curves and diffusion curves for different energy technologies in a stochastic model. However, theirs is only an initial analysis covering three notional technologies. It is necessary to identify the parameters, or rather plausible ranges of values, for such curves for known technologies. Also, there is a question of whether and how the issues of spillovers between technology, R&D efforts and human capital should be addressed. These, together with future changes in the socio-economic structure, are as yet little understood, but are essential for policy analysis.

## Policy implications

### *Cost implications*

Most modelling studies show that induced technical change can dramatically affect aggregate estimates of the costs of addressing large-scale and long-term issues like climate change. By including estimates of technical change functions derived from the empirical engineering literature, it is well within the bounds of uncertainty that long-run challenges like climate change may be addressed at low or zero long-run costs, owing to the long-run accumulation of learning by doing for low-carbon technologies. This is also apparent from more aggregated studies, including the possible evolution of developing countries by Anderson (1999), and the model of adaptability by Grubb *et al.* (1995). Dowlatabadi (1998) notes that incorporating induced technical change has a big impact on costs in the ICAM model.

We do not know whether or not atmospheric stabilisation will prove costly in the long run. However, there is good evidence to suggest that it may not be. If technical change is largely induced, we may never find out unless we start moving towards that goal.

Moreover, most of the available studies suggest that the modelling of induced technical change is crucial to conclusions about the degree and timing of policy intervention and the cost of delay. If technical change is largely autonomous (exogenous to the model), model results suggest it may be cheaper to wait for better technologies to come along. If it is largely induced (endogenous to the model), then most models indicate that the value of early action is far greater, because it is abatement itself that generates the knowledge required to solve problems at low cost and builds up efficient industries and infrastructure. Again, the studies by Anderson illustrate that costs are brought down in part by early action which stimulates the growth of technologies that shift and bring down the peak of the “Kuznet’s curve”. The aggregated model of adaptability of Grubb *et al*. (1995) estimates the costs of delay in addressing climate change to be several times higher with adaptability than when there is no induced technical change.

An implication to emerge from the analysis of costs and technical change is that the positive externalities of innovation are appreciable and have environmental benefits. This thinking underlies the “Porter hypothesis” (Porter and van der Linde, 1995) that environmental regulation may bring economic benefits by stimulating companies to innovate in ways that are economically beneficial and of wider application. Induced technical change is an economic formalisation of this hypothesis. In the context of problems like climate change, the literature surveyed suggests that there may be a significant “first mover” benefit, although this remains extremely hard to quantify.

### *Policy instruments*

This lends support to the argument that technology policy, including support for R&D and the provision of incentives for investment in innovative technologies, should be a key component of climate change policies. There is, however, no straightforward relationship between, say, government R&D and changes in overall technical efficiency over time. This is because the problem has an inherent uncertainty – it is not possible to know what specific technologies will be successful in the future. The energy industry is typical in this respect. There are many different technologies available for energy production, with a wide range of technical and economic characteristics. Therefore, policy should be directed at encouraging the development of many different technologies and providing an economic environment in which R&D is encouraged. This suggests that new technologies that are not in common use and are therefore relatively expensive should be supported. A good example is photovoltaics, which are currently relatively expensive, but whose costs would shrink rapidly with the onset of mass production. Also, a supportive economic environment includes the efficient functioning of the labour market for high-technology jobs and the availability of finance for speculative R&D. These are both policy issues about which much has been written; a detailed discussion of education policy, university research and institutional funding of R&D is, however, beyond the scope of this study.

Specific policies include other investment incentives for the adoption of new, environmentally friendly innovations. The importance of such policies is that they create options that would not otherwise exist, or at least bring their development forward, and that they reduce costs. They also have the merit of reducing the scale of the carbon tax that would ideally be needed to encourage substitution in the long term and seem an ideal complement to the standard instruments of environmental policy. Some limited research has been done on learning curves, but it is elementary. Not enough is known about the parameters of the cost functions and their relation to industry investment, to R&D in laboratories and, more generally, to public policies.

It is also possible to subsidise the purchase of energy from particular sources such as renewables, as is already done in Germany and Denmark. These policies provide price signals to the market that increase the use of the desired technology. Given the economic dynamics involved and the long time scales for significant technical change in the energy industry, it is not practicable to define an "optimal" policy. However, it is possible to identify new or currently small-scale technologies that should be supported based on the principle that the technology has characteristics significantly different from the current main technologies and reduced environmental impact. It also has to be understood that many, and indeed most, technologies that are supported will not take off and are highly risky investments. However, the long-term payoff may be very large indeed, given the potential costs of global warming, for example.

The distinction between autonomous and induced technical change highlights the need for an appropriate mix of policy instruments. Government R&D undoubtedly remains important for some fundamental research, and its decline in liberalised energy markets is a source of concern. However, to the extent that technical change is induced by market pressures, it – and corporate R&D – will also respond to policy. Clear conclusions on this topic cannot be drawn from the aggregate policy literature. However, detailed studies of sectoral policies, such as the promotion of renewable energy markets in Europe (Eyre, 1998) and explicit "market transformation programmes" for energy efficiency (Duke and Kammen, 1999), show the important role of policies that stimulate market-based innovation.

These policies tend to be sectorally specific. In addition, they may often stray from the traditional maxim of cost minimisation. Indeed, in European renewable energy policies, greater incentives are frequently given to stimulate investment in newer and higher-cost technologies that may hold greater long-run promise (such as biomass gasification and photovoltaics). Induced technical change therefore militates against the traditional focus on equalising marginal costs in a single period (and hence single-period cost minimisation) because of the economic dynamics involved.

A better understanding of the problems posed by uncertainty is also needed. Uncertainties extend to the costs of responding to climate change as well as to the external costs of climate change itself. The sheer magnitude of the uncertainties means that the option value of technology policies is likely to be large – something that has so far been ignored by deterministic studies of the climate change problem, indeed by the large majority of studies published and reviewed to date.

### *Spillover and leakage*

Economic models in which technology is exogenous almost invariably find that action by some (industrialised) countries to limit $CO_2$ emissions is partially offset by some "leakage" as polluting industries migrate. The ICAM model (Dowlatabadi, 1998), however, illustrates the opposite effect in the presence of induced technical change, and a study by Grubb (2000) notes that induced technical change has potential implications not only for long-run $CO_2$ and other emissions, but for the whole concept of "spillover" and "emissions leakage" associated with action by industrialised countries.

Economies worldwide are increasingly interrelated through flows of trade, investment, technology and ideas; furthermore, they are becoming steadily more integrated through globalisation. In some sectors, this is already an intrinsic feature of industrial structure, and demands for improved efficiency or low-carbon technologies in the industrialised world – which still accounts for the great majority of such companies' sales – will have a similar impact on their global product lines. There will also be demand-side pressures from the developing countries, which, as they grapple with their own resource and pollution problems, increasingly strive to ensure that they harness the better, cleaner, more efficient technologies developed in the industrialised countries. India, for example, is now the second largest market in the world for renewable energy after the European Union.

The consequence is that lower-technology carbon technologies developed in response to emission constraints in industrialised countries can be expected to diffuse internationally, countering the substitution-based leakage observed in traditional economic models. The net result is a balance of these different forces. The substitution-based leakage has been widely studied; the final draft of the IPCC Third Assessment Report [IPCC (2000); WG-III Chapter 8] notes that:

> "A number of multiregional models have been used to estimate carbon leakage rates (Martin *et al*., 1992; Pezzey, 1992; Oliveira-Martins *et al*., 1992; Manne and Oliveira-Martins, 1994; Edmonds *et al*., 1995; Golombek *et al*., 1995; Jacoby *et al*., 1997; and Brown *et al*., 1999). In the SAR (IPCC, 1996, p. 425) it was noted that there was a high variance in estimates of emission leakage rates; they ranged from close to zero (Martin *et al*. using the GREEN model) to 70% (Pezzey, 1992, using the Whalley-Wigle model). In subsequent years, there may have been some reduction in this variance, in the range of 5% to 20%."

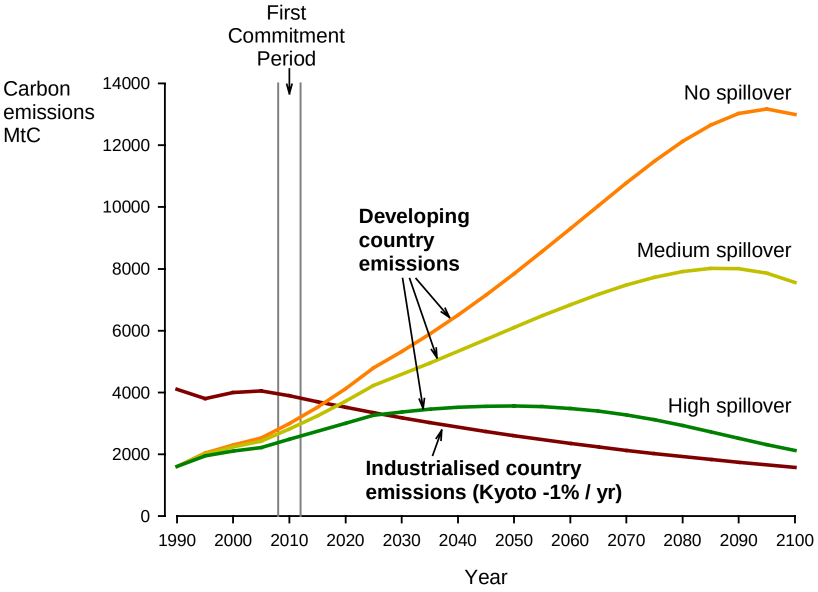
The last is an understatement. Pezzy's was the only study with leakage rates substantially in excess of 20% and he has since retracted this result as invalid (personal communication).

However, no global models yet exist that could credibly quantify directly the process of global diffusion of induced technological change. This is because there are as yet no models that link induced technical change to international diffusion processes. However, the degree of potential intensity improvements arising, for example, from the technologies summarised in Table 2 are frequently an order of magnitude or more greater than traditional leakage rates in the 5-20% range. The international diffusion of technical change is already acknowledged as an important process and is still growing rapidly, owing to many factors.

It therefore seems likely that the international diffusion of cleaner technologies, given time, will outweigh the negative impacts of substitution-based leakage. In the absence of more specific process-based models, Grubb (2000) uses emissions intensity, defined as the ratio of $CO_2$ emissions to economic output, as a proxy indicator of technology choice and international diffusion, as well as other potential international linkages.

In this scenario, in the absence of international spillovers, emission intensities in developing countries are projected roughly to halve in the "business-as-usual" case by 2050, by which time they would have reached roughly the levels of the industrialised world in 1990. By 2100, emission intensities in the developing world are about five times those in the industrialised countries. In the case of full international spillover, however, intensities decline roughly twice as fast to 2050, and, as specified, they converge to the levels of the industrialised countries by 2100, as the technologies and practices induced in the industrialised countries diffuse through the developing world. Figure 5 illustrates the impact on total developing country emissions, which can be very large.

Figure 5. **Spillover and emissions intensity**



Although the parameterisation is highly uncertain, the basic implication is that global emissions are very sensitive to the degree of technology spillover, and that even relatively low levels of spillover are sufficient to offset the classical components of "leakage". Over time, the diffusion of cleaner technologies, induced by action in the industrialised countries, outweighs classical components of leakage (such as the impact of the migration of dirty industries) and the overall result of action within industrialised countries is to reduce emissions elsewhere as well.

## Main conclusions

The main conclusions of this review are summarised in Table 4, which compares the modelling and policy implications of autonomous *vs.* induced technical change. It is apparent that the distinction is very important and should be addressed and better understood. Addressing it properly will require development of new and quite complex modelling techniques and will alter the range of economic and policy implications set out above.

Table 4. **Implications of autonomous *vs.* induced technical change**

| | **Autonomous technical change** | **Induced technical change** |
|---|---|---|
| **Process** | Technical change depends mostly on autonomous trends and government R&D | Technical change depends mostly upon corporate investment (R&D, and learning by doing) in response to market conditions |
| **Modelling implications** | | |
| Modelling term | Exogenous | Endogenous |
| Typical main parameter | AEEI / projected costs | Learning rate / progress ratio |
| Mathematical implications | Usually linear | Non-linear, complex |
| Optimisation implications | Single optimum with standard techniques | Potential for multiple equilibria, perhaps very diverse, complex techniques |
| **Economic / policy implications** | | |
| Implications for long-run economics of large-scale problems (*e.g.* climate change) | Stabilisation likely to be very costly | Stabilisation may be quite cheap |
| Policy instruments and cost distribution | Efficient instrument is uniform Pigouvian tax + government R&D | Efficient response may involve wide mix of instruments, targeted to reoriented industrial R&D and spur market-based innovation in relevant sectors. Potentially with diverse marginal costs |
| Timing implications | Defer abatement to await cost reductions | Accelerate abatement to induce cost reductions |
| “First mover” economics | Costs with little benefits | Costs with potentially large benefits |
| Spillover/leakage implications | Spillovers generally negative (positive leakage) | Positive spillovers may dominate (leakage likely to be negative over time) |

*Appendix 2*

# MATHEMATICAL APPROACHES TO MODELLING ENDOGENOUS TECHNICAL CHANGE

## E3ME

The E3ME model can be seen as a first step. Developing Lee *et al.* (1990), technological progress in each industry and region $T_t$ follows a recursive relationship:

$$T_t = \text{const.} + \text{const.}\ d_t(t1,t2) \tag{A.1}$$

$$d_t(t1,t2) = t1\,d_{t-1}(t1, t2) + (1-t1)\ln(GI_t + t2\,RD_t) \tag{A.2}$$

where

GI is gross investment

RD is R&D expenditure

*t1* is a measure of the impact of past quality adjusted investment

*t2* is a measure of the weighting of R&D expenditure.

## EGEM

In the EGEM model, technical progress is considered in the aggregate energy demand equations and in the production function of the representative firm. Aggregate fossil fuel consumption $C_t$ follows:

$$\ln C_t = a1 + T_t + a2\ln(C/Y)_{t-1} + a3\ln(RP)_{t-1} + E_{i,k}\,\&_{ik})\ln(Z_{i,t-k}) \tag{A.3}$$

and the (partly) endogenous time trend $T_t$ is:

$$T_t = T_{t-1} + B_{t-1} + a4\ln(RP)_{t-1} + E_i 0_i\, X_i + ,_t \tag{A.4}$$

$$B_t = B_{t-1} + <_t \tag{A.5}$$

where

Y is GDP

RP is weighted average real fuel price

Z is a vector of lagged differences in consumption, Y, price

X is a vector of endogenous trend determinants: non-fossil fuel supply, manufacturing component of GDP, trade, investment.

*a1, a2, a3, a4* are (constant) coefficients

& and 0 are parameter vectors

and < are independent stochastic terms.

In the production function, when a variant with endogenous technical change is used, the CES type production function has the energy equations substituted out and includes an exogenous technical trend term and the proportion of labour productivity associated with technical change embodied in capital equipment. The equations and parameters are estimated for each country separately.

## WARM

The WARM model also has an endogenous model of technical change. If

$k_{tot} = k_e + k_p$ A.6

$g_{tot} = g_p + (g_e - g_p)(k_e / k_{tot})$ A.7

where

$k_e$ is environment friendly, $k_p$ is environment polluting capital stock

$g_e$ and $g_p$ and $g_{tot}$ are the respective capital growth rates.

Let

$g_e - g_p = f(x)/(k_e / k_{tot}) + x,$ A.8

and

$g_p = h(w, <)$ A.9

where

x and w are sets of explanatory variables

and < are independent stochastic terms.

Since $g_e$ and $g_p$ cannot be directly observed, equations A.7-A.9 are rewritten in a state space form, incorporating an adjustment speed term, and estimated using a Kalman filter.

## ICAM3

ICAM3 has a relatively complex structure for technological change, with three aspects. Expectations of price increases may lead to technological innovation and diffusion, in region j at time t:

$$T_{t,j} = 6(y_j) + E_{i = 1,3}\,\&_i(\,p_{j,t} - p_{j,t-5i})/\,p_{j,t-5I} \qquad \text{A.10}$$

where

$6(y_j)$ is the base energy efficiency as a function of per capita income

p is the average price of energy (expenditure weighted)

$\&_i$ are constant coefficients, with 5i years lag (the model is solved in steps of 5 years).

Next, given high oil and gas prices above a certain threshold, new extraction activity is generated and the cost of non-fossil production decreases. Finally, the model has been run in a version incorporating reductions in the cost of non-fossil fuel energy $C_t$ due to learning by doing:

$$C_t = C_o\,(Q_t^{-a}/Q_t) \qquad \text{A.11}$$

Where

$C_o$ is the initial cost for the unit product

$Q_t$ is the cumulative units produced

a is the factor by which experience reduces costs.

## MESEMET

The MESEMET model (van Bergeijk *et al*., 1997) uses a macroeconometric model with nested CES production functions and a treatment of human capital with spillovers as follows:

$$HC\rho = \mathit{a1}HC\rho_{t-1} + \mathit{a2})K\rho + \mathit{a3}RD\rho_p + \mathit{a4}\,RD\rho_g + \mathit{a5}E\rho_g + \mathit{a6}\,T\rho \qquad 6.14$$

Where

HC is human capital

)K is investment in physical capital

$RD_p$ and $RD_g$ are private and government research and development expenditures

$E_g$ is government expenditure on education

T is the marginal tax rate on labour

$\rho$ represents rates of change

*a1* to *a6* are coefficients.

Both investment and R&D expenditure have spillovers into human capital, which then impacts on labour productivity as in den Butter and Wollmer (1996). Technology capital accumulates with $RD_p$ and $RD_g$, with the price of $RD_p$ determined by wages, capital costs and tax allowances for R&D. Furthermore, exports depend on the ratios of domestic to foreign technology capital and domestic to foreign human capital.

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*Annex*

# WORKSHOP AGENDA

**21 June 2001, Salle Roger Ockrent, OECD, Paris**

**Chair (morning)** -- Thorvald Moe, Deputy Secretary-General, OECD

**Chair (afternoon)** -- Daniel Malkin, Head, Science and Technology Policy Division, DSTI

**General discussants** -- Jonathan Kohler, University of Cambridge, UK
Frans Berkhout, SPRU, UK
Richard Newell, Resources for the Future, US
Jean-Charles Hourcade, CIRED, Paris

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**First Session**: Technology and Environment: How Economic Theory Informs Policy

*From Exogenous to Endogenous and Beyond* – David Pearce, CSERGE, London

*Discussant:* Alan Sanstad, Lawrence Berkeley National Laboratory, US

**Second Session**: Technology and Environmental Modelling: Lessons for Policy

*Overview of Models and Their Policy Insights* – Michael Grubb, Imperial College, London, and Cambridge University

*Discussant*: Patrick Criqui, IEPE-CNRS, Grenoble

**Third Session**: Role of Technology Policy in Addressing Environmental Concerns

*Technology Policy View* – Risaburo Nezu, OECD Directorate for Science, Technology and Industry
*Economics Policy View* – Nick Vanston, OECD Economics Department
*Environmental Policy View* – Ken Ruffing, OECD Environment Directorate
*Energy Policy View* – Jonathan Pershing, International Energy Agency

**Conclusions**: Future Directions for OECD Analysis

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