

# **Technological Change for Atmospheric Stabilization: Introductory Overview to the Innovation Modeling Comparison Project**

*Michael Grubb\**, *Carlo Carraro\*\** and *John Schellnhuber\*\*\**

## **1. OVERVIEW OF THE ISSUES**

### **1.1 Technology and the sources of innovation**

As climate and energy issues continue their inexorable rise up policy agendas worldwide, there seems to be at least one core fact upon which almost everyone agrees: that the development and diffusion of low carbon technologies will be central to stabilizing the climate over the 21<sup>st</sup> Century. However, innovation is something that economists have long debated as an exceptionally complex area for economic theory.

Like a river, technology collects ideas from myriad sources. Under the force of gravity—the pull of market demand—technology can harness these ideas, through many tributaries of intermediate technologies, into viable products. The continuing advance of ideas in all walks of life, which help to flow into making an improved product, forms a general ‘autonomous’ advance. From a specific technology perspective it just happens; from a modeling perspective this is ‘exogenous’ technological change, built in by assumption.

Yet one feature of economic systems is the increasing pace with which the technology terrain evolves. Starting to understand and represent these forces is the domain of endogenous theories and models of innovation. The broad literature identifies several forces at play.

Seeking new markets, industry itself makes strategic decisions about R&D—where and how hard to try and break through barriers in the terrain, how

*The Energy Journal*, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue. Copyright ©2006 by the IAEE. All rights reserved.

\* Faculty of Economics, Cambridge University, United Kingdom, E-Mail: michael.grubb@econ.cam.ac.uk.

\*\* Department of Economics, University of Venice, E-mail: ccarraro@unive.it.

\*\*\* Potsdam Institute for Climate Impact Research (PIK), Email: schellnhuber@pik-potsdam.de.

much to invest in what kinds of innovation. The extent and direction of this effort is influenced by the perceived opportunities and risks—the strength and nature of the demand-side forces.

Public funding is also important. Publicly funded, targeted R&D programs, along with the macroeconomic equivalent in terms of the publicly funded wider accumulation of knowledge, can themselves carve out new routes through the technology landscape. From an economic perspective, there is thus ‘learning by searching’ both funded directly by governments, and by industry in response to market incentives of various kinds.

Moreover, any technology also acts directly on its own surroundings. Just as a river carves out, deepens and extends its own channels, technology similarly modifies both itself, through experience and market feedbacks, and its surroundings. Technological streams act to reinforce their own competitiveness and dominance, unless other forces block the route or it is traversed by a deeper, better channel.

Technological advance is thus a product of at least three distinct forces—typically classified into public and private sector knowledge investment or ‘learning by searching’, and applied ‘learning by doing’.

Reflecting and quantifying how these forces may act over time to shape the technology terrain is immensely complex. Nevertheless over the past few decades, economic analysis has made considerable progress, with endogenous growth theories beginning to enter mainstream economic thinking and diverse endogenous growth and learning-by-doing models being developed, as surveyed briefly in the Technical Review in this volume (Köhler et al. 2006)

## **1.2 Applying theoretical and empirical insights**

As in many areas of analysis, applying to practical questions the evolving theoretical ideas and models of innovation has proved an even greater challenge. For many areas of public policy—for issues that are short term, which involve marginal changes, or are purely local—this probably matters little. In such cases true innovation may be either not relevant on the scales and timescales considered, or left to events and decisions ‘elsewhere’.

However, the problem of climate change is at the opposite end of the spectrum—long-term, deep and global. The goal expressed in the UN Framework Convention—to stabilize atmospheric concentrations of greenhouse gases—is decades away even under the most radical control scenarios: most scenarios suggest it will take until at least the end of the century and many remain skeptical the goal can be achieved even beyond that point. The intrinsically global nature of the problem also poses new challenges. Decisions taken in negotiations have an impact across the globe, and even decisions in relatively small countries—such as those which Denmark took with respect to wind energy in the 1970s and 1980s—can ultimately have major global repercussions, given a few decades for the resulting technology-industries to grow and spread internationally. How to model technological change is thus central to decision-making around climate change

policy, and different perceptions about technological change processes help to explain differences in current national positions.

Theoretical models of endogenous change, however, are still far from fully applied models that can give quantified insights into the specifics of energy supply and demand and the impact of particular incentives. Moreover, endogenizing technological change in existing global energy-economy models has the potential not only to require different theoretical approaches, but can also vastly complicate the task of computation and interpretation. Applying insights from both theoretical and empirical studies on endogenous technical change in energy systems modeling was first initiated in the 1990s, but is only now beginning to mature as plausible and useable tools.

### **1.3 Innovation in global energy-environment models**

In the first generations of global energy-economy modeling applied to climate change, emerging from the late 1980s roughly up until the mid 1990s, technology entered through a series of exogenous assumptions. In true ‘top-down’ models, supply side technologies were reflected in assumptions about the elasticity of substitution between generic carbon and non-carbon sources (if any), whilst an “autonomous energy efficiency improvement” (AEEI) parameter was used to reflect an assumed degree of decoupling between GDP and energy consumption—a single, fixed parameter encompassing both structural change in the relationship between economy and energy and the development and diffusion of demand-side technologies.

Fully ‘bottom-up’ models, that represented the entire energy system in terms of specific technologies, were also developed and applied (the first global application being Goldemberg et al, 1988). These too had to rely on a series of exogenous assumptions about the future scale of energy demand and technology costs. Many of the models developed in the early 1990s combined top-down modeling of energy demand with bottom-up modeling of energy supply, disaggregated to various degrees, but still relied on essentially exogenous assumptions about both.

The most consistent finding to emerge from all these modeling studies was that technology mattered: the costs of deep emission reductions were almost entirely contingent upon the assumptions that the modelers built in about the pace of decoupling between GDP and energy demand on the one hand (the AEEI), and the cost of low-carbon energy sources on the other. Yet, as both the theoretical literature and empirical studies were already demonstrating, technology would itself be modified by climate policy.

From around the mid 1990s, two very different strands of analysis emerged seeking to endogenize technological change in energy-economy models. The ‘top-down’ modeling community began to explore incorporating both explicit knowledge functions using accumulated R&D, and learning-by-doing equations. At the same time, the ‘bottom-up’ community began building in learning-curves—explicit functions of how scale might be associated with cost reductions—into their analyses.

Unfortunately for policy, these two lines of enquiry appeared to lead to almost opposite conclusions about the implications of endogenous technological change. The initial studies using R&D in cost-benefit studies (in which the stabilization level is determined by the model) by Goulder and Schneider (1999) and by Nordhaus (2002) both highlighted the potential impact of ‘crowding out’ effects—the possibility that inducing more innovation in the energy sector could be at the expense of innovation elsewhere in the economy— and concluded that endogenizing technological change may make little difference either to the long term costs or the near term policy recommendations.

In sharp contrast, the MESSAGE studies pioneered at IIASA (Grubler, Nakicenovic and Victor, 1999), and related developments in the IEA technology program (IEA, 2000), appeared to show that learning-by-doing in the energy sector could, over the 21<sup>st</sup> century, revolutionize the system to such a degree that a very low carbon future could be just as cheap as a high carbon future, and that which emerged would be heavily dependent upon the policy choices taken early in the Century. Arguably, these initial efforts to endogenize technology change thus widened, rather than narrowed, the gulf in perceptions between different analytic communities in ways that perhaps also fed through to conflicting policy stances.

In the third generation of studies, from around the turn of the Century, both the ‘top-down’ and the ‘bottom-up’ lines of analyses have become more sophisticated and more circumspect. In the ‘top-down’ analysis, new models have been proposed in which the menu of effects of technological change that could be modeled was much richer and therefore the role of technological change more relevant than in Nordhaus (2002).<sup>1</sup> For example, as explained in the Technical Overview paper in this volume, strategic R&D investments and international R&D spillovers were introduced in Buonanno, Carraro and Galeotti (2002), crowding out effects between different R&D investments were introduced by Goulder and Matthai (2000), learning by researching and learning by doing were jointly modeled in Castelnovo et. al. (2003), the dynamics of a backstop technology was endogenized by several authors. At the same time, the field has become more conscious of its heritage and the potentials to learn from mainstream developments in endogenous growth theories.

In the ‘bottom-up’ analyses, IIASA has similarly pioneered a recognition that the seemingly unambiguous empirical data on experience curves itself embody at least two very different components—direct knowledge investment, and actual learning-by-doing—and that incorporating this distinction in two-factor learning curves makes the results less strident, and more subtle, than earlier studies.

Now is thus an opportune time to assess the state of the art, with a comparative study traversing both ‘bottom-up’ and ‘top-down’ perspectives in relation to the most over-arching, long-term and global policy question in the field: the implications of trying to stabilize atmospheric CO<sub>2</sub> concentrations.

1. See Clark and Weyant (2002), Carraro and Galeotti (2004) for a survey of how different climate economy models endogenise technical change.

## **2. THE INNOVATION MODELING COMPARISON PROJECT (IMCP)**

This project represents a first systematic attempt to assess and compare the progress made through different modeling approaches, and to offer some first insights into what this may mean for the strategic economics of tackling the biggest long-term challenge in the energy sector, namely the goal of transforming energy systems in ways that could stabilize the atmospheric concentrations of CO<sub>2</sub>. The project aims, for the first time, to ‘open the black box’ of endogenous innovation to scrutiny by comparing the results from different applied modeling approaches and the understanding the reasons for differences.

### **2.1 Background and process**

The IMCP arose out of recognition that the temporal, geographic and interdisciplinary scales of the climate change problem demand a more sophisticated kind of economics, and a more structured and collegiate international approach to analysis, than hitherto developed. Diverse researchers were invited to a brainstorming meeting in Utrecht in October 2003. This meeting marked the foundation of an ‘international program on the economics of atmospheric stabilization’, as a group of researchers with a common interest in pursuing such analysis. Participants debated various potential topics relating to the strategic economics of climate change particularly with reference to atmospheric stabilization. Out of the diverse range of topics discussed, the one universal element in the set of issues suggested by every participant was the need to understand better the representation of endogenous technological change. A follow-on meeting in Paris helped to define the resulting ‘Innovation Modeling Comparison Project’, and an open call was issued, including through the IAEE, for modeling groups interested in participating.

The project then developed through two main workshops. At the first, in Cambridge in November 2004, all modeling groups that had expressed interest presented the current state of their efforts and debated the criteria, issues and process going forward. At the second, at DIW in Berlin in late February 2005, groups presented their modeling results as far as possible on a common basis and critiqued the representation of technological change in more depth, together with a preliminary synthesis of results.

Over the subsequent months, the modeling groups submitted results according to the agreed common reporting format, and drafted papers that were then examined through a double review process—first by the Steering Committee, and then through a minimum of two external reviewers. The principal criterion was not that each paper individually had to represent methodological novelty. Rather, each paper had to show a qualitatively plausible representation of endogenous technological change in some form, together with some representation of the energy-carbon system sufficient to explore implications of ITC under different stabilization levels, and presented with sufficient clarity to enable comparison and interpretation of results. Of almost twenty groups initially expressing interest, the

10 studies set out in the papers here completed this extensive process.

## 2.2 Structure and focus of the analysis

The aim was to encompass a diversity of plausible approaches to modeling endogenous technical change and to compare them against common objectives. The guiding principle was that in each model, the analytic treatment of endogenous change should be consistent between a baseline run, and a set of runs with a constraint on atmospheric concentrations, so as to identify the impact of responses to the constraint in *inducing* technological change.<sup>2</sup>

The studies focus on atmospheric stabilization of CO<sub>2</sub>, principally at levels of 450, 500, and 550ppm CO<sub>2</sub>. Some models were also able to present results for 400ppm CO<sub>2</sub>, others did not find this feasible given constraints on timescale of adjustment.

The decision to focus on CO<sub>2</sub> concentrations reflects a mid-point in a cascade of uncertainties, many of which complicate analysis without adding significantly to insights about the role of technological change.<sup>3</sup> Depending in part on the degree of action on other greenhouse gases, the range 450-550ppm CO<sub>2</sub> translates to a total atmospheric loading of roughly 500-650ppm CO<sub>2</sub>-equivalent when the non- CO<sub>2</sub> gases are added.

The long-standing ‘benchmark’ of climate science studies of stabilizing radiative forcing at a doubling of pre-industrial CO<sub>2</sub> concentrations itself implies a projected CO<sub>2</sub> concentration probably below 500ppm CO<sub>2</sub>, given the increase in other trace gases. However, 550ppm CO<sub>2</sub> has been more widely studied in the economics community, as a goal requiring less ambitious action, and one which some studies suggest would not require significant mitigation yet. Conversely, many scientists have argued for a goal to contain risks by aiming at low stabilization levels, with reference to physical indicators such as that now adopted by the European Council of Ministers of limiting temperature increase to 2 deg.C, which probably implies CO<sub>2</sub> concentrations at 450ppm CO<sub>2</sub> or lower.<sup>4</sup> Our chosen range aims to span these perspectives. Several models were able also to study 400ppm and these demonstrate that such levels would require action far more drastic than being contemplated in current implementation policies and negotiations, and they

2. Note that this terminology differs from that in Grubb et al.(2002), who refer to induced change as the process and endogenous change as a property of models that include induced technological change. In this study, we use endogenous change as the process, and refer to induced technological change as being the change in technological characteristics *induced by the policies or incentives associated with the stabilisation constraint*.

3. Both methane and N<sub>2</sub>O are products primarily of land use changes and agricultural and waste practices, without a strong direct technological component, whilst the industrial trace gases are very sector and process specific and do not raise the same level of economy-wide issues that CO<sub>2</sub> raises. Given the dominance of CO<sub>2</sub>, it is also apparent that overall greenhouse gas concentration cannot be stabilised unless CO<sub>2</sub> itself is brought close to stabilisation.

4. For example presented in Avoiding Dangerous Climate Change Conference hosted by UK Government (2005) and presented in Schellnhuber eds. (2006).

give a useful insight into what might be implied.<sup>5</sup>

The link between fossil fuel CO<sub>2</sub> emissions and concentrations itself depends on the assumed emissions from land-use change and the broader carbon cycle. These were not actively harmonized but the range from the models narrowed after initial comparison. Figure 1 shows the CO<sub>2</sub> emission trajectories across the models associated with (a) 450ppm CO<sub>2</sub> and (b) 550ppm CO<sub>2</sub> respectively. The 450ppm constraint requires global CO<sub>2</sub> emissions to peak soon—sometime in the period 2010-2030—and emissions by mid Century are generally between 5GtC/yr and the present level of 7GtC/yr, with cumulative emissions over the Century around 600GtC.<sup>6,7</sup>

The highest level in the comparison, 550ppm CO<sub>2</sub>, displays a far broader range of trajectories. Three models use the extra ‘headroom’ to sustain a relatively flat emissions trajectory, between about 8 and 10GtC/yr across most of the Century. **Others allows global emissions to continue rising sharply, peaking between 2030 and 2050, and then declining** (in some cases precipitously), implying that in these trajectories the second half of the century sees removal, replacement or retrofit of much of the carbon emitting infrastructure constructed during the first half. Thus endogenizing change in these models does not itself appear to bring much alignment of the time-path of emissions (most but not all are dynamically optimized).

We designed guidelines attempting to reduce another major source of variation through proposing a common reference case, or ‘baseline’, around the ‘Common Poles-Image’ (CPI) baseline case which defines a ‘business as usual’ scenario. In practice, the models varied in their implementation of this—one feature of endogenous change being that the reference case itself becomes dependent upon other assumptions and features in the model and thus much harder to harmonize. Excepting one low and one high outlier,<sup>8</sup> the models have emissions (cumulative over the Century) in the baseline that are similar to within +/-20% around a mean of about 1400GtC, however, baseline GDP projections vary by much more as indicated below.

Figure 3 in the Synthesis paper in this volume (Edenhofer et al., 2006) illustrates the combined impact of the differences in carbon cycle and baselines,

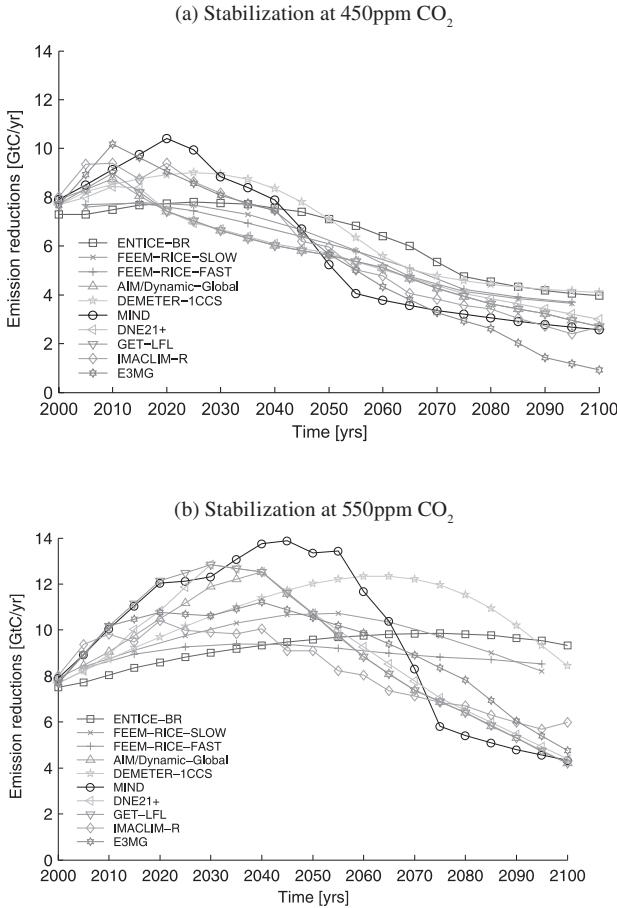
5. Levels significantly below 450ppm CO<sub>2</sub> would also start to preclude use of conventional oil reserves, potentially driving costs up sharply but also underlining the fact that energy resource considerations will anyway require significant technological transitions in energy systems during this Century (IPCC, 2001)

6. Specifically, the mean cumulative carbon emissions 2000-2100 across all the different models is around 600GtC for 450ppm, 780GtC for 500ppm, and 930GtC for 550ppm, with standard deviation about 7% for each level. Note these data also highlight the importance of assumptions around the global reserves and resources of conventional oil, which are generally estimated to contain under 200GtC together, with more than half of this in proven reserves.

7. Note that the rates of decline suggest that even 450ppm does not necessarily require premature retirement of existing capital stock, though it could severely limit the headroom for constructing new carbon intensive stock.

8. FEEM-FAST and MIND respectively.

**Figure 1. CO<sub>2</sub> Emission Trajectories Associated with Stabilization Across the IMCP Models**



in terms of the scale of the cumulative carbon reduction over the century implied by stabilization across the different models. This makes it plain that, particularly for the lower stabilization levels, the scale of the abatement task relative to baseline varies considerably. To some degree, this may be understood not only as indicating considerable genuine uncertainty about ‘business as usual’ trends, but also the considerable scope for different paths of global economic development. These different paths—potentially including land use policies—could do much to make the task of stabilization more or less difficult, even prior to the adoption of specific emission constraints. The far wider range of economic projections also highlight the extent to which atmospheric stabilization, for all its daunting scale,

is a modest factor in the context of bigger influences on the pace and nature of global economic development—including the overall pace and capacity to handle technological change.

### **3. MAIN ECONOMIC FINDINGS OF THE INNOVATION MODELING COMPARISON PROJECT**

The Synthesis paper in this volume examines and compares the influence and dynamics of technical change in the different models. This section aims simply to set all this in context, with a sense of the scale of the undertaking as indicated by the models. The discussion focuses upon the results from the models with endogenous change ‘switched on’, since there is no doubt that technical change is to some degree endogenous and the models themselves span a wide range of perspectives about how important it is. The Synthesis paper illustrates the impact also compared to scenarios in which endogenous change is ‘switched off’.

#### *(a) Marginal carbon prices*

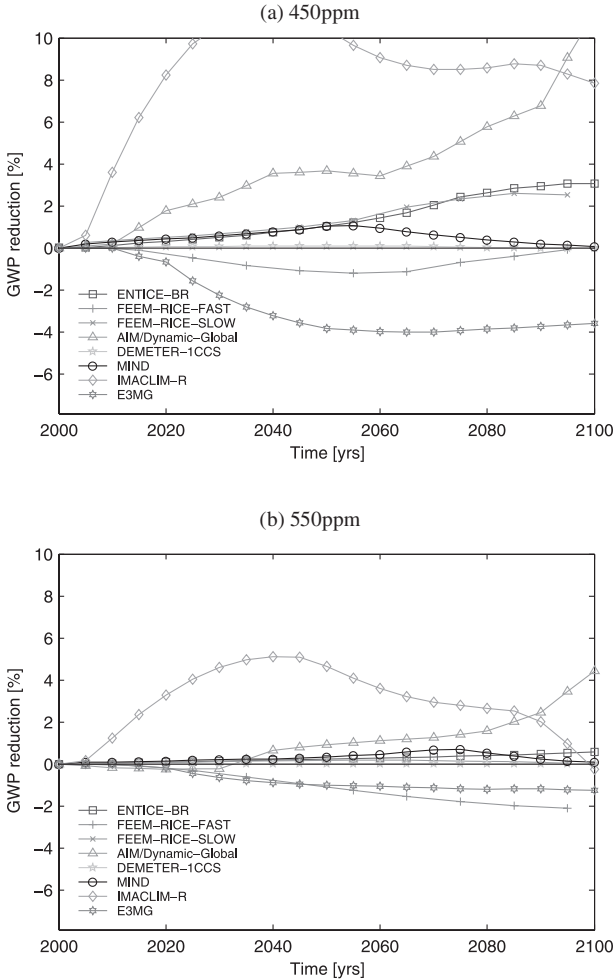
Most models represent incentives to change emissions trajectories in terms of the carbon price required, which not only changes specific investments according to carbon content, but also triggers technical change through the various mechanisms considered in the models (including through various forms of knowledge investment). The Synthesis paper (Figure 10) charts the evolution of carbon prices required to achieve stabilization and shows that they span a wide range, both in absolute terms and in the time profile. For stabilization at 450ppm, for most models carbon prices rise to c. US\$100/tC +/- 50% by 2030 and are in the range US\$50-250/tC by 2050. After that, they diverge enormously. Some go ‘through the roof’ as the allowable emissions shrink to low levels. Others rise more modestly, and one model echoes the results of some simpler studies based on learning curves which suggested that carbon prices might peak in the range US 100-200/tC and then slowly decline as new low-carbon technology systems come to dominate in the emerging economies (e.g. Anderson and Cavendish, 2001).

#### *(b) Dynamics of GDP impacts*

Figures 2 (a) and (b) show the percentage impact over time on global GDP (‘gross world product’) of the constraints represented by the stabilization levels and corresponding emission trajectories in Figure 1. This reveals some striking differences between macroeconomic results that reflect fundamental methodological differences beyond those associated just with technological change.

Out of the eight models reporting global GDP results, **four report losses** that rise steadily to up to 1% of GWP by mid century under 450ppm, and subsequently diverge, **whilst two report much bigger losses and two report gains in GDP (negative loss)- one in particular reporting losses that peak over 10% and are**

**Figure 2. Impact of Stabilization Constraint on %loss in Gross World Product over 2000-2100**



Note: For comparison of total discounted economic impacts between models and at all stabilization levels see Synthesis report, Figure 1(a), which also includes cost metrics for participating models that encompass the energy sector only and not the whole economy (these metrics are less appropriate for mimicking the time profile of whole-economy impacts and hence are not included in this diagram).

sustained close to that under 450pp. The three energy-only models not illustrated in Figure 1 report costs equivalent to GDP impacts well within the central range.

The essential dynamic here is that in both energy sector and endogenous growth models, the early decades are characterized by a switch in *investment patterns*. The associated GDP impacts are initially small for a number of reasons.

First, mitigation policies per se initially target low-cost ‘low hanging fruit’ at low carbon prices, changing the *trajectory* of emissions without high costs. Second, the ‘learning investments’ are in emerging low carbon sectors. Because these sectors are initially relatively small, the scale of learning investment is also limited. Finally, in the growth models, additional investment can boost GDP. In most—but not all—of the models, these factors are ultimately overtaken by the sustained increased costs of the energy system, but again to widely varying degrees that depend largely upon the degree of endogenous technological response.

These dynamic mechanisms are not available in the highest-cost model, an equilibrium model in which carbon prices unavoidably depress GDP contemporaneously by raising an input factor cost (energy); additional features of this model are indicated below.

The mechanisms through which stabilization can increase economic output (**without considering the climate-related benefits**) **differ between the two cases**. In one, the negative costs originate from the Keynesian treatment of demand-side long-term growth; **there are increasing returns to production and employment** depends on relative prices, the recycling of carbon tax revenues therefore has potential to boost output. In the other model, **the mechanism is directly to do with technical change** considered below.

### *(c) Aggregate GDP impacts and the role of endogenous change*

The Synthesis paper examines in depth the role of technology choice, endogenous change and macroeconomic linkages in these processes. Figures 1a and 2a in the Synthesis paper also summarize the GDP impacts in each model in terms of an aggregate comparable indicator, namely the discounted total difference between ‘Gross World Product’ in the stabilization scenarios and under the baseline projection. This is a global indicator defined as the discounted sum of GDP, aggregated across world regions and countries, over the next century. Therefore, it does not show differences across sector, countries and above all time periods. Nonetheless, it is a useful synthetic indicator of stabilization costs.

In one of these models **accelerated development and diffusion of new technologies** induced by climate policy has the potential to boost growth. The model was indeed designed to demonstrate the extent to which technical change can be effective in reducing stabilization costs if appropriate policies and investments are undertaken and if crowding out effects are limited. When these particular features of technical change dynamics are ‘switched-off’, costs become positive and consistent with those estimated by the other models.<sup>9</sup>

In all but two of the remaining models, discounted GWP is reduced but by less than one percent (relative to own baseline), even at 450ppm stabilization levels. The Synthesis paper analysis of the role of endogenous change in driving these cost

9. These two cases are the FEEM-RICE-FAST and the FEEM-RICE-SLOW analyses respectively. See Bosetti et. al (2006), this volume.

impacts highlights big differences between the models. In some models, endogenous change makes a pivotal difference to the results. In others, the impact is modest.

Overall, the nature of the impact of endogenous technological change on stabilization costs may be usefully understood in terms of several different classes of observed impacts:

- (i) *ITC makes little difference to already 'modest' costs.* In some models ITC makes a relatively small difference, but in the context of costs that are already relatively modest. In these cases, ITC does not necessarily lower costs much if major technological advances are projected to occur anyway in the base case. In such cases, low carbon technologies already make significant inroads into global energy and the effect of ITC is to slightly accelerate the process and reduce their costs further.
- (ii) *Big ITC impact with backstop technologies.* In other models, ITC makes a large difference, in some cases reducing the costs of low stabilization levels (450ppm or 400ppm) from several percent to a fraction of a percentage loss in GWP. In general, this appears to be associated with models that have enough technological detail to allow substitution of higher by lower carbon options in supply, and responsiveness to the economic signals that enables the lower carbon supplies to 'break through' in markets on a large scale, leading to structurally different energy systems becoming established with various economies of scale now applying to low carbon instead of high carbon systems.
- (iii) *ITC impacts insufficient to overcome relatively high costs.* In some models the above processes do not occur because the main mitigation option is energy efficiency, without options for substitution by low carbon supplies. As a result, tight carbon constraints can only be met by squeezing heavily on energy/carbon prices and forcing significant decline in energy-intensive processes. The two models for which discounted stabilization costs exceed 1% of GWP share this feature. In addition in the recursive general equilibrium model, the inflexibility of the core equilibrium assumption is exacerbated by the nature of macroeconomic linkages, and by the transport sector in which continued investment in carbon-intensive transport infrastructure in the early decades combines with a lack of viable substitution options. Although ITC does considerably reduce costs in some parts of the energy economy, this assumed lack of long-term foresight on the part of infrastructure investments and lack of substitution options in transport, combines with macroeconomic linkages that make the big rise in transport sector costs very expensive for the global economy.

In general therefore, one key determinant of the scope for induced technological change to lower costs is whether or not the models embody ITC with technological diversity: if they do, the improvement of low carbon "backstop" options limit stabilization costs; if they do not, costs are not capped in this way.

However, overall the studies also emphasize that the global economic

impact of stabilization targets depends not just on technology, but also upon the nature of the assumed macro-economic linkage between the energy sector and the rest of the economy. As indicated, these can either ameliorate or exacerbate the costs incurred within the energy sector as a whole.

## **4. POLICY AND RESEARCH IMPLICATIONS**

### **4.1 Policy implications**

Taken as a whole, the analyses give good grounds for believing that the atmosphere *can be* stabilized (or brought close to stabilization), at or significantly below a doubling of CO<sub>2</sub>-equivalent concentrations (below 500ppm CO<sub>2</sub>) at long-term macroeconomic costs that seem relatively modest—unlikely to exceed one year's foregone economic growth. However, this broad figure over a century hides many distributional impacts, across sectors, across countries and across generations. In particular, stabilization may require big changes in investment patterns in the short run, **which would obviously provoke resistance to the implementation** of effective climate policies. Whether or not the costs *are* actually small, will be a function of policy, and in particular, whether or not the policies adopted send the right signals and get the right mix of investment in R&D at one end, diffusion at the other—and of no lesser importance—all that lies between.

However, **the policy implications that can be drawn from such analyses** are not straightforward. Early discussions of ITC framed the issues as a stark choice between autonomous and government-led R&D on the one hand, versus inducement of innovation in the market through emission caps or carbon prices. Almost all the papers in this study emphasize that the situation is more complex, for several reasons.

ITC itself encompasses different elements **from a policy perspective, the** components of public R&D, private R&D and learning-by-doing all carry very different implications, but the models do not always distinguish between even these broad categories. And **to the extent that technological change is driven by learning-by-doing**, it still does not necessarily follow that emission caps are the only or best way of stimulating this, particularly for some of the less advanced technologies. Such instruments do increase the general prospect of profiting from innovation in low carbon technologies, but a far wider range of market-based policies may be required to stimulate the kind and degree of investment sought.

Moreover, several of the models emphasize the crucial role of expectations. Whilst many of the models optimize dynamically—assuming that all actions look ahead to respond optimally to the stabilization target—others do not.

The importance of technological diversity also highlights the need for explicit technology policy to foster a diversity of options that can serve as 'back-stops'. This already exists in power generation (whether or not it is represented in models), but far less so in the transport sector. The IMCP results therefore underline the importance of knowledge investments to broaden the base of options par-

ticularly for low carbon transport. Those few models that explicitly represent fossil fuel resources and technologies also highlight the importance of understanding and harnessing the associated interactions.

The policy implications are thus far more subtle than choosing between ‘technology led’ versus ‘cap-and-trade’ led approaches. Even with a strong role for ITC, future rounds of the Kyoto Protocol which duplicate the structure of sequential 5-year limits, without any clear and credible signals about the longer term evolution of the system, are unlikely to deliver the depth of innovation and adjustment to infrastructural investments required to minimize long-term costs. On the other hand, a purely supply-driven R&D strategy may generate ideas but not technology-based industries with the capacity to solve the problem, and with no signal at all to redirect ongoing investment and promote prior adjustment of infrastructure appropriate to a carbon constrained world. Thus both R&D, and carbon cap/pricing, appear necessary but in isolation insufficient instruments to deliver stabilization at low costs. What really matters may be combinations of these policies and all that lies between—together with the critical role of framing expectations that really influence the scale and direction of corporate investment in low-carbon knowledge, in learning-by-doing in the nascent technologies and industries, and in the infrastructure appropriate to low-carbon economies.

#### **4.2 Future research needs**

The studies in the IMCP reveal the complexity and richness of innovation issues. They demonstrate that our capacity to analyze one of the most thorny issues in economic theory has moved beyond abstract debates about stylized growth models, into a rich array of applied modeling approaches relevant to a problem in which technical change is central to solutions.

Compared to five years ago, the progress made is impressive, but so are the remaining challenges. Whilst growth models have a strong theoretical grounding, their empirical basis remains very limited, whilst the more energy-system oriented models embody relationships in which theory is weak and hence interpretation of observed data subject to controversy. Although there seems to be a trend to combine the two approaches, far more work is still required to develop tools and to apply empirical data in more theoretically grounded and comprehensive ways.

Moreover, although the models mostly concur that induced innovation can contain the costs of stabilization, they differ enormously in their representation of the different components of public knowledge investment, private knowledge investment and learning-by-doing, or indeed whether they distinguish these. Consequently it remains hard to derive from such modeling conclusions about the specific policy instruments—or mix of policies—that would stimulate optimal kinds of technology and infrastructural investment. In terms of application to the challenges of the global energy system, the extent to which they represent the structure of fossil fuel resources and the implications of moving beyond conventional oil and gas resources—on timescales parallel to those associated with

transitions towards atmospheric stabilization—remain mostly very limited. And they do not yet shed light on the geographic dimension—whether and how technologies induced by action in some parts of the world may diffuse globally. These and other important questions remain to be explored in similar systematic ways.

Yet, developing models that start to reflect the reality that climate policy itself will mould the nature and direction of technology change is the essential precursor to such analyses. Really clarifying how best to represent this, and the more specific policy implications, remains a challenge. If our project has helped to open the door to a new generation of such studies, it will have been worth it.

## ACKNOWLEDGMENTS

We are grateful to the funders of the IMCP project. The UK Department for Environment, Food and Rural Affairs and the German Bundesministerium für Umwelt provided core funding. The UN Foundation and BP recognized the importance of the emerging work and provided funding for the production of this Special Issue. We are indebted to all of them, together with the team at the Energy Journal, and hope that they will consider their investment to have yielded adequate returns.

## REFERENCES

- Anderson, D. and W. Cavendish (2001). “Dynamic simulation and environmental policy analysis beyond comparative statics and the environmental Kuznets curve”. *Oxford Economic Papers*, 53:721-746.
- Buonanno, P., C. Carraro, and M. Galeotti (2002). “Endogenous Induced Technical Change and the Costs of Kyoto”. *Resource and Energy Economics*, 25:11-34.
- Carraro, C. and M. Galeotti (2004). *Does Endogenous Technical Change Make a Difference in Climate Change Policy Analysis? A Robustness Exercise with the FEEM-RICE Model*. Milan: Fondazione Eni Enrico Mattei, Nota di Lavoro 152.04.
- Castelnuovo, E., M. Galeotti, G. Gambarelli, and S. Vergalli (2003). “Learning By Doing and Learning By Searching in a Model of Climate Change Policy Analysis”, Fondazione ENI Enrico Mattei, Nota di lavoro N.11.2003, *Ecological Economics*, forthcoming.
- Clarke, L.E. and J.P. Weyant (2002). “Modeling Induced Technical Change: An Overview”, in A. Grübler, N. Nakicenovic, and W.D. Nordhaus (eds.), *Technological Change and the Environment*, Washington D.C.: Resources for the Future Press.
- Criqui, P., A. Kitous, M. Berk, M. den Elzen, B. Eickhout, P. Lucas, D. van Vuuren, N. Kouvaritakis, and D. Vanregemorter (2003). “Greenhouse gas emission reduction pathways in the UNFCCC process up to 2025”. Technical Report, study contract B4-3040/2001/325703/MAR/E.1 for DG Environment.
- Edenhofer, O., K. Lessmann, C. Kemfert, M. Grubb and J. Köhler (2006). “**Induced technological change: exploring its implications for the economics of atmospheric stabilization: Synthesis Report from the Innovation Modeling Comparison Project**”, *The Energy Journal Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization*.
- Goldemberg, J., T. Johansson, A. Reddy and R. Williams (1988). *Energy for a Sustainable World*. India: Wiley Eastern Limited.
- Goulder, L.H. and S. H. Schneider (1999). “Induced technological change and the attractiveness of CO abatement policies”. *Resource and Energy Economics* 21:211–253.
- Goulder, L. H. and K. Mathai, (2000). “Optimal CO<sub>2</sub> abatement in the presence of induced technological change”. *Journal of Environmental Economics and Management* 39: 1-38.

- Grubb, M., J. Köhler and D. Anderson, (2002). "Induced technical change in energy and environmental modeling: analytical approaches and policy implications". *Ann. Rev. Energy Environ.* 27: 271-308.
- Grubler, A., N. Nakicenovic, and D.G. Victor (1999). 'Dynamics of energy technologies and global change'. *Energy Policy*, 27(5):247-280.
- IEA, (2000). *Experience Curves for Energy Technology Policy*. Paris: IEA/OECD Publications.
- IPCC, (2001). Mitigating climate change, Third Assessment Report of the Intergovernmental Panel on Climate Change, CUP (eg. Policymakers' Summary, para 5).
- Köhler, J., M. Grubb, D. Popp and O. Edenhofer (2006). "**The Transition to Endogenous Technical Change in Climate-Economy Models**". *The Energy Journal Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization*.
- Nordhaus, W.D. (2002). "Modeling Induced Innovation in Climate-Change Policy", in A. Grubler, N. Nakicenovic, and W.D. Nordhaus (eds.), *Technological Change and the Environment*, Washington D.C.; Resources for the Future Press, 182-209.
- Nordhaus, W. D. and J. Boyer (2000). *Warming the World*. Cambridge: MIT Press.
- Schellnhuber, H. J., eds. (2006). *Avoiding Dangerous Climate Change*. London: Cambridge University Press.