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EDITORIAL

The role of technological change for a sustainable development

Herman R.J. Vollebergh[a,*], Claudia Kemfert[b]

[a]Department of Economics, Erasmus University Rotterdam, The Netherlands
[b]Humboldt University and German Institute for Economic Research, Germany

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Abstract

Technological change has become a major focus in environmental policy as well as in energy and climate policy. Indeed, there is a growing body of knowledge about how and in which direction technological change might have an impact on environmental resource constraints and how environmental policy might have an impact on this direction. In this article we introduce the contributions to this special issue showing how they add to recent developments in the field of economics of technological change and sustainability. We also discuss potential avenues for future research.

Keywords: Technological change; Government policy; Sustainable development; Energy

JEL classification: O30; Q1; Q4; Q55

1. Technology and sustainability

One of the major challenges for today's policymakers is to define and implement *sustainable* policy schemes. Sustainable policy strategies must balance intra- and inter-generational equity aspects of policies and should at the same time be compatible with other social, ecological and economic requirements. Recently, governments and international organizations alike seem to believe that policy efforts stimulating innovative technology and its adoption are an example of such sustainable policy schemes. European Union programmes on technological change, such as the Renewable Energy White Paper and SAVE on energy efficiency, aim to stimulate not only innovation in general but environmentally friendly technologies in particular. These technologies are assumed to yield a double dividend: not only would they stimulate economic growth, but they would also be beneficial to the environment in generating fewer emissions. One example is fuel cells. Both the US government and the EU will spend a very large amount of research money in this area. Fuel cells not only have a big potential to become the major fuelling technology in the not-so-distant future, but they seem to be beneficial for the environment as well.[1]

* Corresponding author. Tel.: +31 104081498.
E-mail address: vollebergh@few.eur.nl (H.R.J. Vollebergh).

[1] However, Wald (2004) argues that the net effects may not always match expectations.

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Indeed, technological change or even, more generally, transitions (see, for instance, Kemp, 2000) have become a major focus in environmental policy as well as in energy and climate policy. One important reason for this is that several difficult-to-solve problems deserve serious attention from policy-makers. In particular, environmental problems such as climate change and local air pollution are labelled "orange" or "red" by the OECD (see OECD, 2001), indicating that they affect human welfare negatively but are, at the same time, far from easy to solve. One typical example is climate change. The IPCC believes that currently changing climate change patterns are very likely connected with *earlier* levels of human-induced climate change emissions. However, decoupling of income growth and emissions of CO_2, the principal climate change gas, is not (yet) apparent from the facts for many important economies in the world, as is clear from Fig. 1. For more fundamental changes, radical shifts in the use of energy technologies therefore seem essential. At the same time, this is also one of the most difficult policy areas because of the long-term nature and international dimension of the environmental problem at stake.

It is not always recognized nowadays that it is a remarkable shift in perception to expect technological change to provide relief. Not only environmentalists and others concerned with environmental issues used to be very sceptical about technological change; this was also true of several well-known economists. For instance, Georgescu-Roegen (1972, p. 17) argued fiercely against the view that substitution and technological change would provide an option to escape the physical restrictions imposed by the finite stock of accessible low entropy. According to Georgescu-Roegen, our limited understanding of technological change not only demonstrates how little economists have to say about the really important issues of life, but also leads us to the false belief that solutions exist to the fundamental limits on resource availability. How different is the current perception of technological change in relation to sustainability. We think it is fair to say that few economists, as well as non-economists, nowadays believe that Georgescu-Roegen is still right. Indeed, the current view reflects optimism as to whether technological change would provide the solution to serious and even persistent environmental issues, including

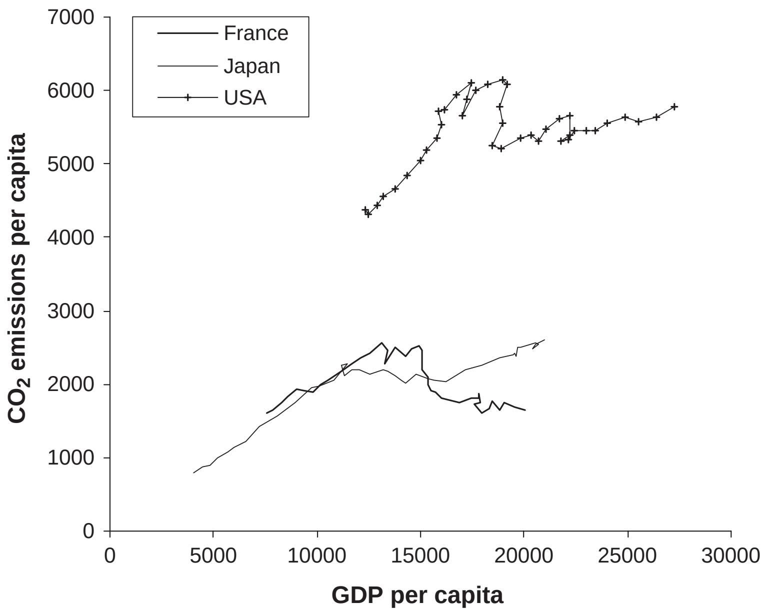

Fig. 1. Relation between CO_2 emissions (kg) and income per capita (1990 US$) in some OECD countries between 1950 and 2000.

resource constraints imposed by finite stocks of mineral and oil reserves. Up to a point, this special issue is another example of this remarkable shift in perspective by economists.

One reason for this remarkable shift has most likely to do with our growing knowledge about how and in which direction technological change might have an impact on environmental resource constraints (including scarcity as a result of using the environment as a sink for waste and pollution). Several renowned economists have always argued that technological change and substitutability are important vehicles for overcoming, or at least alleviating, environmental resource scarcity (e.g. Solow, 1974). Old growth theory focused (with some important exceptions) on exogenous technological change. It considered a certain given path of technological change and explored its implications for factor prices, factor use, production, growth and welfare. Also, the implications of different types of technological progress were explored. New growth theory, however, explicitly allows for the endogeneity of technological change. Economic agents can affect the pace of technological change by changing their behaviour or explicitly devoting resources to technological development. In this literature, which emerged at the end of the 1980s, technology is mainly interpreted as "knowledge" and techniques are often called ideas or blueprints. Moreover, knowledge is assumed to have the characteristics of a public good, i.e. it is non-rival and (partially) non-excludable. The endogenous growth literature is mainly concerned with the determinants of privately generated technological change. The key insight here is that some kind of monopoly power is necessary to explain why private agents develop new technologies (Romer, 1990). Accordingly, the new growth theory places the Schumpeterian profit incentive into an equilibrium framework and attributes private and public properties to new knowledge. The private properties result from the appropriation of new knowledge, but the associated positive externalities (spillovers) represent public properties. These spillovers create dynamic increasing returns and therefore generate long-term growth.

As far as the relationship between these changing concepts of technology in economic theory and their implications for sustainability are concerned, attention has shifted to the link between environmental policy and the *direction* of technological change.[2] Not only have new models facilitated the explicit study of technological change as the mechanism that induces sustainable economic growth, but they have also been helpful in exploring its implication for the potential trade-off between economic growth, measured as income growth, and the environment. A growing empirical literature documents that these mechanisms seem to be important in decoupling economic growth and emissions (see also Section 3).[3]

A (gradual) shift in the direction of technological change is modelled through investment in research and development (R&D) or through so-called learning curves or both.[4] *Investments in R&D* build on the recognition that new knowledge or technology enhances profits and is usually assumed to be appropriable. However, these investments are associated with spillover effects, i.e. investment not only benefits the investor herself but others as well through technology improvements. Investments in R&D are usually modelled as additional capital stocks of human knowledge or research capital. The new capital stocks augment total factor productivity or the productivity of certain input factors (energy or carbon among them) or both. *Learning curves* rely on the concept of learning-by-doing (LbD) and learning-by-using (LbU). The costs of production and/or abatement decrease due to experience, i.e. knowledge is accumulated through production and/or abatement itself. Note that this distinction associates learning with diffusion of technology and/or knowledge across agents (firms, households) and R&D with innovation, i.e. invention and application of new technology and/or knowledge. A crucial assumption about both R&D

[2] This is also often somewhat loosely called *induced* technological change. However, endogenous technological change does not necessarily imply a change in its direction. We owe this point to Sjak Smulders.

[3] This literature has recently been summarized in studies such as Loeschl (2003), Jaffe et al. (2003) and Smulders (2005). See also Smulders (1995) for a somewhat older, though explicit, discussion of the (potential) implications of this literature for the thermodynamic issues raised by Georgescu-Roegen.

[4] Note that we avoid the label "learning-by-researching", which would be an alternative way to describe the role of R&D more explicitly. Also, we note that sometimes the term "experience curve" is used instead of "learning curve" for the aggregation of learning effects over multiple firms.

and learning curves is that they respond to changes in relative prices. Hence, changes in the direction and speed of technological change can be induced by purposive changes in relative prices, for instance by a regulator. Accordingly, sustainability policies such as environmental taxes or regulation provide incentives to redirect innovative activity.

As a final observation, it is important to note that there have been attempts to model technological change in an endogenous fashion in so-called bottom-up as well as in top-down models. Bottom-up models are technology-oriented optimization and simulation models that focus on a detailed description of the various technologies and their economic performances. In these models, technological change is represented by the replacement of one technology by another, due to the better performance of the latter. Top-down models, on the other hand, focus on the representation of the economy as a whole rather than on detailed descriptions of specific sectors. In these models, technological change is represented by factor productivity improvements as a result of price change.

The aim of this special issue is to present, first of all, "state-of-the-art" discussion of recent theoretical and empirical advances in our understanding of the link between technological change and the environment. Accordingly, several papers not only summarize what we have already learned, but also discuss new avenues for research. Second, this issue contributes to the current literature by explicitly discussing the possibilities of inducing environmentally biased technological change through technology policy, environmental policy or both. Finally, in particular in the field of integrated assessment or applied energy-economy models, this issue introduces new and sometimes even unorthodox approaches towards including endogeneity of technological change and its implications for sustainability in general and climate change in particular. Also, several of the papers explicitly aim to bridge the gap between top-down and bottom-up modelling.

This special issue is divided into three parts. The first three papers reflect on recent developments in both economic theory and policy in the context of induced technological change. The second part consists of three papers that present and discuss empirical findings as to how the different mechanisms distinguished in theoretical models account for shifts in technology in practice. The third part focuses on the role of endogenous technological change in what we simply call integrated assessment (IA) models, i.e. applied models that capture aspects of climate change policy and its interaction with the environment, human welfare or both. In this third section, four papers discuss the implications of the endogeneity of technological change for IA modelling from a more-or-less standard economic perspective and two papers use alternative foundations, i.e. non-standard economic modelling approaches.

2. Theory and policy

The relevance and implications of the endogeneity of technological change for both resource exploitation and policy formation are discussed in the first three papers. Bretschger, first of all, reflects on the old question raised by Georgescu-Roegen, i.e. to what extent does the acknowledgement of the endogeneity of technological change justify the current, more optimistic view on the compatibility of natural resource use and economic development? To acknowledge the role of technological change is one thing; to show that it might solve older controversies is quite another. As noted previously, the crucial difference between the current modelling efforts of economists and the older literature to which Georgescu-Roegen refers is that both the rate and direction of technological change are now (allowed to be) sensitive to (price) incentives. Indeed, one of the limitations of the older literature has been its dependence on enough substitutability of inputs to compensate (asymptotically) for the fundamental limits posed by an essential resource. Key to endogenous growth theory, however, is its multi-sector approach, because in addition to one production sector, at least one other sector produces innovations. In this set-up, technological change is simply induced by rising price signals from the essential non-renewable resource which is gradually exhausted. Bretschger argues that although this mechanism compensates for natural resource scarcity, diminishing returns to capital, poor input substitution and material balance constraints, it is not clear whether fading returns to investment in research and rising (marginal) research costs may not still impose a limit to this "salvation" (to borrow a phrase from Georgescu-Roegen). Interestingly, he is also sceptical about the process of deriving long-run predictions from these modelling exercises and argues that only results that survive in different modelling environments would be trustworthy.

Technological change has been considered as a black box in economics for a long time (Rosenberg, 1982). The underlying mechanisms responsible for economic growth, in particular innovation and diffusion of new technology, came to the notice of a wider audience of economists mainly because of endogenous growth theory. Bretschger discusses several of these mechanisms in relation to the environment. One important issue is that the willingness of agents to invest time or money in research or learning is fraught with public goods aspects, i.e. the problematic appropriation of its social value. Since the seminal paper of Arrow (1962), the standard view is that the investor is often not able to get the full return to his investment because new knowledge, once available, is non-rival and only partially excludable through instruments such as patents. Moreover, diffusion of new knowledge is also less likely to be instant and immediate across a heterogeneous population. Add these problems to the standard view that the production of environmental quality is associated with externality and public good aspects as well,[5] and one immediately realizes the complex nature of choosing optimal policy rules in this area.

The paper by Jaffe, Newell and Stavins explains the complications that arise because of these two market failures. They tell the tale that both theory and empirical evidence suggest that the rate and direction of technological change are influenced by market and regulatory incentives and can be cost-effectively harnessed by policies based on well-targeted economic incentives. The public goods nature of R&D requires subsidies that compensate for the difference between the social and private return of a particular investment, whereas negative externalities associated with the production of environmental quality would require corrective instruments such as taxes to restrict pollution. This line of reasoning closely follows an old dictum of Tinbergen (1960) for economic policy, i.e. the number of instruments used by the government should be equal to the number of goals. If both technology and environmental policy are well designed, one might wonder whether there is any room left for policies directed at environmental technology as such.

The Tinbergen dictum assumes a world that allows for well-defined problems that could be addressed by well-targeted instruments. Obviously, we are not living in such a world. Therefore Jaffe et al. also pay attention to the question of what should be done if actual policy deviates from the optimal policy rule. The framework used to discuss such questions systematically is the theory of second-best, and the interaction between technological and environmental policy is another example of this rapidly developing field. Jaffe et al. discuss in detail the role of environmental technology policy as the focal point of the two interacting market failures. Because they believe that it is unlikely that investment in the development and diffusion of new technology occurs at the socially optimal level, a typical case would exist for a second-best policy focused on environmental technology.

A related and old environmental policy issue is the choice of instruments. The Tinbergen dictum still reigns as a benchmark in this area as well. For instance, in an often-cited overview of the earlier literature, Bohm and Russell (1985, p. 397) claim that the "conceptually preferable position is that both goal and instrument must be chosen simultaneously in a grand meta-benefit/cost analysis". Informational limitations to optimal planning would, however, strengthen the case for so-called market instruments, such as taxes and tradable permits, as Baumol and Oates (1971) argued in their famous paper long ago. These instruments would require less information from the regulator than command-and-control instruments, whereas they would produce environmental quality levels at lower cost. At least as important, however, are potential differences in the dynamic incentives of environmental policy instruments, as Requate stresses at the beginning of his paper, i.e. how they affect the development and diffusion or adoption of new technologies.

Requate challenges the standard or textbook evaluation of economic instruments, using new

[5] Note that environmental quality as an output is just the inverse of using environmental pollution as an input (see Copeland and Taylor, 2004).

insights from the signalling literature and their implications for the interaction between environmental policy instruments and technological change. He argues in favour of rankings based on incentives to invest in equilibrium rather than on aggregate cost savings. Although the old preference for market-based instruments remains more-or-less unchallenged, the reason why these instruments would (still) be favourable differs remarkably from that in the older literature. With competitive markets, for instance, market-based instruments are still better than command-and-control because taxes may provide stronger incentives in the long run if the regulator is myopic. Taxes provide similar incentives to tradable permits only if the government can anticipate new technology or reacts to it in an optimal way. Another interesting insight from this literature is that it also confirms older claims that the abatement incentives of tradable permits that are either auctioned or grandfathered are not different at the margin (Pezzey, 1992). Furthermore, timing and commitment of environmental policy would also not be crucial for adoption. With imperfect competition in the output market, however, the ranking becomes ambiguous. In this case, commitment has positive effects if the R&D sector has market power.

3. Empirics

Since the seminal contribution of Rosenberg (1982), economists have gradually opened the black box of technological phenomena. This is not to say that economists did not acknowledge the role of these phenomena or their importance to economic development before. Little attention had been paid, however, to how changes in technology come about and which economic mechanisms are behind these changes. Similarly, economists had little to say about the environmental dimension of these changes for a long time. Recently, however, the delinking of growth and environmental stress (i.e. lower environmental quality because of higher emissions or fewer resources) has been demonstrated empirically in several dimensions (Brock and Taylor, 2004).

It is useful to distinguish between two, often subsequent, phases in environmental innovation once an environmental issue has been brought to the policy agenda. In the first phase, the focus is on immediate problem solving. For instance, in the early 1970s, several environmental problems, such as water and local air pollution, required immediate action once their negative side effects were recognized. When the quality of drinking water dropped to previously unknown low levels, the response from policy-makers was to invest in water sanitation and force industries to purify their water emissions. In turn, industries installed add-on technologies that reduced emission immediately. After some time, these industries usually recognized that emission reduction requirements are like thresholds: once they are adopted, the regulator (almost) never reconsiders these quality levels, and innovators start to integrate the requirements in their process and product designs. Accordingly, one arrives at the phase of what is sometimes called integrated technology.

Because we can observe this dynamic regulatory process in many areas nowadays, we see a rapidly expanding field exploring its implications for technological changes empirically. Indeed, the interaction between environmental policy and technological change is now studied from several different angles. Three papers in this special issue deal with some of these issues in particular. First, Shadbegian and Gray focus on abatement costs for sectors where they are relatively large, in particular for paper mills, oil refineries and steel mills. These pollution abatement costs are defined as the capital expenditures and operating costs, including labour, materials and depreciation, needed to reduce emissions to air, water and ground (including waste reduction). Pollution abatement costs are well below 1.0% of total production costs in most industrial sectors, but they are much higher for the sectors studied by Shadbegian and Gray. Note that pollution abatement costs may provide a measure of external regulatory pressures that help induce technological change, and that some pollution abatement costs are difficult to measure (e.g. the pollution abatement cost component of a new investment project that makes a plant both cleaner and more productive).

A typical economic question is whether environmental regulation might have drawbacks for productivity, for instance because of crowding-out effects on R&D (see Nordhaus, 2002, and Smulders and de Nooij, 2003). A given dollar of investment can be spent only once. When this dollar is spent on (research in) pollution reduction, other perhaps more productivity-enhancing options are no longer possible. Other authors, such as Porter and van der Linde (1995), have a more optimistic view and believe that regulation might also be favourable in some (sub)-sectors if firms take a competitive advantage. Shadbegian and Gray allow their measure of productivity to distinguish explicitly between traditional output and "environmental output" to account for what they call the "mismeasurement effect", i.e. productivity measures that do not differentiate between these different goals of input use. Using a microdata set for plants in the three sectors mentioned before, they find that abatement expenditures contribute little or nothing to production but also have no significant effects on the productivity of non-abatement expenditures. Moreover, further decompositions to allow for heterogeneity in production technologies within these sectors provide little evidence for significant differences across these groups. Note, however, that if environmental technologies become integrated over time, it will be more difficult to measure abatement costs, and under-reporting may become more likely. These productivity effects require analysis that allows for other potential mechanisms as well.

One of these other mechanisms is the role of (induced) R&D investment; its consequences have been studied recently by Popp (2002). Output of R&D activity–whether this involves fundamental process developments or "add-on" technology–can be explicitly measured through patents. Measuring its "inducement", however, requires separating patents into "environmental technology" and "non-environmental technology". Using this distinction, Popp was able to show that there is a clear link between environmental policy and the direction of technological change as measured by patents. In his contribution to this special issue, Popp reflects on his earlier findings and relates them explicitly to other findings in the literature that links environmental policy and technological change, as well as to recent extensions of what we call integrated assessment models (see the next section).

The key insight is that innovation responds quickly to changing incentives. In particular, patents show much more sensitivity than, for instance, in the study by Brunnermeier and Cohen (2003). These authors also find that higher pollution abatement costs lead to more patents, but the magnitude of the effect is smaller than in Popp's paper. One reason could be that Popp looks at the individual reactions of very specific technologies and uses patent citations to control for diminishing returns. Other lessons discussed by Popp are that a time trend is not a substitute for technological change, that social returns to environmental research are high and that the type of policy also affects the nature of new innovations. One of the interesting issues for future research is, according to Popp, to study more explicitly the links and the speed of diffusion between foreign and domestic knowledge. In particular, while these have been studied more generally by others (for instance, Keller, 2004), little work addresses the links between environmental policy and international technology transfer.

One sector that would qualify not only for international diffusion of new (environmental) knowledge but also for testing the Porter hypothesis is the wind industry. Clearly, electricity generation using wind is a very old technology. In particular, windmills date back to at least 1500, but recent advances in generation technology have improved their energy efficiency enormously. According to a recent study about learning curves for electricity generation using wind energy, the cost of electricity production has declined on average by 82% (OECD/IEA, 2000, p. 21). Support for wind energy has also been considerable in many countries, so it would be interesting to see whether the R&D subsidies have made a difference here.

This is the main question in the case study by Klaassen, Miketa, Larsen and Sundqvist in this special issue. They focus on cost-reducing innovation in wind turbines in three countries—Germany, Denmark and the UK. The innovation and diffusion mechanism is studied here using the so-called two-factor learning curve (see Kouvaritakis et al., 2000), which is a typical bottom-up perspective on the development and spread of new technologies. The two-factor learning curve extends the simpler learning curve approach as, for instance, applied in the OECD/IEA study mentioned in the previous paragraph. According to this concept, cost reductions for particular technologies arise out of two kinds of learning. The first mechanism is called searching, and typically arises because of investment in the stock of R&D (and its lagged effect). The second mechanism is labelled "learning-by-doing", but this concept is somewhat more general here because it allows not only for improvements in (on-the-spot) applications of such technologies and their uses, but also for the development of "new" technology. The typical empirical indicator is cumulative capacity, as it is assumed that this type of learning grows with the amount of technology applied.

The findings of Klaassen et al. typically support this two-factor learning curve, showing a robust estimation of a common slope (i.e. similar learning curves for the different countries) as well as heterogeneous intercepts, which point to differences in local (economic or other) environments. Import indicators for the UK (80%) as well as Germany (40%) reflect a leading role for Denmark. This is hardly surprising because Denmark supported investment in innovation for windmills much earlier than the other countries. In contrast, the Netherlands, not studied by Klaassen et al., decided to reduce public subsidization of wind energy R&D and diffusion in the 1980s and lost its leading role. Accordingly, this case study seems to provide casual evidence for the Porter hypothesis, although it remains unclear whether environmental policy is beneficial in this case beyond the environmental dividend itself. Moreover, a case study can never generate a general confirmation of any hypothesis, but this one does seem to give some indication that, at some specific place and time, environmental policy is able to lift the growth of some sectors.

4. Integrated assessment and endogenous technological change

One of the most important and challenging policy areas for sustainability nowadays is climate change. Technological change is also very likely to play a crucial role in this area. Examples are many mitigation options, such as alternative electricity generation processes, carbon sequestration, fuel cells and large-scale storage using mono-ethanol and decarbonization in integrated power plants or in other gasification processes (Anderson and Newell, 2003). A useful tool for evaluating the relevance of such options for climate change policy is applied modelling. Applied models simulate not only the impacts of climate change on the economy but also the economic consequences of global long-term climate policy strategies per se. Knowing that technological change is important and is unlikely not to be changed by climate change policy, one is curious to see how explicit recognition of this link may alter climate change modelling assessments. The third part of this special issue is devoted to this area of research. As noted before, applied modelling efforts that study the economic consequences of climate policy strategies can be classified into top-down and bottom-up modelling approaches. In the top-down approach, first of all, the macroeconomic consequences of technological change are studied. On a macro level, the decision about how much to spend on R&D and the various feedback effects on technological progress are evaluated. Bottom-up models are typically built around the use of energy technologies and their technical as well as economic characteristics. Technological change is often incorporated through learning rates that describe cost improvements with increasing installed capacities of a technology, and these rates may typically vary across (energy) technologies.

Recently, both top-down and bottom-up approaches have started to incorporate the ideas of induced technological change. For instance, Goulder and Mathai (1999) study the economic impacts of induced technological progress–both in R&D expenditures and learning-by-doing–for optimal timing of climate change policy. Their main finding is that if one expects new knowledge from increasing R&D expenditures, carbon abatement could be better postponed to later time periods. However, if it is likely that new knowledge would primarily be obtained through learning-by-doing, an earlier start to carbon emission abatement is optimal. Also, applied models, such as MERGE (Manne and Richels, 1999) and MIT-EPPA (Jacoby and Wing, 1999), now typically include induced technological change through a so-called autonomous energy efficiency improvement factor (AEEI). Recent versions of MERGE also include endogenous representations of technological change through learning-by-doing (Manne and Baretto, 2004). Similarly, energy system models, such as MESSAGE (Grübler and Messner, 1998) as well as new versions of POLES (Kouvaritakis et al., 2000) and MARKAL (Barreto and Kypreos, 2000), include learning-by-doing in special (energy) functions within their energy system framework.

This special issue adds to this fast-growing literature on endogenous technological change and the environment as follows (compare Carraro et al., 2003). First of all, several papers add to the economic analysis of climate change by explicitly allowing for both investment in R&D and learning at the same time. Second, a few papers claim to explicitly bridge the gap between top-down partial equilibrium modelling and bottom-up analysis of the choice of energy technology. Third, some papers incorporate technological change in their integrated assessment models in a non-orthodox way, i.e. without common micro-economic foundations.

The first contribution, by Gerlagh and Lise, develops the partial equilibrium model DEMETER-2E for energy supply and demand with endogenous technological change represented through both R&D and learning-by-doing. The typical bottom-up characteristic of this model follows from the two competing technologies (energy sources) included, a carbon-based and a non-carbon-based technology. Accordingly, the model allows for energy source substitution, which, according to the authors, is important in order to allow for substantial abatement of carbon dioxide emissions, as required, for instance, by the Kyoto protocol. The essential difference from Goulder and Schneider (1999), who also allow for two energy sources, is that DEMETER-2E does not assume a priori that these technologies are gross complements (substitution elasticity below unity). The transition from one energy source to the other is endogenous in the model, with energy production cost functions being variable over time and dependent on the state of technology. Note, finally, that the model includes an R&D sector that requires costly investment, whereas learning-by-doing is–as usually–assumed to be a direct spillover effect of production.

Policy is typically represented in the model through a carbon tax. The model produces a transition from fossil fuel to carbon-free energy sources within the next two centuries, with a pattern that follows the well-known S-curve for gradual diffusion. Moreover, in contrast to Goulder and Schneider (1999) and Nordhaus (2002), the study by Gerlagh and Lise finds that induced technological change can substantially accelerate the substitution of carbon energy for fossil fuel and reduces cumulative emissions over the period 2000–2100 by a factor 3 for given effort. So whether or not ITC is important relative to factor substitution seems to boil down to the issue of complementarity versus substitution, which we already know from the old controversy between Georgescu-Roegen and Solow in the context of exogenous technological change.

Castelnuovo, Galeotti, Gambarelli and Vergalli study the impact of the two general mechanisms that represent induced technological change–investment in R&D and learning-by-doing–in more detail. In fact, they extend the popular growth model, RICE, from Nordhaus and Yang (1996) to incorporate both mechanisms at the same time. As in the paper by Gerlagh and Lise, knowledge accumulates by costly R&D investments and costless learning-by-doing. Furthermore, the model of Castelnuovo et al. assumes six regions playing a Nash game, i.e. each region selects its own optimal consumption and investment path in both capital and knowledge, as well as its own abatement rate and R&D effort in the version of the model with R&D-based knowledge accumulation. To get a feeling for the role of the different mechanisms, the authors simulate policy scenarios for each of the mechanisms involved.

Interestingly, R&D and LbD show quite similar dynamic patterns in the RICE framework. Emission reduction strategies are costly, but each type of endogenous technological change lowers emission abatement costs considerably at the margin compared with the case where technological change is exogenous. However, R&D-driven technological change leads to substantially better outcomes in terms of welfare than the pure learning case, probably because more freedom exists to choose local R&D levels optimally. The results for abatement cost reduction may come as a surprise because empirical measures show a substantial difference between the two, with average cost savings of around 12% due to R&D and 5% for learning (see also Popp's paper in this issue). It would be interesting to see whether the results obtained by Castelnuovo et al. for the RICE model would survive in a framework such as the model developed by Gerlagh and Lise with its greater flexibility in the energy sector. Another interesting extension mentioned by the authors would be to see both mechanisms working at the same time to explore the overall effect of ITC.

One of the suggestions of Bretschger is to pay more explicit attention to sectoral decomposition in growth models. The paper by Edenhofer, Bauer and Kriegler is one such example because its integrated assessment model, MIND, links the mechanisms of endogenous technological change discussed so far (R&D and learning-by-doing) to sectoral decomposition in the energy production sector. This model has much detail in the energy production sector, allowing for a fossil-fuel extraction sector, a generation sector and a renewable energy sector, and it also includes separate R&D sectors for labour and energy efficiency. The model is used to study the cost of ambitious climate protection objectives allowing for a portfolio of mitigation options, i.e. energy efficiency measures, substitution of energy sources ("backstop" technology) and Carbon Capturing and Sequestration (CCS). Edenhofer et al. find that ambitious policy goals are feasible without significant welfare losses because of the role of endogenous technological change. Furthermore, the model shows that different mitigation options are of different importance over time. Improving energy efficiency and CCS are important options to buy time but become too costly as major mitigation options in the long run. In the long run, fossil fuels have to be substituted by renewables because a backstop technology with the potential of learning-by-doing has the strongest impact in reducing consumption losses due to climate protection. So far, however, the results for MIND have only been demonstrated for a planners' economy.

It is instructive to see why these models find such substantially different effects compared with the ENTICE model discussed at length in Popp's paper in this special issue. The ENTICE model is a variant of Nordhaus's DICE model and also includes a fossil-fuel sector and an energy-research sector (see Popp, 2004). Accordingly, the model explicitly links R&D to changes in the price of carbon. Furthermore, the ENTICE model is calibrated using the empirical results mentioned before and also confirms the result, demonstrated in the other models, that endogenous technological change is important. A controversy, however, seems to arise as to whether the opportunity costs of R&D are important. The DICE model, as well as other models such as those in Goulder and Mathai (1999) and Smulders and de Nooij (2003), allows for the crowding-out effects of R&D investment. Popp, in his contribution to this special issue, argues explicitly in favour of an assumption of 50% crowding-out effects between new energy R&D spending and other R&D spending, which is a mechanism not included in the integrated assessment papers of this special issue discussed so far. Indeed, models with "free" learning-by-doing (as a costless device) report much larger potential gains from technological improvement. Accordingly, this controversy seems to boil down to the question of whether there is crowding-out of R&D and whether it makes sense to assume costless learning-by-doing.

The final paper related to this literature is Kemfert's study of induced technological change using her multi-regional general equilibrium model, WIAGEM. This model represents the world economy by different regions that are linked by bilateral trade flows and covers a climate sub-module that simulates the climate feedback effects of changes in climate change emissions. The model also allows for international spillover effects associated with R&D investments, in particular in the context of Clean Development Mechanisms (CDM) and Joint Implementation (JI).

Assuming binding international emission reduction targets, this paper studies how the compliance costs of developed and developing countries are affected if one allows for induced technological change through increased spending on R&D, which, in turn, increases energy efficiency. As a result, Kemfert finds that technological change reduces emission abatement costs considerably. More interesting is the important role of knowledge spillovers from self-enforced investment in CDM projects. Consequently, the share of carbon-free technologies in developing countries rises much faster if one allows for the positive effect of R&D on energy productivity. R&D investment depends on total investment and the crowding-out effect, and therefore captures some aspects of the mechanisms in the ENTICE model. However, this model does not include "optimal R&D spending" behaviour, and only those countries that are (negatively) affected by climate change and take climate control measures spend on R&D.

The final two papers of this special issue deviate from standard economic modelling and use a natural-science-based approach. The integrated assessment model MADIAM, presented by Weber, Barth and Hasselmann, includes both a climate feedback system (non-linear impulse response model) and a systems description of the economy with optimizing agents (multi-actor dynamic economic model). Profit maximization leads to rationalization and increasing labour productivity. This requires technological change, which is therefore the main driver of economic growth. This set-up, according to the authors, would be very different from more traditional CGE models commonly used by economists. Crucial for growth in Weber et al.'s model is the profit motive of business inducing investment in productivity improvement, and not the savings or the purchase of shares by consumers.

Interestingly, the results of this model are not that different from those of more standard economic models. The authors claim that moderate mitigation through a carbon tax has (very) little effect on the growth rate compared with the "business-as-usual" scenario, i.e. a delay of only 1 or 2 years over a period of 100 years. The authors also study an "Induced Technological Change scenario", which is an enhanced mitigation scenario where the 10:90 ratio of tax revenue invested into net carbon efficiency to investments in physical and human capital is changed into 50:50. A double dividend arises with this assumption because carbon dioxide emissions are reduced and economic growth is enhanced. It appears that the enhancement of net carbon efficiency reduces business expenditures on future energy and carbon taxes considerably, which more than compensates for the reduced investments of recycled taxes into physical and human capital. According to the authors, the main difference between MADIAM and conventional CGEs is the ability of MADIAM to resolve the dynamics of different actors (in their case, business, governments and consumers) pursuing different goals on different time scales. Accordingly, the dynamics of long-term climate change would be embedded not only in government policies and technological change, but also in changing business investment decisions, consumer preferences, etc.

Finally, Bruckner, Morrison and Wittmann present an alternative approach to the current strategy in order to reflect technology interactions and technical progress better within established economic models. They present a model of the energy system focusing on the use of what they call distributed technologies in their immediate (social) environment. Distributed energy technologies–according to the authors–differ from existing technologies in that they are usually exploited on a much smaller scale, are less centrally planned and are often (locally) process-integrated, like cogeneration, energy efficiency improvements and waste heat reclamation. These characteristics as well as the relative influence of "network dynamics" would, according to the authors, require a different modelling approach, in particular so-called high-resolution modelling. This approach allows for much more detail in bottom-up models, whereas, in a second step, explicit modelling of "multi-participant" decision-making is required, which is part of what is called entity-oriented (EO) modelling.

The authors discuss several illustrations of their approach and claim that policy models with "less resolution" and "fixed component efficiencies" would fail to capture and capitalize on the operational flexibility contained within energy systems. Moreover, they claim that this approach would also be useful in investigating structural evolution at a more structural, natural level. This is good news, especially for those who believe that an evolutionary approach to system changes would be necessary, for instance in the recent literature on transition dynamics (see Kemp, 2000), and for the design of policies that try to escape "lock-in" of existing technological systems. We agree with the authors that their approach yields "less definitive results", which one could see as a merit given that the evolution of social systems is usually highly unpredictable. However, we also consider it a merit of the existing economic approach that one gets a clear picture of underlying economic mechanisms, such as price changes, that give rise to system changes or, conversely, that prevent these changes from taking off. We still believe that elasticities, although often imprecise, are a useful device to describe the strength of such mechanisms at work in the economy and their role in the actual direction of the system as a whole.

5. Conclusions and future research

We started this editorial introduction with the fundamental question of whether the current optimism that technological change will solve our remaining environmental issues is justified. Looking at the papers in this special issue as well as at other recent contributions to this literature, the answer seems to be "yes". It is remarkable to see how the literature has succeeded in unravelling several not very well-known links between environmental policy and technological change in a relatively short period. What makes this literature particularly convincing is the close link between the different branches of (economic) science, which is also nicely reflected in this special issue.

Indeed, we observe a steady growth of theoretical papers that succeed in showing how the fundamental mechanisms behind what is called directed technological change may at least postpone "absolute" scarcity issues, with small effects on economic growth under some reasonable assumptions. Furthermore, empirical papers demonstrate that these mechanisms are real and do their work in practice, such as shifting R&D efforts as measured by an obvious measure (patents), greatly reducing abatement cost over time, probably due to scale effects and learning-by-doing, and only resulting in moderate productivity drawbacks from abatement costs in highly polluting sectors. Finally, including these mechanisms in (applied) modelling efforts used to evaluate the consequences of climate change policies also yields more optimistic results than business-as-usual scenarios without induced technological change. Accordingly, directed technological change conveys a positive message, i.e. that shifting away from polluting towards non- or less-polluting technologies seems both possible and "manageable" through environmental policy.

Some caveats lurk on the edge, and warnings against an overly optimistic view seem justified. We discuss three broader issues, each of them leading to new avenues of research. First of all, there are now many convincing success stories, as, for instance, explored in more detail in OECD (2001). However, not all our environmental resources can be preserved equally effectively by technological change. For instance, our consumption of nature (land) and its associated environmental good "biodiversity" cannot be. This is not to say that the human species could not be smart enough to deal effectively with such scarcity constraints, but its "salvation" may require very different policies from, for instance, our policy efforts to reduce air pollution. Indeed, most of our success stories so far are linked to changes (reductions) in energy consumption and its composition. It would be useful to see stories about other "red" environmental problems as well. For instance, for the principal greenhouse gas, CO_2, the income effect appears "green" for many countries, but the time-related effects seem to nullify these positive Kuznets effects quite often, as demonstrated in a recent paper by Vollebergh et al. (2005).

Second, recent developments in environmental policy seem to point to a broader and more general approach towards sustainability, such as transition management aimed at decoupling emissions and growth by a factor 4, etc. (Weizsacker et al., 1998). These much more ambitious goals require much more fundamental changes because currently polluting processes are often part of wider, more complex systems. For instance, emissions from road fuel consumption, such as lead and SO_2, can be reduced by installing a catalyst and improving the efficiency of the fuel-burning process. However, this consumption is closely linked to other technologies, such as refineries, petrol stations and distributing networks of trucks. The introduction of fuel cells would require a transition of this whole system. Therefore, one might call such radical changes "system innovation" or "transitions". That these radical changes are also "manageable" through policy, be it environmental policy, technology policy or both, is still hard to believe. Environmental policy that aims to "pick the winners" runs a serious risk of failure. A more viable strategy seems to allow for a portfolio of potential sustainable options, i.e. both non-fossil-fuel energy and Carbon Capturing and Sequestration, and let the market decide among them.

Finally, a widespread belief seems to exist that environmentally induced technological change would yield a double dividend. The introduction of learning-by-doing into (applied) modelling especially seems to play an important role in generating this optimistic view. Many papers in this special issue indeed demonstrate its importance for our cost estimates of climate change abatement strategies. At the same time, however, it is somewhat unsatisfactory from an economic point of view that learning-by-doing would not have any opportunity costs and is assumed to be a "free" good. Although learning-by-doing is not entirely free, of course, because it requires economies of scale and therefore investment in otherwise scarce (capital) resources, the additional cost-saving effect ("positive externalities") does not require additional investments. This is somewhat unsatisfactory as it is not easy to see how learning-by-doing can spread among a population without any additional effort. Diffusion of knowledge is costly as well and it would be useful to understand the mechanisms behind this process better. In particular, it seems that our understanding of diffusion and its link to private and public decision-making is still rather limited and could be considerably improved.

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This special issue contains 12 papers presented at two separate workshops. The first workshop, "Economic Modelling of Environmental Policy and Endogenous Technological Change", held in Amsterdam on 21 and 22 November 2002, was organized by a joint initiative of the Fondazione Eni Enrico Mattei (Carlo Carraro), CentER of Tilburg University (Willem van Groenendaal), the IVM of the Free University Amsterdam (Marjan Hofkes), OCFEB of Erasmus University (Herman Vollebergh) and MERIT of Maastricht University (Rene Kemp) and has been sponsored by the Netherlands Organization for Scientific Research (NWO). The aim of this workshop was to discuss whether and how environmentally biased technological change could be induced through technology policy, environmental policy or both. The three main topics were a state-of-the-art discussion on the economic analysis of (endogenous) technological change and the environment, recent developments in the economic theory of policy instruments in relation to technological change, and the role of technological change in empirical analysis and applied policy modelling.

The second workshop, "Sustainable Technologies for the 21st Century", held on 12 and 13 December 2002 in Delmenhorst (Germany), was organized by Oldenburg University (Claudia Kemfert), with co-assistance from the Hanse Wissenschaftskolleg and the European Climate Forum (ECF). The workshop brought together scientists, engineers and consultants working in related areas such as climate change, economic modelling and technology development. The central topic of the workshop was how to assess the role of sustainable technologies for the 21st century and the economic impact of the implementation of such technologies. The workshop focused on the representation of technological improvements and technological learning using a variety of modelling tools, such as bottom-up system engineering modelling and top-down computable general equilibrium (CGE) and integrated assessment models.

Together, these workshops provided interesting, state-of-the-art material in this rapidly developing field. The workshop in Amsterdam more-or-less focused on empirical analysis and reflection; the workshop in Delmenhorst focused on applied modelling, in particular the modelling of technological change in relation to climate change policy. This special issue brings together a selection of the papers presented at the conferences (after the normal refereeing procedure).

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