2. Environmental policy, induced technological change and economic growth: a selective review

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1. INTRODUCTION

Technological change has long appeared to play a backstage role in economic thinking. Its impact was typically described in terms of variables that change exogenously with the progress of time. It is only with the advent of the new growth theory (reviewed in the monographs by Barro and Sala-i-Martin, 1995, and Aghion and Howitt, 1999), in which technological change is endogenously determined, that issues of technological change have become a focus of economic research. Specifically, the important role of environmental policy for inducing technological progress through creating constraints and incentives has been increasingly recognized. The discussion concerning the optimal time path of carbon taxes in the presence of induced technical change illustrates this. Wigley et al. (1996) argue for a policy that makes postponement of abatement attractive in order to optimally exploit the reduction of abatement cost resulting from technological progress. However, work by Grubb et al. (1996) indicates that a policy that favors more abatement in the short term is superior to a 'wait-and-see' approach when technological progress advances through learning-by-doing.

This chapter reviews the relation between environmental policy, the technological change that it induces and the resulting consequences for economic growth. Through its inclusion of growth aspects it complements an earlier review by Jaffe et al. (2002) and the reviews by Clarke and Weyant (2002) and Grubb et al. (2002), which focus on climate change and energy policy. The review is selective in that it does not attempt to mirror the burgeoning literature on the subject but rather aims to highlight different routes of analysis and to portray in broad strokes the current state of discussion. Specifically, the review aims to give state-of-the-art answers to the following questions: does the presence of induced technical change lower the cost of achieving emission abatement targets? How does induced innovation affect the timing of optimal abatement? To what extent might exogenous technology models understate the welfare gains from environmental policies? And what are the implications of endogenous technological change for environmental policy?

To bring some structure into the diversity of models that analyze the relationship between environmental policy and technological change, it is convenient to organize them according to a scheme proposed by Clarke and Weyant (2002). The simplest types are *cost-function models*, in which the technological advances induced by environmental policy translate only into changes of the abatement cost function. One step up on the ladder of complexity are *intertemporal partial equilibrium models*. These models study the equilibrium consequences of policy interventions in the market for environmentally focused innovation over time by ignoring effects on other markets. The boundary between both groups is not sharp and to a large extent marked by the model's emphasis rather than methodology. In fact, the first two models that we consider in this review can be seen as belonging to either category. The model by Goulder and Mathai (2000), which we review in section 3, focuses mainly on the determination of an optimal emission path for an economy in response to some policy criterion. It challenges the claim that the presence of induced technological change calls for a more cautious environmental policy. The welfare aspects that are attributable to induced technology innovation, and in particular their magnitude in relation to the Pigouvian welfare gains of an optimal emission tax are examined in section 4 using the model by Parry et al. (2002). This model shows that for a broad range of circumstances the Pigouvian welfare gains dominate those from technological innovation.

More difficult both in conception and in the use of mathematical tools are *growth models* in which technological change is endogenized. We review in section 5 a series of rather general models of this type that explicitly include environment–economy interactions (Bovenberg and Smulders, 1995, 1996; Smulders 1995, 1998). The analytical tractability of these models makes them a good vehicle for gaining a conceptual understanding of the implication of technological change.

A brief discussion of *intertemporal general equilibrium models* in section 6 follows. These models are typically computer-based, involve explicit representations of markets and their interactions over time, and as they shed light on the role market ineffciencies play for environmental technological innovation, they add a dimension to the analysis that is absent in the other types of models. As representatives for this model type we select the models by Goulder and Schneider (1999) and by Popp (2002), whose main field of application is the analysis of greenhouse gas abatement policies.[1] We conclude in section 7 with a brief discussion of the implications of the models for environmental policy.

To lay the ground for our discussion we continue in the next section with a brief outline of some of the salient features of technological progress.

2. KEY FEATURES OF TECHNOLOGICAL CHANGE

Technological progress as understood here manifests itself through its impact on the macroeconomic production function thereby changing the input–output combinations and society's production possibilities. *Induced* technology progress occurs in response to policy intervention and, as such, is different from exogenous progress that is just a result of the passage of time. There is a multitude of channels through which public policy can affect technological advance. An incomplete list includes changes in the relative prices of polluting and non-polluting goods, which could result, for example, from the imposition of an emission tax; research grants to private firms; or subsidized research and development at national laboratories and universities.

Technology, a form of knowledge, has properties of a public good. That is, technology knowledge is

- *nonrival*, that is, the use of technology by one agent does not preclude others from using the same technology. Conventional private goods, in contrast, are rival. A piece of capital equipment, for example, can only be used in one place at a time. An immediate implication is that the production and allocation of technological knowledge cannot be completely governed by competitive market forces. Once technological knowledge has been created, the marginal cost of supplying it to an additional user is almost zero. It follows that a competitive market, in which private gains stem from marginal cost pricing, does not provide the economic incentives for the creation of knowledge, because the innovator will typically fail to appropriate most of the returns generated by the new knowledge. Some departure from the competitive model is therefore needed to explain why firms embark on knowledge creation;
- partially *nonexcludable*, meaning that the creators of technological knowledge often have difficulties in preventing others from using it. This attribute of knowledge distinguishes it, to stay with the above example, from a piece of capital equipment, which is readily excludable. The degree of 'excludability' depends both on the nature of the knowledge itself – encoded TV satellite transmissions are highly excludable, while computer software is less excludable – and on the economic institutions governing property rights, and is therefore partly a function of policy choices.

There is a variety of forces that govern the accumulation of technological knowledge, including (Romer, 1996):

- *Public funding of basic research*. Society may deem it worthwhile to incur costs for funding of basic research when no private firm would undertake it. Obvious examples are research on public health and the environment. Since the results of this research are given away for free and their cost is not re•ected in the price that private firms using the results charge for their goods, this mode of knowledge accumulation has a positive externality. The basic scientific knowledge that it creates very often provides the technology paradigm for subsequent innovation by private firms.

- *Industrial R&D*. Industrial R&D can be a channel to accumulate knowledge for private gains. The provision is that the creators of knowledge are able to appropriate (for instance, through patents, trade secrets, lead-time effect, and so on) at least some of the benefits from their inventive efforts. The part of knowledge that is not appropriated and that cannot be prevented from entering the public domain represents the technological spillover associated with private R&D. The accepted view is that knowledge spillovers, because of their generic nature, are extremely difficult to prevent (Arrow, 1962a). They will add to a pool of public knowledge serving as an input to future research. The accumulation of public knowledge will thus lower the cost of future generations to achieve some technological breakthrough. Such cost reduction suggests a mechanism whereby private investment incentives can be preserved despite the tendency for the private returns from innovation to fall as result of increases in the number of competing technologies. Knowledge spillovers can thus be a source of long-term economic growth (Grossman and Helpman, 1997).
- *Learning-by-doing*. Technology can advance as a consequence of the production and use of technology (Arrow, 1962b). Technological progress is then 'free' in the sense that it does not require investment in R&D. Firms learn better ways to produce as an accidental by-product of the production process. For instance, the more photovoltaic cells a firm produces, the better it becomes at it. This type of knowledge accumulation is referred to as learning-by-doing.

Common to the last two types of knowledge accumulation is that they regard, in one way or another, profit-optimizing decisions by firms as the major source driving technological advance.[2] The difficulty profit-optimizing firms have in appropriating rents from knowledge they create leads to inefficient, monopolistic behavior and probably to an underinvestment in innovation. On the other hand, competition for patents can also generate an excessive amount of R&D, if firms do not take into account that their own research activities reduce the likelihood for others to win patents (Wright, 1983).

These remarks show that in the presence of induced technological change environmental policy faces a twofold challenge. It needs to address the market failure resulting from environmental externalities, and it has to respond to the public-good character of environmentally focused innovations.

3. COST-FUNCTION ANALYSIS

Lots of mileage for analyzing questions about the effect of environmental policy on induced technological change can be gained by concentrating exclusively on abatement costs. Such an approach was used by Goulder and Mathai (2000), who analyzed not only the optimal timing of CO_2 abatement but also the optimal time path of an emission tax under both a cost-effectiveness and a benefit–cost criterion. In addition, they considered different specifications for the accumulation of knowledge, namely investment in R&D and learning-by-doing.[3] We start our review by focusing on a situation in which R&D investment drives technology change, and the policymaker adopts a cost-effectiveness criterion.

Let C denote abatement costs, I_t the investment in knowledge, q the real price of investment, H_t the stock of 'knowledge' (or 'technology') and θ the social discount rate. Then the mathematical problem for a social planner willing to implement a cost-effective environmental policy is to choose time paths A_t for abatement and I_t for investment that minimize the discounted sum of abatement costs and R&D expenditure into the infinite future, that is,

$$\min_{A_t, I_t} \int_0^\infty (C(A_t, H_t) + q(I_t)I_t)e^{-\theta t}\, dt, \tag{2.1}$$

provided that atmospheric CO_2 concentrations S_t meet a target concentration $\bar{S}$ at time T and remain after that always below the target ($S_t \leq \bar{S}$, $\forall t \geq T$).

Goulder and Mathai take abatement costs C to depend both on the amount of abatement A_t and the knowledge stock H_t. It appears natural to assume $C_A(\cdot) > 0$, $C_{AA}(\cdot) > 0$, $C_H(\cdot) < 0$, and $C_{AH}(\cdot) < 0$, expressing the idea that abatement cost and marginal abatement cost will increase with abatement, and that knowledge H_t decreases both cost and marginal cost of abatement.[4]

To keep the model analytically tractable Goulder and Mathai assume that abatement affects atmospheric CO_2 concentration by the simple relation

$$\dot{S}_t = -\delta\, S + E_t^0 - A_t, \tag{2.2}$$

where δ is the natural rate of removal of atmospheric CO_2, and E_t^0 denotes baseline CO_2 emissions. Equation (2.2) states that changes in the atmospheric

CO_2 concentration, $\dot{S}_t$, are equal to current net emissions $E_t^0 – A_t$ diminished by the amount of CO_2 that is removed naturally from the atmosphere.

In light of the discussion above, knowledge accumulation can be accomplished through various channels. Goulder and Mathai assume that technological change accumulates both exogenously and endogenously, and in the latter case via investment in abatement technology, that is,

$$\dot{H}_t = \alpha_t H_t + k\, \Psi(I_t, H_t), \tag{2.3}$$

where α_t denotes the rate of exogenous technological change and k is a constant parameter ($k > 0$) that indicates the presence of induced technological change. The knowledge accumulation function Ψ is endowed with the properties $\Psi > 0$, $\Psi I > 0$, and $\Psi II < 0$ to capture the idea that knowledge increases with investment but at a decreasing rate.

Requirement (2.1) represents a dynamic optimization problem for the control variables A_t and I_t; S_t and H_t, whose time evolution is described by (2.2) and (2.3), play the role of state variables. The problem can be solved by employing the maximum principle (for example Chiang, 1992) using as the current-value Hamiltonian

$$\mathscr{H}_t = -(C(A_t, H_t) + q(I_t)I_t + p_t(-\delta\, S_t + E_t^0 - A_t) + \mu_t(\alpha H_t + k\Psi(I_t, H_t)), \tag{2.4}$$

for times $t < T$, and the Lagrangian

$$\mathscr{L}_t = \mathscr{H}_t + \eta_t(\bar{S} - S_t), \tag{2.5}$$

for $t \geq T$. The symbols p_t and μ_t denote co-state variables, and η_t is a Lagrange parameter. Restricting attention to $t < T$, the equations most interesting for the present discussion are the ones that are implied by the requirements $\partial H_t/\partial A_t = 0$ and $\dot{p}_t = p_t\, \delta + \theta p_t$ of the maximum principle, namely

$$C_A(\cdot) = -p_t, \tag{2.6}$$

$$\dot{p}_t = (\theta + \delta)pt, \tag{2.7}$$

where $-p_t$ can be interpreted as the shadow cost of CO_2 emissions, which in a decentralized, competitive industry equals the optimal CO_2 tax. With this interpretation, equation (2.6) states that at all times the optimal level of abatement is achieved, when marginal abatement cost equals CO_2 tax. The co-state equation (2.7) implies that the optimal CO_2 tax increases over time exponentially with rate ($\theta + \delta$). Note that the effective discount rate is larger than θ to account for the natural removal of CO_2 along the optimized abatement path.

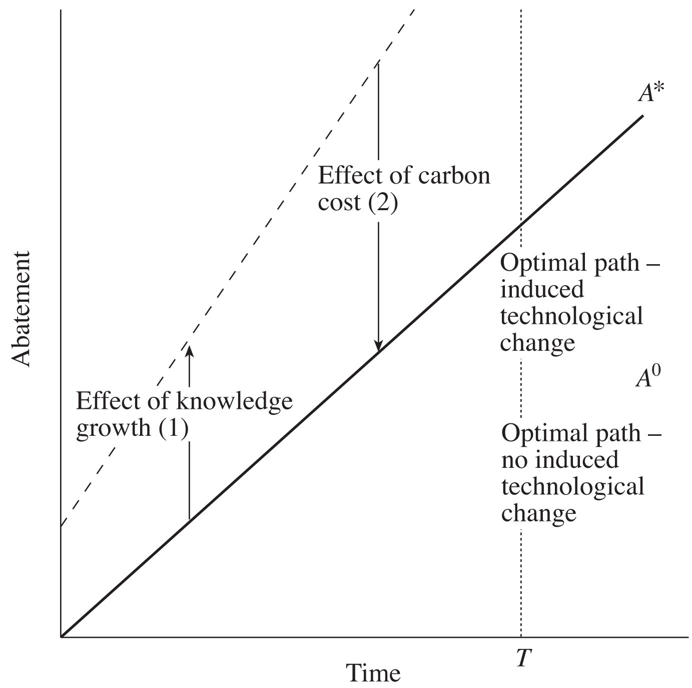
The parameter k in equation (2.3) provides the means to analyze the consequences of induced technological change for the scenario considered here. Obviously, the larger k, the larger the increase in knowledge stock that results from investment I_t at fixed knowledge stock H_t. To quantify its impact on the optimal abatement profile Goulder and Mathai differentiate equation (2.6) with respect to k totally[5] to obtain after rearrangement

$$\frac{d\,A_t}{d\,k} = \frac{\dfrac{d(-p_t)}{dk} - C_{AH}(\cdot)\,\dfrac{dH_t}{dk}}{C_{AA}(\cdot)}. \tag{2.8}$$

If one neglects for the moment the effect of technological change on the optimal carbon tax itself, that is, assumes that $d(-p_t)/d\,k = 0$, then equation (2.8) shows that technological change stimulates abatement, $dA_t/d\,k > 0$, provided that $-C_{AH} > 0$ as assumed earlier. Goulder and Mathai refer to this as the 'knowledge growth effect'. Figure 2.1 depicts the situation schematically.

Assuming for simplicity a linear abatement schedule, A^0, induced technological change leads to pivoting of the abatement curve upward. The new path coincides with the original optimal path at time $t = 0$ at which the technology stock has the same value in both scenarios. Clearly, the new path cannot be optimal as too much abatement is undertaken, and consequently atmospheric CO_2 concentration at time T is less than the target concentration $\bar{S}$. It is the effect of k on the shadow price p_t, which we have neglected so far, that corrects the situation. To prevent an overshooting of the total amount of abatement one would expect the sign of $d(-p_t)/dk$, the first term in the numerator of equation (2.8), to be opposite of the second term, and the more detailed mathematical analysis of Goulder and Mathai does indeed confirm that the presence of induced technological change lowers carbon taxes.[6] The intuition is that it is easier to achieve CO_2 emission reductions with advance technology than without it. This will lower the shadow cost of CO_2 emissions and, hence, the tax. As indicated in Figure 2.1, the additional effect of k on p_t yields an optimal abatement path, A^*, along which abatement levels are initially below those realized without technological change but the increase is steeper with time. Put succinctly, the prospect of technological change justifies delaying abatement until it is less costly.

Next Goulder and Mathai consider the situation that the stock of abatement knowledge H does not grow by investment in abatement technology, but is rather accumulated via learning-by-doing. The optimization problem is then



Source: Goulder and Mathai, 2000. The 'knowledge growth' effect leads to pivoting of the abatement path upward (1). This is counteracted by the effect of technology on the shadow price of CO_2 (2).

Figure 2.1 Effects of knowledge growth and shadow cost on optimum abatement schedule

$$\min_{A_t} \int_0^{\infty} C(A_t, H_t)\, e^{-\theta t}\, dt, \tag{2.9}$$

where now

$$\dot{H}_t = \alpha_t H_t + k\Psi(A_t, H_t), \tag{2.10}$$

and all other conditions remain unchanged. The problem (2.9) can again be solved with the usual mathematical tools, and we shall discuss here only the most pertinent results. First, as the co-state equation (2.7) remains unchanged, the optimal carbon tax grows, as before, at rate $(\theta + \delta)$ for $t \leq T$. However, instead of equation (2.6) we now have

$$C_A(\cdot) - \mu_t\, k\Psi_A(\cdot) = -p_t, \tag{2.11}$$

indicating that the marginal social cost of abatement is no longer C_A but rather $C_A - \mu_t\, k\Psi_A$ because of the cost reduction associated with the learning-by-doing stemming from that abatement.

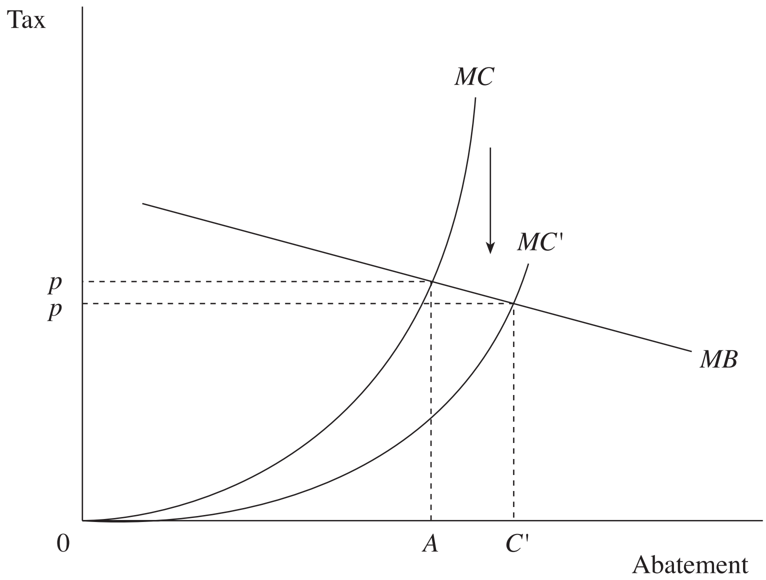
The impact of induced technological change is described by

$$\frac{d\,A_t}{d\,k} = \frac{\dfrac{d(-p_t)}{dk} + \mu_t \Psi_A(\cdot) - C_{AH}(\cdot)\,\dfrac{dH_t}{dk}}{C_{AA}(\cdot)}, \tag{2.12}$$

which is obtained by differentiating (2.11) totally with respect to k. On the righthand side of this equation $\mu t \Psi_A > 0$ represents a positive learning-by-doing effect. This effect strengthens the knowledge growth effect $-C_{AH}(dH_t/dk) > 0$ on abatement but is opposed to the shadow price effect for which $d(-p_t)/dk \leq 0$. Thus the net effect of all three contributions is ambiguous, and it is certainly not clear that learning-by-doing always justifies lower *initial* abatement as was the case for R&D-induced technological change. The intuition is here that future abatement costs determine how much abatement should be moved to the future. However, as future abatement costs are determined by the near-term abatement effort and are the lower the more abatement is undertaken near term, it is clear that no general statement concerning the level of initial abatement can be made.

In their benefit–cost models, Goulder and Mathai obtained similar results. Here, the objective of the social planner is to minimize both the costs of achieving the desired abatement target and the damages resulting from CO_2 emissions over an infinite time horizon.[7] As before, the impact of induced technological change on abatement is given by (2.8), and (2.12) respectively. Again, we are confronted with a positive knowledge-growth effect and a negative shadow-cost effect: as long as induced technological change reduces marginal abatement costs, abatement tends to rise. This is counteracted by the negative effect on the shadow costs of today's emissions, which justifies postponing some abatement until marginal abatement becomes cheaper. Thus, under the benefit–cost criterion the presence of technological change induced by R&D implies that optimal abatement levels fall in early years, but rise later. When knowledge is accumulated via learning-by-doing, the overall effect of induced technological change on optimal abatement is again analytically ambiguous.

The total amount of optimal abatement is *higher* in both settings than it would be without induced innovation. Since new technologies reduce the marginal abatement costs over time, a higher amount of abatement becomes



Note: Innovation leads to a shift of the marginal abatement cost curve from *MC* to *MC´*. As a consequence the total abatement level increases from *A* to *A´* while the optimal tax rate decreases from *p* to *p´*, if marginal benefits *MB* decrease with abatement.

Source: Goulder and Mathai, 2000.

Figure 2.2 Optimal carbon tax in the static benefit–cost case

optimal. Perhaps somewhat contrary to intuition, this increase in cumulative abatement is accompanied by a lower tax rate, provided the marginal benefits (*MB*) decrease with abatement level, as will typically be the case. In this situation, depicted in Figure 2.2, technological progress shifts the marginal abatement cost curve downwards (*MC´*), which increases the optimal amount of abatement (*A´*) and reduces the optimal environmental tax rate (*p´*). If, on the other hand, the marginal benefit curve slopes upward, as would be the case if damages were concave in the CO_2 concentration, induced technological change will increase the optimal tax rate, and cumulative abatement will be lower than without induced innovation.

The analytical results obtained by Goulder and Mathai are summarized in Table 2.1. A key finding is that under typical conditions the presence of induced technological change implies a lowering of the optimal tax path. A lower tax is all that is needed to achieve the abatement goal, even when the desired total extent of abatement is higher, as is the case when the government

Table 2.1 Summary of results of the Goulder and Mathai (2000) model

Channel	Optimal solutions		Induced technological change	
	Tax path	Abatement path	Tax path	Abatement path
Cost-effectiveness criterion:				
R&D	exp. growth	slopes upward	falls	A_0 falls; path is steeper
LBD	exp. growth	ambiguous	falls	ambiguous
Cost–benefit criterion:				
R&D	slopes upward*	slopes upward*	falls	A_0 falls; path is steeper
LBD	slopes upward*	ambiguous	falls	ambiguous

Note: The first column refers to the optimal tax and abatement paths in the presence of induced technological change. The second column summarizes the effects of induced innovation on the slope of the optimal paths.
*Provided that damages are convex and optimized CO_2 concentration rises over time.

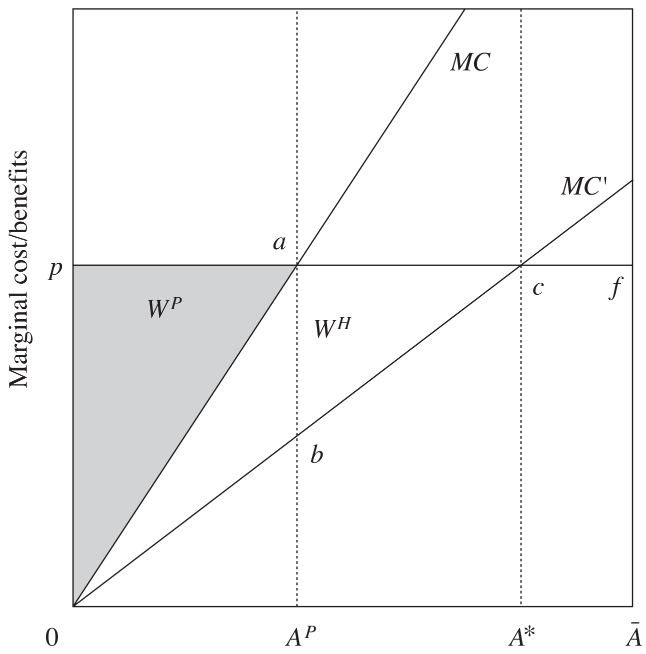
employs a benefit–cost policy. Another key finding relates to the optimal timing of abatement. If abatement knowledge is generated through R&D, induced technological change makes it optimal to shift some abatement efforts from the present to the future. In contrast, no general statement pertains to the timing of abatement when learning-by-doing is the channel for knowledge accumulation.

4. WELFARE ASPECTS

This section discusses the welfare gains resulting from environmental policy. Specifically, we will have a closer look at the claim that the welfare benefits from induced technological innovation outweigh the Pigouvian welfare gains resulting from correcting social excessive pollution from firms (Orr, 1976; Parry, 1998). This would seem to imply that the focus of environmental policy should be on environmental technology innovation rather than on pollution control. In addition, we will explore how the different instruments of environmental policy are suited to achieve soical optimal emissions levels when the effect of induced technological change is accounted for.

4.1 Welfare Benefits from Environmental Regulation and Innovation

Parry et al. (2002) compared the welfare gains associated with a Pigouvian tax with the welfare benefits from induced technological change, using a dynamic social planning model in which investments in R&D enhance the stock of knowledge, thereby reducing future abatement costs. Their analytical and



Note: Area W^P represents the Pigouvian welfare gain from abatement. Innovation causes the marginal abatement cost curve *MC* to rotate downwards (*MC´*), yielding welfare gain W^H.

Source: Parry et al. (2002).

Figure 2.3 Welfare gains resulting from abatement cost reduction due to technological innovation

numerical results indicate that the welfare gains from induced technological innovation are typically smaller than the welfare gains resulting from pollution control. Only in special cases will the welfare gains from innovation exceed those from the Pigouvian tax.

Some of the insights obtained by Parry et al. can be explained with the help of Figure 2.3, which plots for one time period the marginal abatement cost curves before and after an increase in the 'abatement knowledge stock'. To keep the discussion parsimonious it is assumed that marginal benefits from avoiding pollution are constant. The optimal abatement level is the point where marginal abatement costs, *MC*, equal marginal benefits of pollution control, p. In the absence of technological innovation this level is reached at A^P in Figure 2.3. The corresponding total abatement costs are given by the area of the triangle $0aA^P$, while the total benefits corresponding to this level of abatement are given by the rectangle $0paA^P$. The difference between these two areas, triangle $0pa$, is the welfare benefit W^P of the Pigouvian tax in one period. Since the stock of knowledge is constant along the optimal abatement path, the present value $\hat{W}^P$ of the Pigouvian welfare gain over the entire time horizon, defined as the discounted sum of the net benefits in each period, is

$$\hat{W}^P = \sum_{t=1}^{\infty} \frac{W^P}{(1+\theta)^t} = \frac{W^P}{\theta}, \tag{2.13}$$

where θ denotes the social discount rate.

The welfare gain from innovation W^H is represented by triangle $0ac$ in Figure 2.3, and consists of the reduction in marginal abatement costs (area $0ab$) and the additional benefits from higher abatement (area acb). If one assumes that R&D investments leading to innovation are undertaken only in period 0, the present value $\hat{W}^H$ of all future benefits from innovation is

$$\hat{W}^H = \sum_{t=1}^{\infty} \frac{W^H}{(1+\theta)^t} = \frac{W^H}{\theta}, \tag{2.14}$$

Parry et al. compared the discounted welfare gain from innovation, $\hat{W}^H$, with the discounted Pigouvian welfare gain, $\hat{W}^P$, using the ratio $\hat{W}^H/\hat{W}^P$. To get a first feeling for the magnitude of this ratio we notice that for the welfare gain from innovation to be large relative to the Pigouvian welfare gain, $\hat{W}^H/\hat{W}^P$ must be greater than unity. Since in our simplified analysis $\hat{W}^H/\hat{W}^P$ is equal to W^H/W^P, we can easily establish a bound on the magnitude of $\hat{W}^H/\hat{W}^P$ by using Figure 2.3: assume that R&D in period 0 reduces (marginal) abatement costs in period 1 by a factor β with $0 \le \beta < 1$. Then $MC' = (1-\beta)MC$, and[8]

$$\frac{\hat{W}^H}{\hat{W}^P} = \frac{W^H}{W^P} = \frac{\beta}{(1-\beta)}. \tag{2.15}$$

According to this equation, even an abatement cost reduction of as much as 50 per cent ($\beta = ½$) would still yield an innovative welfare gain that is smaller than its Pigouvian counterpart, that is, $\hat{W}^H < \hat{W}^P$. We see already in this highly simplified analysis that the net benefits from induced technological change are limited by the maximally feasible reduction in abatement costs. In most situations, they are likely to be smaller than the Pigouvian welfare gains.

However, it is possible for $\hat{W}^H$ to exceed $\hat{W}^P$: consider the arrival of a new, 'disruptive' technology that completely and instantaneously eliminates all abatement costs. Then, the marginal abatement cost curve MC' in Figure 2.3 coincides with the horizontal axis and the ratio $\hat{W}^H/\hat{W}^P$ corresponds geometrically to the area of the trapezoid $0af\bar{A}$ divided by the area of the triangle $0pa$. In this case, Parry et al. calculated an upper bound on the ratio $\hat{W}^H/\hat{W}^P$ of respectively 19, 4, 2.3 and 1, when the initial Pigouvian abatement level is 10 per cent, 40 per cent, 60 per cent, and 100 per cent. Thus, only when innovation substantially reduces abatement costs and the Pigouvian abatement level is fairly modest can the welfare gain from induced innovation be significantly greater than the Pigouvian welfare gain. The intuition here is that for a pollution problem that is already severe enough to warrant a high level of abatement without R&D, additional welfare gains from innovation will be relatively small. Conversely, if abatement is initially too costly to justify major emission reductions, the gain from innovation could be more substantial.

A more thorough discussion has to take into account that it needs time, perhaps decades, to accumulate the knowledge required to substantially reduce abatement costs. During this intermediate time the marginal abatement cost curve in Figure 2.3 will only gradually rotate downward, so that the benefits from innovation will be smaller than the benefit that is realized when knowledge accumulation is instantaneously complete. In addition, the direct costs of R&D that were neglected in the argumentation so far need to be taken off the discounted stream of benefits to obtain the true discounted welfare gains from innovation.

As far as the timing of these R&D expenditures is involved, Parry et al. note that a balance must be struck between the gain of immediate increases in the knowledge stock and the cost-saving from gradual adjustment. This is of course the same type of dynamic optimization problem that we encountered earlier and discussed in the context of the benefit–cost policy criterion of Goulder and Mathai (2000). Parry et al. choose to tackle the problem by means of a numerical simulation. They explore different scenarios for the time it takes for knowledge accumulation to produce a 50 per cent reduction in abatement cost.

Table 2.2 summarizes the results of the base case simulations by Parry et al. that were carried out for a discount rate of 5 per cent. For different values for the initial Pigouvian abatement level in the first column, the table specifies in the three subsequent columns the $\hat{W}^H/\hat{W}^P$ ratios corresponding to these initial levels depending on the various time periods in which abatement costs reduction of 50 per cent are achieved.

In line with the earlier observation, the simulation shows that the ratio $\hat{W}^H/\hat{W}^P$ decreases when the Pigouvian abatement level rises. The aspect that is new concerns the impact on welfare gain of the time period over which abatement costs are reduced. It is seen from the table that the longer it takes to

Table 2.2 Ratio of welfare gains from innovation to welfare gains from pollution control, WH/WP.

Pigouvian abatement level (%)	Time lag until abatement costs halve 10 years	20 years	40 years
10	2.98	0.88	0.16
40	1.07	0.46	0.16
60	0.79	0.41	0.17

reduce these costs, the smaller is the welfare gain from innovation. Thus, according to the table, $\hat{W}^H$ and $\hat{W}^P$ are almost the same when the Pigouvian abatement level is 40 per cent and abatement cost are reduced by 50 per cent in ten years. But if it takes 20 years or more to achieve this cost reduction (because it is more expensive to develop new technologies), then $\hat{W}^H$ is significantly smaller than $\hat{W}^P$. The key message here is that the conditions for $\hat{W}^H$ to be large relative to $\hat{W}^P$ are very stringent: the initial abatement level must be fairly modest *and* innovation must have the potential to reduce abatement costs rapidly.

Parry et al. show that this result is robust against different assumptions for research cost function and choice of planning horizon. The effect of an increase in the discount rate is to lower $\hat{W}^H/\hat{W}^P$ as then the benefits from innovation are more heavily discounted.

A practical demonstration for the application of the results in Table 2.2 is furnished by the Kyoto treaty on climate change. The treaty commits the European Union to cut emissions of CO_2 and other greenhouse gases 8 per cent below the 1990 baseline level during 2008–12. Assuming for the sake of the argument that the target of the envisioned emission reduction is set optimally, then one would expect in this example that $\hat{W}^H$ will be significantly smaller than $\hat{W}^P$. This is because of the difficulty of achieving cost reductions of 50 per cent or more within a decade or so, without significant deployment of abatement technology. In an analogous case, the cost of technologies to reduce sulpher emissions from power plants decreased by 20 per cent over the last decade (Boward and Brinkman, 1998).

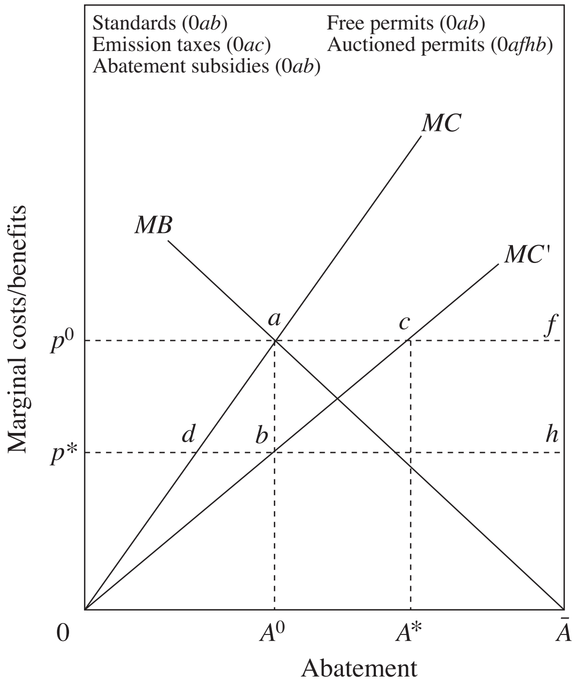
The results of Parry et al. appear to imply that pollution control – rather than technological innovation – should be the dominant factor in the design of environmental policies. However, it is important to realize that this conclusion is based on the analysis of policy-induced welfare gains in only a single market, namely the market for novel abatement technology. In a following section, we shall examine whether Parry et al.'s policy recommendation keeps its validity if one allows for market interactions and, in particular, accounts for inter-market technology spillovers. To set the context for this discussion, we next take a look at the various instruments available to a policymaker to address environmental externalities and technology spillovers.

4.2 The Role of the Policy Instrument

The discussion so far has focused only on a single instrument of environmental policy, namely taxes. As policymakers have more options to achieve environmental objectives, we consider briefly in this section the incentives of alternative policy instruments for inducing technological change. A more comprehensive review of this topic can be found in Jaffe et al. (2002) and Kemp (1997); a short discussion in the context of climate change policy is given by Fischer (2000).

Environmental policy instruments are usually grouped into market-based instruments, such as taxes, subsidies and tradable permits, and the so-called 'commandand-control' instruments, which include emission standards and other forms of direct regulation. While the former type is the favorite of economists because of its cost effectiveness for achieving emission reductions, both types of control are likely to spur some technological progress. Thus a discussion of the consequences of the various policy instruments for inducing technological change has to start with the motives of firms to invest in novel abatement technologies. These include cost-savings that the new technology promises, reduction in emission tax payments, the prospects of gains from patent royalties, subsidy payments, or perhaps public relation motives, that is, the wish to be seen as 'green'. Early papers have concentrated on elucidating how in a competitive setting the different policy instruments affect a firm's decision to invest in abatement technology on the premise that a firm wants to reduce its marginal abatement costs (Downing and White, 1986; Magat, 1978, 1979; Zerbe, 1970). This is also the starting point for the analysis by Milliman and Prince, who studied the issue first for the case of a single representative firm (1989), and later extended their analysis to firms with heterogeneous abatement cost (1992).

In their 1989 study Milliman and Prince used essentially a graphical argument of the kind depicted in Figure 2.4. Shown on the axes of the graph are the levels of abatement, and the marginal costs and benefits associated with it. These quantities are assumed to vary linearly with the degree of abatement. Technological progress is pictured as a rotation of the marginal cost curve in the direction of decreasing costs. The incentives the different policy instruments give to a firm to use novel abatement technology result from the cost-savings they imply. In the graphical representation these incentives correspond to certain areas, which are indicated in Figure 2.4. By comparing the size of these areas Milliman and Prince established in their 1989 paper the following



Note: A firm facing an emission tax of p^0 realizes savings corresponding to area *Oac* if it adopts novel technology that lowers its marginal abatement cost curve from *MC* to *MC´*; with the novel technology the firm will abate to level *A´* instead of A^0, provided that the policymaker does not adjust the level of control. The source of the savings is the reduction in abatement costs (area *Oab*) plus the net reduction in tax payments (area *acb*). The savings given by the other policy instruments are as indicated in the figure.

Source: Milliman and Prince (1989).

Figure 2.4 Firm level incentives to adopt under pollution control

ranking for the potential of different policy instruments to promote the adoption of novel emission-reducing technology: (i) auctioned permits; (ii) emission taxes and subsidies; and (iii) standards and free permits. Later work by Milliman and Prince (1992) and Jung et al. (1996) extended the analysis to the situation of heterogenous firms, but did not yield results that change this ranking order.

Some authors have investigated if and how the ranking would change if some of the rather ideal assumptions underlying the work by Milliman and Prince were relaxed. A rather obvious shortcoming of the model is that it regards the permit price as exogenous and as independent of the adoption decisions of the firms. Since the adoption of novel abatement technology lowers the permit price, it reduces the anticipated cost-savings of firms over time, and thus their incentive to adopt the new technology.[9] The issue was analyzed in papers by Keohane (1999) and Requate and Unold (2003), who concluded that taxes provide higher incentives for adoption than tradable permits, and that auctioned and freely allocated permits have equal incentives if permit price is endogenous.

Another extension of Milliman and Prince's work has been undertaken by Fischer et al. (2003), who considered the incentives of firms to develop and to adopt environmentally friendly innovations when other firms can imitate. These authors could not establish a unique ranking of the policy instruments. For example, with full imitation, auctioned permits tend to be superior to emission taxes, because innovators can effectively appropriate the gains from the fall in permit price. However, when barriers to imitation are high, emission taxes are the preferred policy instrument for inducing environmentally friendly technologies, because the rents from innovation under a tax outweigh innovators' profits under a permit scheme.

This evaluation changes when the policymaker has only limited information on the aggregate abatement cost function. Focusing on the special situation that environmental marginal damages do not vary substantially with emission levels, Biglaiser et al. (1995) argue that, for the purpose of inducing technical change, taxes are superior to tradable permits. The reason is that, unlike taxes, a permit scheme would allow firms to strategically delay their plans to invest in novel clean technology in order to oppose more stringent future emission targets.[10]

The theoretical studies reviewed above indicate that market-based instruments generally provide greater incentives for firms to invest in environmentally friendly technologies than direct regulations. The magnitude of these incentives depends on the model context and assumptions, meaning that no general ranking of the policy instruments on their 'innovation-promoting' potential is possible. Moreover, all of the results on the effects of the policy instruments obtained so far neglect innovation by firms in non-polluting markets and the associated economy-wide consequences. Moving beyond this limitation requires a general equilibrium approach, which is the subject of the following sections.

5. THE GROWTH THEORY PERSPECTIVE

In this section we discuss some macroeconomic aspects of the interaction of environmenta policy with technological change using the vehicle of endogenous growth theory. Models of endogenous growth differ from the 'standard' neoclassical Solow theory in that they do not rely on exogenous technological advance falling like 'manna from heaven' to explain growth. Instead, dedicated profit-seeking investment in knowledge by firms is seen as the cause for long-run growth. Since knowledge is difficult to appropriate by firms, it spills over, thus creating positive externalities. Both R&D investment *per se* and knowledge spillover appear as the combined source for endogenous growth in these types of model. They endow the macro-scale production function with the properties that are sufficient to guarantee steady-state growth (Romer, 1990; Arrow 1962b).

In-depth reviews of the burgeoning literature on endogenous growth can be found in work by Barro and Sala-i-Martin (1995) and Aghion and Howitt (1999). The inclusion of environmental aspects into the framework of endogenous growth models is usually accomplished through the assumption that society 'cares' about the environment, which is then formalized by including some measure of environmental quality as a variable in the utility function that a social planner optimizes. In fact, all the environmental growth models discussed in the monograph by Aghion and Howitt (1999, ch. 5) follow this construction. However, this approach falls short of capturing the productivity effects associated with environmental quality. These arise, for instance, because a cleaner environment improves the health of workers, thereby boosting labor productivity, or because enhanced biodiversity provides a larger pool of genetic information, thereby spurring productivity in R&D. A set of rather general growth models that also include these types of ecologic–economic interactions was constructed in a series of papers by Bovenberg and Smulders (1995, 1996) and Smulders (1998) that are the subject of this section.

The simplest type of these models (Smulders, 1995) lumps together physical and knowledge capital and so maintains the one-sector production structure of the Solow-type neoclassical growth models. It offers insight, in particular, into the consequences of optimal environmental policy on long-run economic growth, but suffers from the underdeveloped representation of the process of knowledge accumulation, which is simply modeled as a by-product of production. Despite this shortcoming, we include the model in this review as it provides both a conceptual and formal stepping stone for the construction of more complex and more satisfying growth models. Of interest here is the model extension by Smulders (1998), which provides both for endogenous and exogenous knowledge accumulation and is capable of illuminating the interaction between the optimal setting of policy targets and technological change.

5.1 A One-sector Endogenous Model

Models of endogenous growth and the environment have to account for a variety of interactions between economic activities, technology and the environment. To lay bare the various interdependencies and to avoid getting confused by details we will first give an overview of the structure of these types of models (Smulders, 1999). After this preparation, we proceed to study specific model realizations in more detail.

5.1.1 Prototypical model structure

As before, we assume the existence of a social planner whose objective is to optimize social welfare over an infinite planning horizon. This requires that one specifies a social utility function U, and the factors on which it depends. Taking aggregate consumption X and environmental quality, as measured by an indicator N, as the relevant variables ($U_X > 0$, $U_N \geq 0$), and assuming furthermore that the social planner discounts the utility of future generations by θ, the relevant welfare function reads

$$W = \int_0^\infty U(X,N)e^{-\theta t}dt. \tag{2.16}$$

For the sake of convenience we disregard population growth and normalize population size to 1, so that there is no distinction between per capita quantities and their aggregate counterparts.

Focusing next on modeling the ecosystem, we denote the productive services from the environment by R, and stipulate that the change in environmental quality resulting from production can be described by

$$\dot{N} = Q(N) - R, \tag{2.17}$$

where the function $Q(N)$ describes the regenerative potential of the ecosystem. It is useful, but not necessary, to think of the function $Q(N)$ as having the humpshaped appearance familiar from the theory of renewable resources (Clark, 1990). Of special interest in the following is the case for which $\dot{N} = 0$, and so $R = Q(N)$. It pertains to a situation in which environmental services are used exactly to the degree with which they are regenerated, and which with some justification could be labeled 'sustainable'.

Production Y is allocated to consumption X, and to investment in both manmade and human capital that we collectively denote by M. Thus,

$$\dot{M} = Y(N,R,M) - X, \tag{2.18}$$

where $Y_N > 0$, $Y_R > 0$, $Y_M > 0$, and all inputs are necessary. The crucial aspect here is that production Y depends, in addition to capital M, on environmental quality, N, and services R.

Equations (2.16)–(2.18) form the basis of many environmental growth models (Verdier, 1993; Gradus and Smulders, 1993; Bovenberg and de Mooij, 1997). Here we follow Smulders (1995) in developing this prototypical model into a form that allows one to draw definite conclusions.

5.1.2 Optimal long-run growth

Smulders (1995) splits man-made capital M into two components, namely physical capital K and knowledge H,

$$M = K + H, \tag{2.19}$$

so that the production function Y can now be written as

$$Y = Y(K,H,N,R). \tag{2.20}$$

It is assumed that $Y(\cdot)$ exhibits the standard neoclassical properties, including constant returns to scale in K and H.

With a view to ensuring the existence of steady-state growth, Smulders follows the common practice (for example Barro and Sala-i-Martin, 1999, p. 64) and employs a utility function

$$U(X,N) = \frac{(XN^{\phi})^{1-1/\sigma}}{1 - 1/\sigma}, \tag{2.21}$$

for which the elasticity of intertemporal substitution σ,

$$\sigma = -\frac{U'(X)}{X\,U''(X)}, \tag{2.22}$$

and the share of environmental amenities in utility ϕ,

$$\phi = \frac{U_N N}{U_X X}, \tag{2.23}$$

are constant. As will be seen later, the parameter ϕ can be also interpreted as the social preference for environmental amenities.

A social planner opting to conduct optimal policy will aim to maximize utility over an infinite time horizon with respect to X, R, K and H, subject to the ecological constraint (2.17) and the goods market constraint

$$Y = X + \dot{K} + \dot{H} \tag{2.24}$$

that is implied by (2.18) and (2.19). The corresponding optimality conditions read:

$$Y_H = Y_K \tag{2.25}$$

$$\sigma[r - \theta + (\frac{U_{XN}N}{U_X}) \frac{\dot{N}}{N}] = \frac{\dot{X}}{X} \tag{2.26}$$

$$\frac{U_N/U_X + Y_N}{Y_R} + Q_N + \frac{\dot{Y}_R}{Y_R} = r, \tag{2.27}$$

where in the last two equations we denoted the return to capital by r, that is,

$$YK \equiv r. \tag{2.28}$$

The first condition, equation (2.25), is a requirement for the statically optimal allocation of physical and knowledge capital and states that both types of capital must yield the same returns in an optimum. As mentioned earlier, there are strong reasons to believe that this condition cannot be satisfied in a perfectly competitive market without help of governmental intervention. The difficulties of firms in appropriating the knowledge they generate through environmental R&D translate into a lack of incentives to accumulate knowledge capital to the socially optimal extent, so that satisfaction of (2.25) is likely to require policy intervention.

We will not pursue this issue further but rather focus on the two dynamic optimality conditions (2.26) and (2.27). We first note that if $\dot{X}/X > 0$, then consumption is low today relative to tomorrow (that is, consumption grows). Equation (2.26) then says that households are more willing to postpone consumption the more they benefit from it, that is, the more the interest rate r exceeds their pure time preference θ, and the more they value future improvements in environmental amenities, as expressed by the term involving U_{XN}. Through the presence of this term equation (2.26) furnishes a generalization of the standard Ramsey equation (for example, Barro and Sala-i-Martin, 1995, p. 63).

Equation (2.27) is a generalization of the Hotelling rule, and guarantees that in an optimum the exploitation of the environment yields a return r^N, given by its left-hand side,

$$r_N = \frac{U_N/U_X + Y_N}{Y_R} + Q_N + \frac{\dot{Y}_R}{Y_R}, \tag{2.29}$$

which equals the return r on alternatives capital goods, that is,

$$r_N = r. \tag{2.30}$$

If the environment were a non-renewable resource without amenity value and with only the capacity to provide services to production by resource depletion, we would recover from the last two equations the usual version of the Hotelling rule. The price of environmental service Y_R should then grow at the rate that equals the rate of interest to compensate for the loss of future revenue from current depletion. The Q_N term in equation (2.29) indicates that the price of a renewable resource has to rise at a rate faster than r as long as Q_N is negative. The reason is that the extracting use of the environment not only depletes the resource but also reduces its future capability of regenerating. This reduces the revenue from the exploitation of the environment, which has to be compensated by an additional price increase.

Next we focus on the implication of equations (2.26) and (2.27) for the characterization of steady-state growth. The model allows this type of growth provided environmental quality is at the sustainable level N^* for which $Q(N^*) = R$ and $\dot{N}^* = 0$. Smulders shows that to N^* corresponds a constant value r, which when used in the Ramsey equation (2.26) ensures a steady-state growth rate $g = \dot{X}/X$ for consumption that is non-zero at the fixed value

$$g = \sigma(r - \theta) > 0, \tag{2.31}$$

and that physical capital, knowledge and production also grow in the long run with g, meaning that the characterization of the steady state is completed through the equations

$$\frac{\dot{Y}}{Y} = \frac{\dot{K}}{K} = \frac{\dot{H}}{H} = \frac{\dot{X}}{X} = g. \tag{2.32}$$

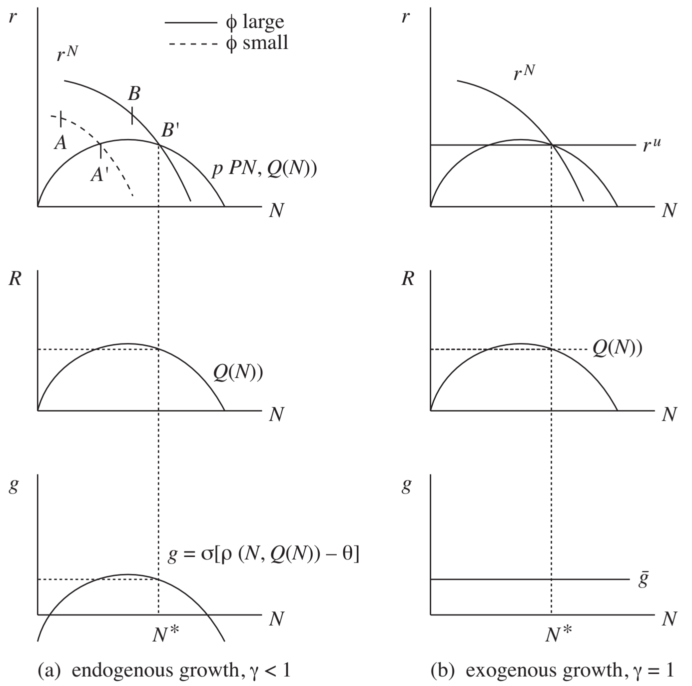
These results show that sustainable growth is feasible provided that there are constant returns in production with respect to knowledge factors.

5.1.3 Policy consequences

Further insight into the long-run prediction of the Smulders model can be gained through a graphical analysis. We first note that from (2.30) and the assumption of constant returns to scale in production the return on capital r depends only on N and R. In the steady state, environmental use R equals the absorption capacity of the environment $Q(N)$, so that r becomes simply a function ρ of N^*,

$$r = \rho(N, Q(N)), \tag{2.33}$$

where we have dropped the asterisks to simplify notation. The upper part of Figure 2.5a depicts the variation of ρ with N in a schematic fashion. Obviously, the rate of return to capital is zero for the value of N at which $Q(N) = 0$, as then the environment does not provide the services R that are essential for production. It increases for low levels of environmental quality N, since



Source: The upper panels depict schematically the variation of r^N with N together with those of ρ (endogenous growth) and r^u (exogenous growth). The optimal state is achieved at the point of intersection of the corresponding curves. The lower panels show the levels of services provided by the environment (R) and the growth rate (g or $\bar{g}$) in the social optimum.

Figure 2.5 Steady-state solution for the endogenous and exogenous growth case (Smulders, 1995, 1998).

production benefits from improved environmental services, but decreases for high values of N as less productive use is made of the environment. The growth rate g, which according to (2.31) differs from ρ only by constant factors, follows the same pattern and is depicted in the lower part of Figure 2.5a.

Next we turn attention to the rate of return to environmental quality r^N, equation (2.29). By examining the dependence on N of the various terms comprising r^N, it can be shown that this rate will tend to fall with improvement in environmental quality, so that $dr^N/dN < 0$, as indicated in the upper part of Figure 2.5a. Changes in the parameter ϕ, which characterizes the social preference for environmental amenities, cause the r^N curve to shift. If a higher amenity value is attached to the environment, investment in the environment will pay a higher return, and the r^N curve moves outward. At the value N^*, at which the r^N and the ρ curves intersect, the rates of return of environmental and man-made capital are equal, and environmental quality is socially optimal according to (2.30).

All the elements are now in place to analyze graphically some of the consequences of environmental policy. We consider first the case that society attaches a large value to environmental amenity, as quantified by the parameter ϕ, and that accordingly the level of environmental quality, as expressed by N, is also large. Nonetheless we assume that it is still suboptimal, so that the return on natural capital exceeds that from physical capital (point B in Figure 2.5a). As a result of governmental policy, which aims at full internalization of all the benefits of the environment, the optimal growth equilibrium at the intersection of the ρ-curve and r^N-curve is realized (point B'). As the corresponding growth rate g (lower part of Figure 2.5a) is smaller than the one in the initial state, optimal policy will in this case hurt long-run growth. Thus there is a tradeoff between economic growth and environmental quality.

This conclusion changes, however, when initial environmental quality is suboptimal at low levels of N and ϕ (point A in Figure 2.5a). Governmental policy correcting this situation will then strive to reach state A'. As the growth rate in the optimum is now larger than the one in the initial state, optimal environmental policy will now stimulate long-run growth.

The model can be used to illuminate the economic consequences of environmental policy for a range of circumstances. Nonetheless, it does not provide much insight into the specific role played by technological change that is induced by environmental policy. The reason for this failure lies ultimately in the constraints implied by the one-sector model structure, which requires knowledge to grow endogenously as a by-product of production, and which cannot capture the process of knowledge accumulation with the required detail. Much more suited for our purpose are growth models whose representation of the knowledge accumulation process is flexible enough to account for both endogenous and exogenous knowledge accumulation. Being able to vary the degree of 'endogeneity' in a model allows one to directly assess the economic consequences of environmental policy for different assumptions concerning the strength of the interaction between environmental policy and technological change. A model for this purpose has been developed by Smulders (1998). It builds in its formal structure on the presentation given earlier in this section and relies on previous work by Bovenberg and Smulders (1995, 1996).

5.2 Technological Change and the Cost of Environmental Policy

5.2.1 Extending the basic model

The Smulders model (1998) regards knowledge H as a composite good comprising a component h_{en} that is accumulated endogenously through investment in R&D, and a second component h_{ex} that increases as result of exogenous technological progress. No explicit stipulation is made concerning the relative weight with which h_{en} and h_{ex} contribute to H. It is rather assumed that H is determined by some function H of h_{en} and h_{ex}, so that the accumulation of composite knowledge can be described by

$$H \equiv H(h_{en}, h_{ex}), H_{hen} > 0, H_{hex} > 0. \tag{2.34}$$

H is taken to be homogeneous of degree 1 in its arguments, implying that $H = Hh_{en}h_{en} + Hh_{ex}h_{ex}$. The share of endogenous and exogenous knowledge is then quantified through the respective elasticities

$$\gamma = \frac{Hh_{en}}{H} h_{en}, \qquad 1 - \gamma = \frac{Hh_{ex}}{H} h_{ex}. \tag{2.35}$$

Knowledge H is regarded as 'resource augmenting', meaning that it enhances the efficiency with which environmental services R are employed in production. This is captured by specifying the production technology as

$$Y = G(N)F(Z,K), \tag{2.36}$$

where

$$Z = H \cdot R \tag{2.37}$$

measures the efficiency with which environmental services are employed in production, and F exhibits the usual neoclassical properties and, in addition, constant returns to scale. The effect of environmental quality on productivity is accounted for through the term $G(N)$.

The model is completed through the goods market equation,

$$Y = X + \dot{K} + q\dot{h}en, \tag{2.38}$$

which states that production is used for consumption, accumulation of (physical) capital goods, and knowledge creation. The symbol q quantifies the price of knowledge in terms of the final good.[11]

It is easy to see that when $\gamma = 1$ and all technological change is endogenous, the model reduces to the one-sector endogenous growth model of the previous section. The similarities go even further. It can be shown that the optimal intertemporal allocation conditions are formally identical to the ones for the one-sector endogenous model so that (2.25)–(2.27) retain their validity. The only difference is that now Yh_{en}/q replaces Y_H. As before, long-run growth is characterized by a constant value of environmental quality and by a common growth rate for the economic variables according to equation (2.32).

It is here that the similarity stops. Unlike in the one-sector model, where the growth rate g was endogenously determined from equation (2.31) and (2.32), the growth rate is now given by the rate of exogenous technological progress and equals $\dot{h}_{ex}/h_{ex}$. The intuition is here that when $\gamma = 0$, the model reduces essentially to the standard neoclassical Solow growth model, in which diminishing return to capital in the production function is compensated by exogenous technological progress to yield non-zero long-run growth. This dynamics remains intact even for the more general case: as long as $\gamma < 1$, diminishing returns to investment in man-made capital mean that growth rates exceeding $\bar{g} \equiv \dot{h}_{ex}/h_{ex}$ can only be maintained by devoting an increasing fraction of production to investment. This finally reduces consumption to zero, which is clearly suboptimal. Consequently, the long-term growth rate is $\bar{g}$ for all γs smaller than 1.[12]

It is important here that $\bar{g}$ is independent of environmental quality N. The same applies then to the long-run rate of return that is calculated from $\bar{g}$ through the Ramsey equation (2.36) as

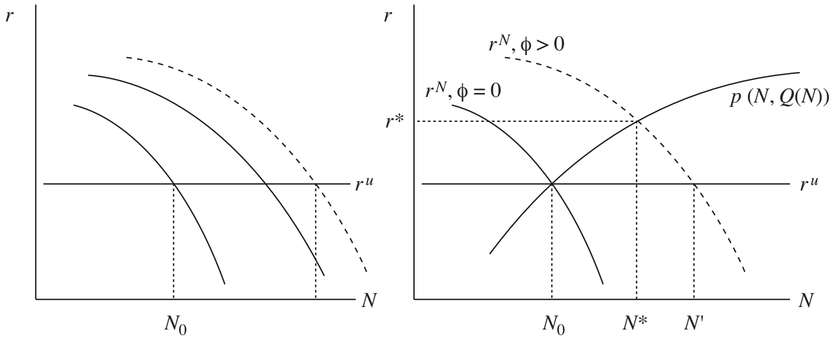
$$r^u = \theta + \frac{\bar{g}}{\sigma}, \tag{2.39}$$

where all terms are independent of N. In the graphical representation, Figure 2.5b, r^u appears as a parallel to the N-axis. Its intersection with the r^N-curve determines the socially optimal environmental quality N^*, as the optimality condition (2.30) now takes the form $r^N = r^u$.

5.2.2 Policy implications

Figure 2.6 compares the consequences of environmental policy when technological progress is exogenous to the situation reached when progress is endogenous. Focusing first on the exogenous case, we consider an economy that is initially in a suboptimal state with environmental quality N_0. The government puts policy in place aimed at more fully accounting for consumption externalities. Smulders models this 'policy shock' by an increase in the value of the parameter ϕ, equation (2.23), which measures the weight of amenities relative to produced consumption. Figure 2.6a shows that the increase in ϕ will increase the long-run optimal value of environmental quality N, but the improvement is less pronounced when γ is relative large, and technological progress is to a larger extent endogenous.

The intuition here is that a larger role of endogenous technology development requires more investment to acquire the knowledge that stimulates long-run growth. This absorbs output that would otherwise go into consumption, and there is less room to invest in amenities. Smulders refers to this as the 'burden-of-investment effect' of endogenous growth. It follows that governmental policy that does not account for the burden of investment resulting from induced technological change may overestimate the efficacy of policy for improving the environment. Technological change makes tight environmental



(a) exogenous case, $\gamma < 1$ (b) endogenous case, $\gamma = 1$

——— $r^N, \phi = 0$ ⋯⋯ $r^N, \phi > 0, \gamma$ high - - - - $r^N, \phi > 0, \gamma$ low

Note: The effect of environmental policy is modeled by shifting the r^N-curve to the left. This results (a) when growth is exogenous in an increase of the socially optimal environmental quality; (b) for endogenous growth, however, the optimal improvement in environmental quality is less pronounced and is accompanied by a larger interest rate.

Figure 2.6 Impact of environmental policy on long-term environmental quality and interest rate policy less desirable as the burden of investment effect impedes environmental improvement.

Figure 2.6b illustrates the different outcomes of environmental policy for exogenous and endogenous technological advance. When technological advance is exogenous ($\gamma < 1$) and environmental quality is initially at state N_0, optimal policy will improve the level of environmental quality to N' without affecting interest rate r^u. When technical progress is endogenous ($\gamma = 1$), however, the optimum state is given by the intersection of the r^N with the ρ-curve at which both environmental quality N^* and interest rate r^* are increased relative to the situation without policy intervention.[13]

The induced change in the interest rate r^*, which is absent in the exogenous growth model, occurs in addition to the 'burden-of-investment effect'. The direction of this effect depends on the initial value of N and the shape of the ρ-curve. If the rate of return to man-made capital increases in the long run, as is shown in Figure 2.6b, optimal environmental quality (N^*) is smaller than in the exogenous growth model (N'), because investment in economic growth is rewarded by a higher return than investment in the environment.

This mechanism counteracts policy aimed at improving environmental quality in the long run. Together with the burden-of-investment effect it reduces the level of optimal long-run environmental quality relative to the one that is socially optimal when technological progress is exogenous.

To gain insight into the impact of endogenous technological change on the optimal timing of abatement and environmental policy, Smulders (1998) employed numerical simulations to study the transitional dynamics of both the endogenous and exogenous growth models. Contrary to the result obtained by Goulder and Mathai (2000), the outcome here is that endogenous technology change justifies higher near-term abatement and disfavors a 'wait-and-see' strategy. The reason is that in the presence of induced technological change environmental policy temporarily lowers the rate of return to man-made capital and it does so for a longer period of time than is the case for exogenous technical advance. In consequence, the incentives to invest in clean environment increase. While this 'interest rate effect' justifies higher initial abatement, it diminishes over time as the rate of return to man-made capital recovers. Hence it is optimal for abatement and the stringency of environmental policy to decrease with time.

In summary, then, the main insights provided by the Smulders model are:

1. Governmental policy to improve environmental quality can both stimulate and hurt long-term optimal growth depending on the initial level of environmental quality and on the value society attaches to environmental amenities.
2. The presence of induced technological change provides a reason for a

more ambitious environmental policy. It will typically act to stabilize long-term environmental quality at a level that is below that which could be optimally achieved when technology progress is exogenous.

6. TECHNOLOGICAL CHANGE IN GREENHOUSE GAS ABATEMENT MODELS

All the models reviewed so far have focused only on one type of market failure, namely the one associated with environmental externalities, but have neglected R&D inefficiencies resulting from technology spillovers. To complete our survey we next review models that are capable of accounting for both deviations from the efficient market paradigm. Models of this type have been developed and used to simulate the consequences of policies aimed at mitigating climate change resulting from industrial atmospheric emissions of greenhouse gases. Because of their extended scope, these models are fairly complex, and thus no longer analytically tractable.

A prominent representative for this class of models is the DICE-99 model (Dynamic Integrated model of Climate and the Economy) developed by Nordhaus (see Nordhaus and Boyer, 2000, for an extensive review), which is a highly aggregated global model linking together global production, energy consumption and a climaterelated sector. DICE-99 builds upon the more detailed RICE-99 (Regional dynamic Integrated model of Climate and the Economy) model by the same author, which represents a geographically disaggregated eight-region view. While both DICE-99 and RICE-99 treat technological progress as exogenous, they have spawned a series of models in which technological change is endogenized.

In his R&DICE version of DICE-99 Nordhaus (2002) uses a fixed proportion production function to separate the effect of induced innovation from that stemming from input factor substitution. Technology change is taken to manifest itself through the development of greenhouse abatement technology that lowers the carbon emissions required to produce a fixed output. RICE is also the parent of a model developed by Buonanno et al. (2003) for which the authors coined the acronym ETC-RICE. It borrows from RICE the neoclassical production and climate change sector, and implements induced technology change in the same way as R&DICE, namely through its effect on the carbon intensity of output.

From the perspective of this review perhaps the most interesting variant of DICE-99 is the model developed Popp (2002). A feature of this author's ENTICE (for Endogenous Technological Change) model is that it can account for a multitude of channels through which technological progress can affect greenhouse gas emissions, including not only progress in abatement technology but also improvements in energy efficiency and fuel switching.

In ENTICE the production sector is modeled by a Cobb–Douglas type production function, in which, next to capital and labor, energy services appear as an input factor. This input comprises both fossil fuel use and 'energy-related human capital', and is related to these quantities through a constant elasticity-of-substitution (CES) functional form, in which the substitution parameter provides an indication of the ease with which input switching is feasible. ENTICE assumes that carbon-saving 'energy knowledge' increases with the accumulation of research through costly R&D in the energy sector, and depreciates as new knowledge supersedes old.

The economic damage caused by industrial greenhouse gas emissions is modeled in the same way as in DICE: the damage function is taken to depend quadratically on the mean global temperature increase resulting from industrial CO_2 emissions, which in turn is calculated on the basis of a set of geophysical relations. This damage is included in the production function to cause a fractional reduction in output.

As discussed earlier, markets tend to invest in R&D at a socially suboptimal level because of technology spillovers and the difficulties associated with the appropriability of technology innovations. ENTICE models this type of market failure in an approximate and heuristic way. Taking up a suggestion by Nordhaus (2002), ENTICE implements a constraint in its objective function that forces the returns on energy R&D to be a multiple of the returns on physical capital. This inflates innovation costs and forces the market to underinvest relative to the social optimum at which investments would give equal returns to all forms of capital, both physical and non-physical. Specifically, the multiplier is given the value 4 in broad alignment with statistical data for the USA.

Investment in R&D in the energy sector will crowd out research in other sectors. Since the return on energy R&D is assumed to be four times greater than that of other investments, full crowding out would imply that an increase in energy R&D leads to a fourfold decrease in the value of investments in the non-energy sectors. Popp argues that such a high crowding-out factor is not supported by statistics, and accordingly assumes in his ENTICE base case simulations only a 50 per cent crowding out.

After the model has been calibrated against empirical estimates of energy-saving R&D on induced innovation in the energy sector, it furnishes, in particular, a quantification of the welfare gains resulting from a socially optimal carbon tax. Popp differentiates the 'direct welfare effect' of new knowledge, which is associated with immediate environmental benefits, from a 'productivity effect', which refers to the fact that new knowledge makes future R&D more productive. In his ENTICE simulation Popp is able to differentiate between the two effects and to show that it is the latter that makes the dominant contribution to welfare over longer time periods, even when knowledge depreciation is accounted for.

Popp finds that the effect of induced technological change on key economic variables is small and is outweighed by that of factor substitution. Specifically, carbonsaving technological innovation induced by an optimal carbon tax imposed in 1995 will increase output, but only by 0.5 per cent in 2105.

Another model that explores the connection between greenhouse gas abatement policy and technology change is the one developed by Goulder and Schneider (1999). Its scope is different from ENTICE and in fact from the other models considered so far as it does not adopt a social planning framework and refrains from ascertaining optimal policy. It rather takes a carbon tax as given, and simulates how profitmaximizing economic actors are responding to it.

The model considers a conventional, carbon-based energy industry, and an alternative emissions-free industry. An R&D service sector is introduced whose function within the model is twofold:

1. It supplies both industries with innovations that allow them to reduce the cost of producing the particular sort of energy. This means specifically that technology advance in the conventional energy sector is modeled as productivity improving, a feature that is in clear contrast to ENTICE, where technology progress is carbon-saving.
2. As the services the R&D sector provides are not free, its inclusion in the model provides a way to capture the opportunity cost resulting from a policy-induced reallocation of a supply of R&D services.

Intrasectoral innovation spillovers are captured in the Goulder and Schneider model in a way that is somewhat more systematic than the ENTICE treatment of this externality while still remaining heuristic: it is assumed that the magnitude of knowledge spillover within a sector is proportional to the industry-wide level of expenditure on R&D.

Because of its structure, the Goulder and Schneider model offers an expanded view on the mechanisms through which carbon taxes affect technology change when knowledge spillover and policy-induced reallocation of R&D services are present. As far as the latter is concerned, the model demonstrates that it is the magnitude of the R&D opportunity cost that determines whether induced technology change retards or promotes economic growth when the carbon tax is exogenously fixed. While in the base case simulation-induced technological change suppresses output, the situation changes significantly when R&D is 'free'. In this case induced technological change is output enhancing.

The opportunity costs associated with R&D reallocation are dependent on the level of knowledge spillovers. High spillovers within a sector mean that the social returns to R&D in this sector are larger than those in a sector with fewer spillovers and higher level of technology appropriability. A tax-induced reallocation of R&D away from the high-spillover sector will imply significant opportunity cost and a corresponding loss of output, as is indeed observed in the simulations.

To put the effect of R&D opportunity costs into perspective Goulder and Schneider remark that irrespective of their value, the presence of induced technological change always increases the net benefit from a given tax in the sense that the output loss associated with achieving any level of greenhouse gas abatement is lowered by induce technological change.

7. CONSEQUENCES FOR ENVIRONMENTAL POLICY

It is not straightforward to draw robust conclusions from the models that we reviewed on the interactions between environmental policy and technological change. This is partly due to differences in the way the concept of 'technological progress' is formalized. In the models by Goulder and Mathai (2000) and Parry et al. (2002) technological advance manifests itself through its impact on abatement costs – it lowers them. This is in contrast to the way Goulder and Schneider (1999) and Nordhaus's R&DICE treat technological progress, namely as output enhancing. Smulders (1998) champions yet a different perspective: his concept of technological progress is 'resource augmenting' meaning that technological progress enhances the services that the environment provides. A 'realistic' model of technological change in the environmental field would have to encompass all of these different concepts. The ENTICE model (Popp, 2002) is probably the one furthest developed in this respect.

Keeping in mind the diverse meaning of 'technology progress', we use the insight that the models provide to answer the earlier questions concerning the relationship between environmental policy and technological innovation.

The Costs and Benefits of Environmental Policy

All studies indicate that induced technical change has positive effects on the costs and benefits of environmental policy. Goulder and Mathai (2000) showed that in the presence of induced technological change any environmental policy target, for example a certain CO_2 concentration in the atmosphere, can be achieved at lower costs. However, if the policymaker adheres to a benefit–cost criterion, an induced reduction in marginal abatement costs implies that a higher amount of abatement becomes optimal, which results in greater total abatement expenditures. Since this translates into larger net welfare gains, the presence of induced innovation strengthens the case for pollution control. The model by Parry et al. (2002) quantifies the welfare gains stemming from induced innovation and shows that they are typically small relative to the benefits associated with pollution control. This result is consistent with the general equilibrium models by Goulder and Schneider (1999) and Popp (2002), which account also for the opportunity costs of investing in environmental R&D. The reallocation of resources to research and to develop 'green' technologies will crowd out R&D in other sectors of the economy, with detrimental effects on growth. However, these results need to be qualified as the models consider only one channel of knowledge accumulation, namely investment in R&D.

The Optimal Timing of Abatement

The source of knowledge accumulation plays an important role for conclusions about the optimal degree and timing of environmental policy. While a 'wait-and-see' strategy is appropriate when technological progress is autonomous, this is, in general, not the case when technological progress is endogenous. Specifically, when knowledge is generated via R&D, Goulder and Mathai (2000) as well as Popp (2002) showed that it is optimal to postpone some abatement to the future until the accumulation of knowledge lowers marginal abatement costs. But when abatement itself accumulates the knowledge via learning-by-doing, there is no general result concerning the optimal timing of abatement activities. Nonetheless, it is expected that in this case the potential of future cost reduction typically requires more near-term abatement.

Smulders (1998) found that endogenous 'resource-augmenting' technical change provides a rationale for higher near-term emission reductions. The reason is that pollution control reduces the productivity of the economy for a longer period of time, so that investment in a clean environment becomes more attractive than investment in production. However, this effect is reversed when improvements in environmental quality outweigh production losses due to emission reductions.

The models reviewed do not provide general results on the impact induced technological innovation has for altering the optimal time profiles of abatement and emission taxes. While the details of these changes are related to the mode of technology accumulation adopted by the model, most authors seem to agree that their magnitude will be rather modest.

Policy Instruments

In the presence of induced innovation the function of environmental policy is twofold: Setting constraints on environmentally damaging activities and stimulating environmentally friendly innovation. There appears to be general agreement on the superiority of market-based instruments over commandand-control regulations not only to correct environmental externalities cost-effciently but also to stimulate private investments in 'green' technologies. Which type of market-based instrument should be used in a concrete situation depends on a variety of factors, including present and future marginal abatement costs and damages, and the information the regulator has about these quantities. Based on the models reviewed here, it can be said that endogenizing technological advance does not substantially alter the policy recommendations obtained from environmental economic models without technology change.

8. CONCLUSIONS

While relatively simple models of the type discussed in this review elucidate important aspects of induced technological progress, they fall short of accounting for the complexity of the real world. Some comments regarding potential modeling extensions seem therefore to be in order.

Technology advances through a variety of economic interactions. As we have seen, two idealized representations of this interaction have been to date the main subject of economic theorizing, namely technology advance driven by R&D and by learning-by-doing.

Technology advance involving R&D proceeds through the costly allocation of resources to the task of innovation. Accordingly, if society allocates all its resources to production and nothing to R&D, then technology progress comes to a standstill. Conversely, when progress is the result of learning-by-doing, it is the sole consequence of the production and use of technology. Technological progress is then 'free' in the sense that there is no need for investment into R&D, although opportunity costs do arise.

While both the R&D and the learning-by-doing approach tie well to real-world phenomena, they do not give a complete picture of reality, so that models that are based exclusively on one or the other are bound to miss important determinants of technological change, a fact that has been specifically emphasized by Clarke and Weyant (2002). Thus the learning-by-doing approach disregards historic public and private expenditures, and therefore tends to underestimate the cost of technological advance. There are problems with the R&D approach, too. For one, the R&D approach misses learning-by-doing effects. Moreover, investment in research should not be interpreted as emanating exclusively from R&D labs. Kline and Rosenberg (1986) argue that the notion that innovation is initiated by research of the scientific sort is wrong most of the time. Innovation evolves through cycles of design, testing, production and marketing, all of which draw on state-of-the-art knowledge and interact with public policies.

A second aspect that is not included in state-of-the art models of induced technological change relates to the discontinuous nature of technological progress. It arises when previously uncompetitive technologies reach market acceptance. While before market acceptance R&D investment has typically limited impact on aggregate production, this changes dramatically at the point of market acceptance where aggregate production undergoes a discontinuous shift. Discontinuities of this type can be simulated with bottom-up models that explicitly consider hundreds of technologies and that can therefore give detailed representations of changes in the aggregate production characteristics (Seebregts et al., 1999). However, analytical modeling of the discontinuous characteristics of technology progress is still in its infancy.

Finally, the usefulness of models of induced technological change could be improved by explicit inclusion of uncertainties related to technological progress. Uncertainty about how far technology might advance, how fast it will do so, and how costly it will be translates into uncertainty about how the production function responds to policy stimuli. Given that it is unknown when technological change will occur and how abrupt it will be, the best approach is to employ an uncertainty framework that embraces a range of possibilities about the nature and extent of future technological change.

The point here is that there is still a gap between how economic models depict the process of technological change and what happens in reality. Closing this gap is a challenge for the next generation of models of induced technological change and a requisite for an improved evaluation of the consequences of environmental policies.

NOTES

1. We exclude from consideration *bottom-up energy system models* (Seebregts et al., 1999; Edmonds et al., 2000). At the heart of these models is a detailed, typically computer-based, representation of the cost and performance characteristics of technologies in the energy sector, which is taken as the basis for modeling the pattern of technology penetration. They are thus less suited for shedding light on the macroeconomic consequences of environmental policy.
2. While the description we just gave roughly summarizes key elements of the commonly accepted explanation of technological advance, there is a variant perspective. The 'evolutionary' approach to technological change, as pioneered by Nelson and Winter (1982), abandons the idea that firms can optimize R&D investment decisions. Because of the large uncertainties surrounding the outcome of R&D investments, firms will face significant difficulties in rationalizing their R&D expenditures. It is rather argued that firms embark on a purposive search for profit that is guided by their 'routines' and 'rules of thumb' to decide on how much to invest in R&D. The most successful firm is the one which adopts in the most efficient way to the competitive environment. The similarity of this view to the theory of biological evolution is obvious. From the evolutionary perspective, firms may miss opportunities for increased profits simply because they do not look hard enough when they face a competitive business climate. An external policy shock such as a new environmental constraint can therefore provide a stimulus to new search, possibly leading to discovery of

previously undetected profit opportunities. These new ways of doing may actually be more profitable, leading to the 'win–win' outcome that was asserted by Porter and Van der Linde (1995), and whose existence cannot be easily explained within the framework of profit optimizing firms.

3. While the Goulder and Mathai model is particularly tailored to deal with CO_2 emissions, their conclusions apply to a wider context. However, as CO_2 and climate change issues provide politically relevant and concrete examples, we will adhere to Goulder and Mathai's terminology.
4. First (second) derivatives are denoted by single (double) subscripts to function symbols. Dots over function symbols refer to time derivatives.
5. This gives

$$C_{AA}(\cdot)\,\frac{d\,A_t}{d\,k} + C_{AH}(\cdot)\,\frac{d\,H_t}{dk} = \frac{d(-p_t)}{dk}.$$

6. This picture is of course completely consistent with the static view as espoused in the textbook literature (for example, Endres, 2000). If technological change lowers marginal abatement costs, then the optimal tax required to achieve a target level of abatement is reduced correspondingly.
7. It is assumed that damages are a convex function of changes in the atmospheric CO_2 concentration.
8. As obviously $W^P + W^H = (½)A^*p$, one finds after division by $W^P = (½)pA^P$ that $1 + W^H/W^P = A^*/A^P$. Expressing the ratio A^*/A^P in terms of β by taking advantage of $A^P = (1 - \beta)A^*$ then yields equation (2.15).
9. This argument can be illustrated with the help of Figure 2.4. Consider again a competitive industry under a tradable permit system. Assume further that the permit price will fall from p^0 to p' when all firms adopt the new technology. Jung et al. calculated that in this situation the cost-savings of the industry under auctioned permits equal area 0*afhb* in Figure 2.4, which consists of the reduction in abatement costs (area 0*ab*) plus the reduction in payments for permits due to the lower permit price (area *afhb*). However, these aggregate cost-savings are not identical with the incentives for firms to adopt the innovation. To see this, assume that all firms but one have adopted the cleaner technology, so that the permit price is approximately p'. For the last firm, being a price-taker in the permit market, the cost reduction from adopting the new technology is given by area 0*db*, which is smaller than the aggregate cost-savings 0*afhb*. Thus, under a tradable permit system the incentives for firms to invest in cleaner technology decrease over time when the new technology spreads. In addition, this result holds whether tradable permits are freely allocated or auctioned, because the distribution itself does not affect firms' decisions.
10. This result echoes Weitzman's (1974) rule that a price instrument is more efficient than a quantity instrument, if marginal damages are constant and information about marginal abatement costs is asymmetric.
11. In the one-sector model, the relative price of knowledge equals unity because there is only one production technology.
12. It is worth pointing out that in the Smulders model the *qualitative* difference between completely endogenous growth ($\gamma = 1$) and only partly endogenous growth ($\gamma < 1$) is maintained irrespective of how closely γ approaches unity. As long as $\gamma < 1$, environmental quality N does not influence long-term growth, which is determined by exogenous factors. However, environmental quality does have permanent effects on growth when $\gamma = 1$.
13. In the figure, we have drawn the r^N-curve intersecting the ρ-curve at the upward-sloping part. This is appropriate, as discussed before, for low preference for environmental quality.

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