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Pollution-Reducing and Resource-Saving Technological Progress

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Pollution-Reducing and Resource-Saving Technological Progress

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Christian-Albrechts-Universität Kiel

Department of Economics

Economics Working Paper

No 2004-07

Pollution-Reducing and Resource-Saving Technological Progress[*]

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Abstract: In this paper we survey the theoretical literature on both pollution-reducing and resource-saving technological progress. The literature can be divided into two strands. One strand deals with microeconomic models which investigate incentives to adopt and to develop environmentally more friendly technologies for different policy tools and in different economic environments, such as market structure or timing and commitment structures. It turns out that, firstly, price based instruments such as emission taxes and tradable permits perform better than command and control policies, and secondly, that under competitive conditions ex ante end ex post optimal policies are equivalent. Under imperfect market conditions the policy conclusions are more subtile. The second strand of literature deals with both pollution-reducing and resource-saving technological progress within endogenous growth models. Most of these models are characterized by three market imperfections: market power for new (intermediate) products, positive R&D spillovers, and pollution. These imperfections can be mitigated by subsidies on intermediate products, subsidies on R&D effort, and a tax on emissions. Moreover, in most models there occurs a trade-off between the speed of growth and environmental quality.

Keywords: pollution-reducing technological progress, resource-saving technological progress, environmental innovation, endogenous growth models, emission taxes, tradable permits

1 Introduction

In the literature of innovation and technological progress, one usually distinguishes between product and process innovation. *Product innovation* reflects the idea that consumers either enjoy higher quality of certain products, which in principle serve the same purpose as the old products, or they enjoy a greater variety of products. *Process innovation*, by contrast, means the same products can be produced at a lower cost.[1] Both kinds of innovations are driven by market forces: A firm which offers a new product gains a rent, either because it is able to exploit the difference between the price charged by the competitors and its own marginal cost, as is the case with process

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[*] We are grateful to Paul Mensink for valuable comments.

innovation, or because the consumers' willingness to pay for a new product is larger than for the conventional products.

Resource-saving technological progress can fall into both categories. A product innovation can be resource saving in two different ways. The new product may require less resources as input for production, or it might itself need less energy in the process of consumption. However, it is usually not the case that new products which yield higher utility to consumers are automatically also less resource intensive than old products. A good example are innovations of cars: cars that are faster and safer typically require more resources for production, and, even more severe, they need more energy when being employed by consumers.

If a producer of some commodity is able to produce the same amount of output with smaller quantities of input resources, we can consider this as a case of process innovation. The existence of a new production process which induces lower unit costs does, however, not imply that the new process requires smaller amounts of *all* resources necessary for production. Rather, the new production process might substitute some inputs for others. From an economic perspective this is in principle not a problem and is even socially beneficial as long as prices reflect the true scarcity and the true social costs of all the resources. This, however, need not always be the case for at least four reasons[2]: First, some resources may not be subject to well defined property rights but rather are harvested from a common pool, such as deep sea fish and timber. In a case like this, input prices reflect only the harvest cost but not the shadow prices of scarcity. Secondly, during the production process some resources may cause pollution and thus a damage to society which is not accounted for in the resource prices. Prominent examples are sulphur dioxide and carbon dioxide, the first one causing direct damages through asset rain, the second one generating indirect damages, notably to future generations, through global warming. Thirdly, as Farzin [24] has pointed out, if the unit costs of extraction depend on the size of the remaining stock, a unit of the resource exploited today will inflict an intertemporal externality to future generations by pushing up extraction costs at all future dates. And, finally, market prices of some resources, particularly non-renewables such as fossil fuels, may differ from their social value for another intertemporal reason: market interest rate may not necessarily reflect the social discount rate.[3]

Therefore, pure market forces emerging in a competitive non-regulated economy might not per se induce resource- or pollution-saving technological progress. Even if they do, the right direction of technological progress is not guaranteed, i.e. not necessarily those resources with the highest social shadow prices are saved in the first place.

In cases like these, environmental and resource policy can help to close the gap between market and social shadow prices. Hence, the issue of pollution-reducing and resource-saving technological progress cannot be studied properly without including environmental policy instruments into the analysis.

The aim of this paper is to survey recent developments on pollution-reducing and resource-saving technological progress. In particular, we emphasize environmental policy instruments as the driving forces for this special kind of technological progress. The bulk of literature can be classified in different ways. We decided to make the following distinction. Firstly, there is the literature on incentives to reduce pollution, both in the short and in the long run. Secondly, there is the intertemporal aspect of resource-saving technological progress. In particular the endogenous growth theory has incorporated the issue of resource-saving technological progress in order to answer the question whether or not non-declining growth paths are feasible in the presence of finite amounts of certain resources, in particular energy stemming from fossil fuels.

Hence, the paper is devided into two parts: In section 2 we first set up some definitions and model frameworks in order to define pollution-reducing technological progress. Then we survey the literature on pollution-reducing technological progress, studying microeconomic models. In section 3 we summarize the work on pollution-reducing and resource-saving technological progress in the framework of endogenous growth theory. Although those models consider different stages of aggregation, the macroeconomic perspective prevails.

2 Pollution-Reducing Technological Progress

We start to survey microeconomic partial equilibrium models which are static or quasi-dynamic in the sense that they allow for sequential decisions by a regulator, an innovating sector, and firms which adopt new technology. Except for Parry et al. [60], the authors of these models do not explicitly capture the aspect of time. It is convenient to first introduce some definitions and basic concepts which are typically used in the literature of pollution-reducing technological progress to be summarized below in more detail.

2.1 Definitions and Model Frameworks

2.1.1 Abatement Technology and Pollution-Reducing Technological Progress

For a polluting firm there are basically two strategies to reduce pollutants: either to reduce gross emissions by reducing output, or to keep output constant and to reduce emissions by employing an abatement technology. In general, a mix of both will be optimal. Concerning the abatement technologies, experts usually distinguish between *end-of-pipe technologies* and *process integrated technologies*. The latter leads to a decline in gross emissions, whereas with the former gross emissions remain unchanged and are subsequently decreased, for example through a filter. In both cases the abatement technology can be represented by its abatement cost function $C(e)$, which represents a firm's cost to reduce emissions from the laisser-faire emission level $e_{\max}$ to some lower level $e < e_{\max}$. Typically, both the abatement cost function and the *marginal* abatement cost function are downward sloping. Note that a firm's abatement cost is nothing else than its forgone profit incurred by reducing emissions.[4] It is straightforward to show that such an abatement cost function can be derived from a firm's joint cost function which may incorporate both cost of production and cost of abatement.[5] Note further that if firms are small and thus cannot influence the output prices, there is no need to explicitly pay attention to the output market.

Pollution-reducing technological progress can now be defined by a downward shift of the abatement cost curve. In most of the literature an even stronger assumption is made, namely that also the *marginal* abatement cost curve shifts downwards. If, by contrast, pollution is proportional to output and if there is no further short run abatement technology, pollution-reducing technological progress can be modelled by decreasing emission coefficients (i.e. reducing the emission-output-ratio). In this case, lower emission coefficients do not necessarily lead to declining *marginal* abatement costs if emission levels are already low.

2.1.2 Pollution Control Instruments

As mentioned above, pure market forces do not necessarily induce pollution-reducing technological progress, a fact which calls for regulation. Economists distinguish mainly between two types of pollution control instruments: command and control, and market based instruments. The most common instruments of command and control are *technological standards* (a regulatory authority might prescribe the firms to adopt the best available technology), *emission standards* (firms are constrained by an absolute upper emission level), and finally, so called *generation performance* or *relative standards* (firms face a cap on the ratio of emissions per output), which is the most commonly applied standard in reality.

Market based instruments, by contrast, provide incentives to reduce emissions through prices, and firms are free to decide how much they want to emit or to abate. The most commonly used market based instruments are emission taxes, subsidies on abatement of emissions, and tradable permits. Under emission taxes and abatement subsidies the prices for emissions are administrated by a regulator. If she levies a linear tax per unit of a pollutant or pays a subsidy per unit of abated emissions, then each firm has to pay (gets) the same marginal price for each unit of pollution it emits (abates). Under permits, a firm must hold one permit for each unit of pollution it wants to emit. Usually, firms can trade those permits with other firms. There are two allocation schemes for permits: free allocation according to historical emission or output levels (often referred to as grandfathering) or auctioning off the permits in which case the firms have to pay for each unit of the pollutant they are going to emit. In contrast to the tax rate, the market price of permits is determined endogenously by the market mechanism.

Economists usually prefer market based over command and control instruments by virtue of their static efficiency. For, under competitive conditions, market based instruments lead to equalization of marginal abatement costs across firms, a necessary condition for achieving an aggregate emission target at least costs.If markets are competitive, regulation by prices (taxes or subsidies) and regulation by quantities (tradable permits) is equivalent. The dynamic properties, in particular the innovation incentives of these instruments are, however, more complex and subject to discussion below.

2.1.3 How to Compare Incentives for Adoption, Diffusion and Innovation

When comparing the incentives for adoption, diffusion, and innovation provided by different policy instruments, it is natural to begin with the incentives for *adoption*. In a first step this can at best be analyzed from the perspective of a single firm. The incentive for adoption is simply given by the firm's additional total profit from switching to the new, exogenously given technology. In case of a market based instrument like an emission tax or a system of tradable permits, a firm adopts a new technology if and only if

$$C_I(e_I) + pe_I + F < C_0(e_0) + pe_0 \qquad (1)$$

where $C_I(e_I)$ and $C_0(e_0)$ are the abatement costs of the new and the old technology, respectively, F denotes the fixed investment costs and p the price of emissions, which can be the tax rate or the price of tradable permits, respectively.[6]

The *rate of diffusion* refers to the percentage of firms adopting the new technology. The incentives for adoption and the rate of diffusion are interrelated. In particular in the case of tradable permits the market price of permits depends on the number of firms which adopt the new technology.

The incentive for *innovation* refers to the benefit a firm enjoys from developing and inventing a new technology. Firms engaging in the research and development of pollution-reducing technologies are either part of the polluting industry itself and thus use the new technology themselves or they engage in R&D exclusively in order to sell or license their new technology to a polluting sector. In the first case, the innovator's benefit is determined by the change of her compliance costs (including short run abatement cost, revenues from emission subsidies or permit sales, expenditures for emission taxes or permit purchases) and the change of her profit on the output market. This benefit might be enhanced by license fees, and it may be reduced by other firms imitating the new technology. In the second case, the innovator's benefit depends on the polluting firms' willingness to pay for the new technology, which in turn is determined by the adoption costs, by the change of compliance costs, and by the profits those firms accrue from adopting the new technology. Again, the possibility of imitation has a diminishing effect on the innovator's benefit. Figure 1 illustrates the change of an adopting firm's compliance costs under an emission tax.[7]

Depending on the kind of regulation, a potential innovator will put a certain effort into R&D. A higher effort may either lead to a higher degree of innovation (for example a more radical shift of both the abatement and the marginal abatement cost curves), or induce either an increased probability or an earlier date of success. A profit maximizing innovator chooses an effort level such that the marginal (expected) benefit equals the marginal cost of R&D. Denicolò [19](p. 186) points out that the innovation incentive of the different instruments can be correctly measured by the innovator's respective profits if her "R&D investment cannot affect the nature of the innovation and hence the reduction in effluent emissions that it entails." Otherwise, "it is the marginal profit that matters to determine the innovator's incentive to invest."

It is important to note that the distinction between investment into adoption and into innovation is not always sharp. Some authors such as Phaneuf and Requate[64], Petrakis and Xepapadeas[62], or Gersbach and Requate [28] assume cost functions of the form $C(e,k)$ where e denotes emissions and k can be interpreted as both investment into abatement equipment *or* R&D effort. In the literature survey following below, we subsume a paper under a *model of innovation* (in contrast to a *model of adoption*) when the respective model contains at least *one* of the following aspects: Firstly, a stochastic element is incorporated, i.e. the size of innovation, its date, or the R&D success is uncertain, secondly a patent is granted on the innovation, thirdly spillovers occur, or finally imitation is accounted for.

2.1.4 Possible Timing and Commitment Strategies of the Regulator

When analyzing diffusion, innovation, and technological progress it is important to distinguish the possible timing and commitment strategies of the regulator. This basically boils down to the question of who is the first to move, the regulator or the firms. If the regulator moves first and is able to make a commitment to the level of her policy instrument, we talk about *ex ante regulation* or *ex ante commitment*. A *myopic* regulator does not anticipate a new technology and therefore commits ex ante to a level of her policy instrument which is optimal with respect to the conventional technology. If, by contrast, the firms move first, by engaging in R&D or by adopting a new technology, and the regulator moves second, by adapting the level of her policy instrument to the respective R&D outcome or to the rate of adoption of new technology, we talk about *ex post regulation*. If the regulator has no incentive to change her behavior after firms have moved, her policy is called *time consistent*. The adjustment of her policy in case of a time inconsistent policy is sometimes called *ratcheting*. Note, that ex post regulation is always time consistent.[8] The early literature usually considers the regulator as the natural first mover whereas more recent contributions emphasize the importance to also study the regulator's reaction on innovation and technology adoption.

2.2 Results of Models on Adoption, Diffusion and Innovation Incentives

In this section we focus on theoretical microeconomic partial equilibrium models. Among those we can distinguish two types of models: firstly, those which analyze the incentives for adoption and diffusion of the environmental policy instruments only; secondly, models which look at both, the innovation and diffusion incentives. We will not review the early papers on this topic in detail. The interested reader is referred to Kemp [42], Jaffe et al. [39].

2.2.1 Models of Adoption and Diffusion Only

The models summarized in this section differ, on the one hand, with respect to the behavior of the regulator, who is assumed to either act myopically or to engage in ex ante or ex post regulation. On the other hand, they differ with respect to whether or not they pay attention to the output market, or whether or not they include uncertainty. Table 1 summarizes the different features of the models that we describe in more detail below.

2.2.1.1 Myopic Regulation

The first contributions dealing with adoption of a new abatement technology are those by Downing and White [22], Milliman and Prince [51], and Malueg [49]. For different types of pollution control instruments the authors compare the aggregate cost savings incurred by industry when adopting a new technology. By ex ante assuming an industry wide adoption of the new technology, Milliman and Prince arrive at the following (descending) ranking of policy instruments with respect to those cost savings: 1) auctioned permits, 2) emission taxes and abatement subsidies, 3) free permits, 4) emission standards. Jung et al. [40] confirm this ranking employing a more formal analysis.

Both, Kennedy and Laplante [44], and Requate and Unold [73] criticize the approach by those authors by pointing out that, firstly, equilibrium considerations must be taken into account when studying the incentives to adopt new technology, and secondly, that the number of firms which adopt the new technology must be determined endogenously.

One of the scenarios investigated by Requate and Unold [73] corresponds to those studied by both, Milliman and Prince [51] and Jung et al. [40], in assuming the regulator to be myopic.[9] For this scenario Requate and Unold look at the incentives to adopt the new technology in equilibrium and compare those for emission taxes, abatement subsidies, free and auctioned permits, and an emission standard. Assuming symmetric firms, they find that taxes usually provide higher incentives than permits and standards, and that the comparison between standards and permits is ambiguous, i.e. depending on parameters, standards may even provide stronger incentives to adopt the new technology than permits. Moreover, in this scenario, one will typically observe overinvestment under regulation by taxes and underinvestment under regulation by permits. In a model which explicitly accounts for both production cost and output market, Requate [69] comes to similar results for the case of free market entry.

2.2.1.2 Anticipating New Technology, Timing, and Commitment

We now turn our attention to scenarios where the regulator anticipates the evolution of a new technology, and focus on the issue of timing and commitment, and the difference between ex post and ex ante regulation.

Kennedy and Laplante [44], analyze a similar model as Requate [69] where symmetric firms behave as price takers on the output market and choose whether or not to adopt a new abatement technology that lowers their marginal abatement costs but incurs fixed investment costs. Considering a scenario where the regulator anticipates the new technology and makes an ex ante commitment to the level of her policy instrument, the authors study the time consistency of emission taxes and permit policies. They find that, if the environmental damage function is linear, ex ante commitment is time consistent for both instruments, no matter how many polluting firms are in the market. If, instead, the damage function is convex, time inconsistencies arise if the number of firms is relatively small. By contrast, ex post regulation, referred to as “ratcheting”, is time consistent by definition. However, firms then tend to underinvest in the new technology under permits (too little adoption) and to overinvest under taxes (too much adoption). For a continuum of firms no inconsistencies arise even if the damage function is convex. In a model with many (a continuum of) asymmetric firms, Requate and Unold [72] come to a similar result. They even show that both, optimal ex ante and optimal ex post regulation lead to first best allocations for all of the following environmental policy instruments: emissions taxes, subsidies on abatement, auctioned permits and free permits. Uniform standards, of course, cannot induce the optimal rate of adoption due to their static inefficiency. In the symmetric version of the model Requate and Unold [73] confirm the optimality of ex ante and ex post regulation for the case of permits. Under taxes, by contrast, a first best allocation can only be obtained for the case of ex post regulation. For the case of ex ante regulation taxes may induce inefficient equilibria is case that partial adoption is socially optimal.

Petrakis and Xepapadeas [61] investigate regulation of a single monopolistic polluting firm that can choose among a menu of new technologies where the emissions-per-output-coefficients are lower than the one of the conventional technology. Assuming specific functional forms, in particular linear damage, and focusing on an emission tax as the only policy instrument, the authors compare ex ante commitment[10] to "non-credible environmental policies" with respect to the optimal level of investment, the optimal emission tax, and welfare. In the latter scenario the regulator cannot credibly commit ex ante to an emission tax rate and the monopolist anitcipates the regulator´s change of the tax rate after his investment decision. Since the monopolist then can influence the tax rate, she will always invest more than in the case of ex ante commitment. Therefore, both the emission tax and welfare are always higher under ex ante commitment.

Amacher and Malik [3] analyze the incentive for adoption for a single firm under an emission tax only. The firm can choose between a "cleaner" abatement technology that incurs high fixed but low marginal cost and a "dirtier" technology which incurs low fixed but high marginal cost. A first best outcome is achieved if the firm adopts the "cleaner" technology and emits the respective socially optimal emission level. The second best outcome is defined as the firm adopting the "dirtier" technology and emitting the corresponding socially optimal amount of emissions. If the regulator commits ex ante to an emission tax rate and if the damage function is strictly convex, then it is possible that neither the first nor the second best outcome will be achieved: The Pigouvian tax, optimal with respect to one technology may prompt the firm to adopt the other one, and the emission level would not be socially optimal. With ex post regulation by contrast, the first or the second best outcome are the only possible equilibria. The authors show that the firm is always better off under ex post regulation whereas the regulator, depending on parameters, may either prefer ex ante or ex post regulation.

2.2.1.3 Imperfect Competition

In all the models discussed so far, the authors have either explicitly or implicitly assumed that the output markets are perfectly competitive. A couple of models pay explicit attention to imperfect competition on the output market and its consequences for adoption and regulation.

Requate [70] reconfirms the phenomenon of multiple equilibria under ex ante commitment to a tax policy, known from Requate and Unold [73], for the case of a polluting Cournot oligopoly with free entry.

Carraro and Soubeyran [14] study a Cournot-duopoly with polluting firms that choose how many plants to run, whether to use a "cleaner" or "dirtier" technology, and the respective capacity utilization. The "cleaner" technology is associated with a lower emissions-per-output coefficient but with higher fixed and variable costs than the "dirty" one. The authors derive the ex ante optimal emission tax, when only the "dirtier" plants' emissions are taxed and show that it is lower than marginal damage, which is assumed to be linear. Further, they derive the optimal innovation subsidy, where the regulator pays a proportional part of the fixed costs of the "cleaner" plants. Both instruments prompt the firms to use the "cleaner" technology if its supply is not constraint. Otherwise both technologies are used. The welfare comparison of the instruments is ambigous: If the output contraction induced by the tax is negligible or if the regulator considers output contraction as undesireable and the supply of "cleaner" plants is unlimited, welfare turns out to be higher under innovation subsidies. If instead the supply of the "cleaner" plants is limited and the number of "dirtier" plants which the firms keep using is large, the emission tax may become the appropriate policy instrument.

Montero [53] is mainly interested in the investment incentives of tradable permits and two kinds of standards, emission and performance standards, but rules out the possibility of taxation. Besides allowing for perfect and imperfect competition on the output market, he is one of the very few researchers who models imperfect competition on both, the output and the permit market.[11] In his model ex ante symmetric firms produce a homogenous good and emit a pollutant. The firms can choose among different abatement technologies that are associated with lower marginal abatement costs than the conventional one. In contrast to the other approaches, however, there is no damage function, and thus optimal pollution levels are not considered. Rather, the regulator aims at enforcing an exogenously given aggregate emission standard. The R&D incentives are compared by means of the respective marginal profits. The total effect of a typical firm's investment decision consists of a direct cost effect and, in case of imperfect competition, of a strategic effect on both the output and the permit market. The direct effect, which always prompts the firms to invest, is the same for permits and emission standards. Under performance standards it is lower. The strategic effect with respect to the output market causes the firms to invest more under standards, but less under permits. In the former case the investment lowers the competitors output, in the latter it raises its output. It turns out that the strategic effect from the permits market is only relevant under auctioned permits: since all firms are permit buyers, they benefit from a lower permit price due to higher investment. Hence, for *imperfect competition on both markets* Montero finds the following: Both, an emission standard and a regime of auctioned permits provide a higher incentive to invest than free permits, whereas a performance standard may provide a higher, a lower, or the same investment incentive than both free permits and the emission standard. Finally, both types of standards may provide a higher, a lower or the same incentive to invest than auctioned permits. If there is *perfect competition on both markets*, only the direct effect matters. Thus an emission standard, free and auctioned permits provide the same incentives, whereas the incentive provided by the performance standard is lower. Interestingly, the results are qualitatively the same if there is imperfect competition on the permit market only. For imperfect competition on the output market only, Montero finds that the incentives for tradeable and auctioned permits are equivalent whereas an emission standard may provide a higher incentive than permits. These findings are in line with those of Requate and Unold [73] who implicitly assume perfect competition on the output market.[12]

2.2.1.4 Including Uncertainty

A couple of contributions take into account different kinds of ex ante uncertainty in dynamic models with two or three periods where the uncertainty will usually be resolved in the second period: Laffont and Tirole [45] assume uncertainty about the benefits which the firms accrue from emitting pollutants, Kennedy [43] considers uncertainty about environmental damage, whereas in Phaneuf and Requate [64] the abatement cost is subject to uncertainty. Van Soest and Bulte [90] and Van Soest [89] take into account the uncertainty about technological progress.

Laffont and Tirole [45] analyze optimal regulation of many (a continuum of) potentially polluting asymmetric firms in a two period model, where in both periods, firms can either emit one unit or nothing. Firms are regulated by emission permits. In the first period full abatement requires the firms to cease production, whereas in the second period they can use an abatement technology which they had to purchase in the first period. In the first period firms know their benefit from pollution in period 1 but not that of period 2. Only the probability distribution of those benefits is known. This uncertainty is resolved in the second period. A novelty of this model is that the shadow cost of public funds is taken into account. Thus the regulator chooses the optimal Ramsey permit price (respectively the corresponding amount of permits) in period 1. The authors show that if the permit market is a pure spot market, i.e. if the regulator issues permits in each period, and in the first period is not able to make a commitment about the second-period permit price, then excessive investment incentives are created. A too high permit price prompts the firms to bypass the permit market via adoption of the abatement technology. By commiting to a lower second-period permit price, especially by introduction of a futures market, the regulator can enhance welfare by discouraging unwanted investment. However, committing to a lower second-period price in the first period, is not time consistent. For, a marginal increase in the number of permits in the second period increases welfare. A price support policy or options to pollute, issued in period 1, allow the regulator to solve this problem of time inconsistency. It is important to note, however, that the overinvestment result hinges on the assumption that the regulator wants to collect money from auctioning off permits in order to mitigate the social costs of public funds.

Kennedy [43] sets up a two period model where in the first period the (constant) marginal damage may be high or low. Given this uncertainty, a large number of polluting firms has to decide whether or not to adopt an improved abatement technology which incurs fixed costs and lower marginal abatement costs. Kennedy assumes a very special scheme of permit trading, rarely used in real existing policy frameworks: one permit allows the emission of one unit of pollution in each period of time (rather than just for one period).[13] When uncertainty about the marginal damage is resolved in the second period, the regulator can adjust the number of permits. Kennedy considers two kinds of adjustment rules which both implement the social optimum, if announced in period 1: firstly, open market operations, i.e. buying back permits if the marginal damage turns out to be high, and auctioning off more permits if the damage is low, and secondly, a proportional adjustment rule, where firms lose a fraction of their permit endowment if the damage is high, or get more permits proportional to their initial endowment if damage is low. Kennedy argues that the first rule is unlikely to be implemented since firms will be rewarded if the expected damage turns out to be higher than expected. Phaneuf and Requate [64] examine the effects of *banking* permits on the incentives to invest in advanced abatement technology if there is *aggregate uncertainty* about the abatement cost. To this end they set up a three period model where in the pre-regulation period 0, firms can invest in an abatement technology. In the periods 1 and 2, respectively, the uncertainty about the abatement cost is resolved. Banking allows firms to postpone investment until more information on the abatement costs is revealed. The authors find that, if the discount factor is sufficiently small, and if period 1 costs are revealed to be low, then there will be positive banking but no first period investment. If instead period 1 costs are revealed to be high, there will be no banking but positive first period investment. The analysis of the constrained (total endowment of permits is fixed) socially optimal response of the firms to the resolution of uncertainty shows that the regulator will be interested in some banking, but that private and social optimal response to the resolution of uncertainty are not identical. This can lead to sub-optimal levels of investment in improved technology. A unique conclusion concerning the savings of social cost through banking is not possible, though. For a quadratic cost and damage function it is shown that banking leads to lower costs for society if the damage function is relatively flat. Otherwise non-banking is preferred.

Van Soest and Bulte [90] study the problem of technology adoption for the case that future technological advances are uncertain. For this purpose they apply the option value approach developed by Dixit and Pindyck [20], and having been applied to the problem of technology adoption by Farzin et al. [25], and improved by Doraszelski [21]. Van Soest and Bulte show that even if adoption of new technology pays according to the criterion of net present value comparisons, it may not be profitable if further improvements may occur. Hence the firm is better off by postponing the adoption decision to the point of time when an even better technology is available. Using this calculus they offer an explanation why firms do not invest, although it seems favourable to do so. In a companion paper Van Soest [89] uses this approach to compare energy taxes to absolute energy use standards with respect to the incentive to adopt improved energy-efficient technologies. However, no unambiguous ranking of the two instruments is possible with respect to better stimulating early adoption of new technology. Moreover, he surprisingly finds that firms tend to postpone the adoption of improved technology if environmental policy is more stringent.

2.2.1.5 Regulation and Hold up

Gersbach and Glazer [27] identify incentives for firms to hold up innovation. In their model the regulator aims at prompting all (ex ante symmetric) firms of an oligopolistic, polluting industry to adopt a certain abatement technology at a fixed cost and to abate the corresponding optimal amount of emissions. If a firm does not invest, it can only abate emissions by reducing its output. A crucial, and most unusual assumption is that the social benefit of the last unit of output exceeds its social cost of pollution. Hence, the regulator will never force a non-investing firm to abate emissions. Anticipating this dilemma of the regulator, firms have an incentive not to invest into the new technology. Gersbach and Glazer show that this hold-up problem can be overcome by ex post issuing free permits, assuming a competitive equilibrium on the permit market. In equilibrium all firms invest if the number of firms is as least two.

2.2.2 Models of Innovation and Diffusion

We now include innovation into the analysis. The models summarized in this subsection have mainly in common that, ex post, there is always one innovator whereas ex ante there may be several potential innovators engaging in a patent race. The innovator can either sell or license the technology to other firms which decide whether or not to adopt it. The various models differ with respect to the following main issues: firstly, which policy instruments are subject to investigation, secondly which timing and commitment strategies are feasible for the regulator or which strategy she is assumed to pursue, thirdly, whether R&D success is stochastic or deterministic, forth, whether the marginal damage is constant or increasing, and finally whether or not special attention is paid to the output market. Table 2 gives an overview about the special features and assumptions of the different models.

2.2.2.1 Innovation Incentives and Welfare Gains under Perfect Competition

Biglaiser and Horowitz [6] and Parry [58], [59] were the first to rigorously combine the issues of innovation and adoption. Biglaiser and Horowitz [6] look at a competitive polluting industry with an exogenously given number of ex ante symmetric firms each of which can engage in R&D. The new technology is randomly drawn from a cumulative distribution which is the same for all firms. Thus, innovation size and R&D success are stochastic. A patent is granted to a successful firm, and other firms can use this technology when paying a license fee and installation costs. Since adoption costs are independent of which particular technology is adopted, the regulator always wants an adopting firm to adopt the best available technology. If the regulator ex interim[14] (i.e. after R&D but before adoption) commits to both an emission tax equal to marginal damage and to a technological standard, which either specifies the firms which have to adopt the best available technology or which specifies the firms which have to adopt the "lowest acceptable" technology, then efficient pollution, production and adoption are induced. The level of R&D effort, however, is too low, compared to the socially optimal level.

Parry [58] sharply separates the polluting sector from the R&D sector. There is free entry on both markets. Each upstream firm conducts one R&D project to develop a new abatement technology for the polluting downstream sector but does not need it for its own production. Both the probability of R&D success and the industry's R&D cost rise with the number of R&D firms. If a firm is successful, it is granted a patent and becomes a monopolist. The ex ante symmetric downstream firms can adopt the new technology by paying a license fee. Parry shows that a rising tax rate leads to a smaller number of polluting firms in the downstream market. Since those with the highest willingness to pay for the new technology stay in the market, a higher tax also induces a higher license fee. Parry studies only the tax instrument with the regulator committing to the tax rate before the upstream firms engage in R&D.He derives the second best optimal tax rate for the cases of -convex damage and linear damage with and without the possibility of costless imitation. If imitation is not possible, the second best optimal tax rate turns out to be smaller whereas with imitation it may be smaller or greater than marginal damage.

In another variant of this model Parry [59] allows for incomplete diffusion and besides taxes also studies tradable permits and an instrument mix consisting of a performance standard and a production quota. For permits and performance standards he distinguishes the cases of ex ante and interim commitment. Employing numerical simulations he finds that emission taxes yield higher welfare than permits, with the difference depending crucially on the potential size of innovation. The same holds for performance standards under ex ante commitment. For interim commitment, however, the difference in efficiency almost vanishes. The case of emission taxes shows that imitation does not necessarily imply large inefficiency in the R&D market. Therefore, imitation does not call for "research subsidies or tightening envrionmental regulation beyond the Pigouvian level."(p.252)

Fischer et al. [26] abstract from R&D races by considering a model with a large number of competitive polluting firms, only one of which, called the innovator, is able to engage in R&D in order to improve its own abatement technology in the first place. The other symmetric polluting firms can either pay a license fee to adopt the new technology, or they can freely use an (im)perfect imitation. Despite this possibility, complete diffusion is socially optimal. Considering emission taxes, auctioned and free permits as policy instruments the regulator is assumed to be myopic by ex ante committing to the Pigouvian levels with respect to the conventional technology. For the case of constant marginal damage the authors find that if no imitation is possible, emission taxes induce the first best outcome, whereas permits do not. If imitation *is* possible, the welfare gain under taxes is higher than that under free permits. Depending on the degree of imperfection of imitation, welfare under taxes might exceed or fall short of welfare under auctioned permits. Emission taxes are superior if imitation is easy. For the case of increasing marginal damage the authors find that the steeper the marginal damage curve the more do permits dominate the tax regime. Note that in equilibrium imitation never occurs. It only serves as an outside option for the polluting firms and thus drives down the licence fee. Note further that in contrast to Requate and Unold [72] and [73], free and auctioned permits are not equivalent in this model since the innovator is able to exercise market power and his price strategy depends on his own initial endowment of permits.

Laffont and Tirole [46] study the innovation incentives of permits in a regime where, just as in their companion paper[45], the regulator faces a shadow cost of public funds and thus is interested in reducing the burden on taxpayers by means of permit revenues. A single upstream firm engages in R&D and might invent a pollution-free technology. The authors show that if the regulator commits ex interim (after R&D but before innovator's pricing decision) to a permit price, the innovator does not engage in R&D because she will make no profit. Since permits and innovation are perfect substitutes, the innovator will always undercut the permit price which drives down the price to zero. Laffont and Tirole further find, that if the regulator prior to R&D sells a certain amount of permits and commits himself not to issue additional permits on the spot market after R&D success, then the innovation incentive is still sub-optimal and induced adoption may be sub-optimal as well.Emissions are too high in case of R&D success. However, the regulator can restore the first best outcome by offering an optimal ex ante incentive contract to the innovator, committing to purchase the invention at a certain price and to sell the licenses at the Ramsey price. If the regulator is unable to contract ex ante with the potential innovator, the regulator can implement a second best allocation by issuing securities prior to R&D. The securities allow the holders either to purchase permits or to sell the securities to the regulator after R&D.

2.2.2.2 Timing and Commitment

As has become clear from the above summaries, most authors either assume that the regulator moves first and is able to *ex ante commit* to both the type and the level of his policy instrument, or that the regulator moves after observing R&D success and/or the degree of adoption, which we referred to as *ex post regulation*. Under pure adoption and under competitive conditions, it has been shown by Requate and Unold [72], [73] that ex ante and ex post regulation are (almost) equivalent. If, by contrast, there is only one firm to be regulated this equivalence breaks down, as Amacher and Malik [3] have shown. If we study innovation, there are typically few firms which engage in R&D and even fewer will be successful. Hence, we would expect the timing to be crucial for the incentives to innovate. This is the focus of the papers by Denicolò [19] and Requate [71] who compare the different timings and commitment strategies with respect to welfare.

Denicolò [19] was the first who explicitly compared ex ante and ex post regulation for both emission taxes and tradable permits in a model with an upstream monopolistic R&D firm and many polluting downstream firms. The perfectly competitive firms produce an output with constant returns to scale. Emissions are proportional to output. The new technology has a lower emissions-per-output-ratio than the conventional one and the degree of reduction depends on the R&D investment. Denicolò finds that taxes and permits are equivalent for ex post regulation. For ex ante commitment, however, the instruments are not equivalent but both always lead to underinvestment in R&D. If the regulator commits to the second best level of the instruments, it depends on the social cost of pollution, whether taxes perform better or worse than permits. Despite the distortions Denicolo finds that usual ex ante commitment welfare dominates ex post regulation.

Requate [71], similar to Parry [58], looks at a monopolistic upstream innovator who with a certain probability invents a new, exogenously given abatement technology. The R&D effort determines the probability of success. In case of R&D success, the innovator produces the new technology at constant marginal cost. A large number of asymmetric polluting downstream firms decide whether or not to adopt the new technology. The incentive for both, to adopt new technology, and to engage in R&D, is analyzed for two policy instruments: auctioned permits and emission taxes. Moreover, four different timing and commitment scenarios are considered: firstly, ex post regulation after both R&D success and adoption of the new technology, secondly interim regulation, which means that the regulator commits to a tax rate or the permit policy after observing R&D success but before the innovator prices his new technology. Finally, two types of ex ante commitment strategies are considered, one with a single tax rate or quota of permits, the other one with a commitment to a *menu of tax rates* or quotas of permits contingent on R&D success. The main result is that commitment to a menu of tax rates dominates all other policies. Moreover, taxes are superior to permits for both interim regulation and commitment to a menu of policy levels contingent on R&D success. The reason is that under permits the effective inverse demand function for the new technology is more elastic than under taxes and thus the distortion is more severe under permits.

2.2.2.3 The Impact of Imperfect Competition on the Final Goods Market

The next group of papers investigates incentives to innovate with the special focus on imperfect competition on the output market. Katsoulacos and Xepapadeas [41] assume Cournot competition whereas Innes and Bial [38] assume Bertrand competition with homogenous goods. Montero [54] considers both the case of price competition with differentiated commodities and Cournot competiton.

Katsoulacos and Xepapadeas [41] study a Cournot duopoly with emissions proportional to output. Both firms are able to reduce their emissions-per-output ratio by investing into R&D and enjoy spillovers through the other firm's R&D effort. The regulator ex ante commits to both an emission tax and an R&D subsidy (which can also take negative values). The authors find that the optimal tax rate falls short of marginal damage while the optimal subsidy is positive if the spillover effects are sufficiently high, and negative otherwise. The intuition for this result is straightforward: on the one hand, firms tend to underinvest in R&D because the private return from R&D is smaller than the social return and because they do not account for consumers' surplus. On the other hand, firms strategically tend to overinvest in R&D in order to increase market shares.

Innes and Bial [38], by contrast, look at a Bertrand duopoly with homogenous products. Investing in R&D, the firms can find a certain incremental innovation that would lower both their marginal cost and their marginal abatement cost. Since R&D success is stochastic, no, one or both firm(s) might be successful. If firms are ex post symmetric, the regulator is able to implement efficient pricing, production and abatement by levying the corresponding Pigouvian tax. If, however, firms are ex post asymmetric, the regulator is not able to implement the first best allocation by levying a tax only. The emission tax that is optimal with respect to the new technology would enable the R&D winner to capture the entire market and produce less than efficient. The regulator can solve this problem by combining an emission tax lower than marginal damage with a non-uniform relative standard which requires the winner to comply with the first best standard and the loser with a laxer standard. The authors further look at a setting where the regulator is not able to costless observe R&D outcomes. Surprisingly, the regulator can induce the firms to truthfully report their technologies and thus can implement the first best allocation. For this purpose he ex ante commits to levy an emission tax and to set a non-uniform relative standard contingent on the firms' technology reports. Moreover he announces to monitor those firms that claim to be a loser of the R&D race but offer a positive output.

Building on his companion paper [53], Montero [54] allows for R&D spillovers and assumes imperfect competition on output and permit market throughout the analysis. He studies both Cournot and price competition with differentiated products. Besides emission standards and permits he also analyses emission taxes. Montero finds that there is no strategic effect when levying an emission tax, as the marginal cost of both firms is constant. Taxes can provide more, less, or the same incentive to invest in innovation than emission standards and auctioned permits, whereas free permits offer less incentive than taxes. With Bertrand competition on the output market, taxes provide a higher incentive than an emission standard which in turn provides a higher incentive than free permits. Auctioned permits again can offer more, less or the same incentive than taxes. Montero concludes, that in the Cournot case, either emission standards, taxes, or auctioned permits can provide the highest incentive whereas in the Bertrand case this holds either for taxes or for auctioned permits.

We would like to close this section by emphasizing a recent contribution by Parry et al. [60] who open up a somehow anti-innovative perspective by showing within a dynamic framework, including the aspect of time explicitly, that the net present value of the additional welfare gain from even optimally employing new technologies may be relatively small compared to optimally exploiting existing abatement opportunities, i.e optimal pollution control without innovation. Thus, they conclude: “These findings appear to contradict earlier assertions by some economists that technological advance might be more important than achieving optimal pollution control in the design of environmental policies.” (p.252)

3 Models with Growth, Exhaustable Resources and Pollution

Up to this point we have studied models with limited dynamics such as two- or three-stage models in the tradition of the theories of industrial organization and regulation. Technological progress is, of course, also an important issue in models of economic growth. The question of whether or not an exhaustible resource can be substituted by man-made capital, and whether or not a sustainable growth path with non-declining wealth is feasible, has been an important issue of research since the late seventies. Path breaking essays in this field are, among others, the works by Dasgupta and Heal [16], [17], Solow [84], and Stiglitz [85]. It would burst this survey to summarize all the special features and results of this early literature.[15] If at all, technological progress enters these models in an exogenous way, for example by assuming that technological progress is resource-augmenting. The issue of technological progress has enjoyed a new boost with the rise of *endogenous growth theory,* which, since the late nineties, was subsequently applied to questions of resource-saving and pollution-reducing technological progress.

In this realm of theories we can first of all distinguish between *one-sector* and *multi-sector models*. Among the latter we can further differentiate between *aggregated* and *disaggregated models*. In the following we will only briefly summarize the one-sector and the aggregated multi-sector models.[16] We will put more emphasis on the disaggregated multi-sector models since those, by modelling R&D explicitly, have a stronger link to the models of section 2.

3.1 One-Sector Growth Models

In the one-sector models aggregate output can either be consumed or converted into physical capital. Long-term growth is feasible due to constant returns to scale with respect to man-made factors of production. The models can be classified according to the respective engine of growth.

In the so called AK-models growth relies on the accumulation of capital.[17] The basic model is characterized by a production function that features constant returns to scale with respect to the only input, i.e. capital. Since the basic model does not allow for input substitution and for non-man-made factors entering the production function as essential inputs, most of the authors apply AK models to environmental and resource problems where the pollution is a by-product of capital. Among those Gradus and Smulders [29], Ligthart and van der Ploeg [47], [48], Smulders and Gradus [83], and Stokey [86] assume that an environmental damage is caused by a flow of pollution. Baranzini and Bourguignon [4], Withagen [93], Mohtadi [52], Chevé [15] study environmental problems through stocks of pollution. By contrast, Aghion and Howitt [2], and Groth and Schou [33] take into account renewable and non-renewable resources, respectively. A main result of this literature is that if there is a critical ecological threshold of pollution, or if the resource is non-renewable, the pollution intensity of production or the input intensity of the resource, respectively, must go to zero in order to guarantee unlimited growth in consumption. Aghion and Howitt and other authors identify conditions under which sustainable growth in the sense of non-declining utility is possible. The authors of this literature are less interested in the comparison of different policy instruments in order to spur technological progress.

In another type of one-sector models growth relies on positive externalities such as in Romer [75]. In this kind of model, investment in physical capital exerts an externality in the sense that knowledge spills over to a human capital stock ("learning by doing") which is a public good and is responsible for augmenting technological progress with respect to the non-reproducible factor. The following authors use such a model to analyze environmental or resource problems: Musu [55], van der Ploeg and Ligthart [87], Ligthart and van der Ploeg [48], Musu and Lines [56] set up models with renewable resources, whereas Michel and Rotillion [50] a model with pollution.

Barro [5] developed a model where growth relies on public spending. He incorporates two man-made production factors, i.e. physical capital and productive public spending. This approach has been applied to resource and environmental economics by Ligthart and van der Ploeg [47], [48], van der Ploeg and Ligthart [87], den Butter and Hofkes [18] for renewable resources and by Nielsen et al. [57]and Bovenberg and de Mooij [7] for pollution.

Finally, there are models that link one-sector and multi-sector models by considering physical and human capital that are accumulated separately but whose production technology is identical as e.g. Smulders [81], [82].

3.2 Aggregated Multi-Sector Growth Models

In contrast to the one-sector models, the multi-sector models allow for the input intensity of non-man-made factors to vary since the factors are used in different sectors/processes. The *aggregated multi-sector* models are characterized by several sectors of man-made goods (e.g. a physical capital/consumption good and human capital) that are accumulated separately and that are produced by different production technologies. Physical capital and human capital usually enter the production function as reproducible factors. Non-reproducible factors can be included as well. Knowledge is often assumed to be a public good and to be productivity augmenting. The "Uzawa-Lucas" model is an example for an aggregated multi-sector model. Here production of human capital is independent of physical capital. Applications of aggregated multi-sector models in Environmental and Resource Economics are the contributions of Gradus and Smulders [29], Bovenberg and Smulders [8], [9], Smulders [81], van Ewijk and Wijnbergen [88], Hofkes [36], Rosendahl [77], Byrne [13], Aghion and Howitt [2], and Schou [79]. The main issues of those models are, first, the trade-off between growth and environmental quality, secondly, conditions for feasible and sustainable development paths, thirdly, the question whether or not sustainable paths are optimal and vice versa, and last but not least the question how environmental policy instruments affect welfare.

3.3 Disaggregated Multi-Sector Growth Models

The *disaggregated multi-sector* models explicitly model the R&D sector. They highlight the microeconomic foundation behind investment in R&D and shed some light on the mechanisms leading to non-decreasing returns. The development of new varieties of capital, consumption, or intermediate goods constitutes technological progress. These new varieties can arise on a horizontal and on a vertical dimension. Both Romer [76] and Rivera-Batiz and Romer [74] explain endogenous growth by increasing horizontal product differentiation where innovation can be depicted as introduction of new final goods or of new types of intermediate or differentiated capital goods. In the first case, it is the households' preferences for diversity that gives rise to increasing returns, in the second case, it is the growing specialization that prevents the marginal product of reproducible factors from falling.

Grossman and Helpman [34] and Aghion and Howitt [1], by contrast, explain unlimited growth by vertical product differentiation where product quality of intermediate goods is improved through

R&D. Higher quality of intermediate products, in turn, boosts growth by being more efficient in production. The producer of an intermediate good is a monopolist and holds a patent for his innovation. Other firms engage in R&D to find a better product and substitute the former innovation by a new one. This process is sometimes called the “process of creative destruction.

Disaggregated multi-sector models have been applied to renewable resources by Grimaud [30], to non-renewable resources by Scholz and Ziemes [78], Bretschger [10], Bretschger and Smulders [11], Grimaud and Rougé [32], and finally by van Zon and Yetkiner [91] to a resource whose scarcity is indirectly considered by assuming that its price rises exogenously over time. Furthermore, it has been applied to accumulating pollution by Grimaud and Ricci [31], and to a mere flow of pollution by Hung et al. [37], Verdier [92] and Elbasha and Roe [23]. Schou [80] combines the aspects of depletion of a non-renewable resource and pollution. In table 3 we list the main features of all the different models. They have several features in common. There are usually two or three market imperfections. Even without the aspects of environmental amenities and depletion of exhaustible resources almost all the models work with the assumption of a monopolistic market structure for some intermediate good. The authors justify this assumption by innovation. Suppliers of new products usually earn a monopoly rent. The second market imperfection comes from the public good character of new ideas. The positive spillovers of new knowledge are usually not internalized. The third market imperfection is created by pollution, in case that this is included into the model. Depletion of resources, by contrast, does not cause market imperfections in this field of literature. The reason is that all authors assume that the property rights for the exhaustible resources are well defined (private ownership economies) and that the private rate of time preference does not differ from the social rate. Hence, if authors come to study decentralized economies, the same policy tools are applied throughout the literature in order to correct for those market imperfections: a subsidy for the monopolist who offers the intermediate good, a subsidy on R&D, usually paid as a subsidy on wages in the R&D sector, and a tax on the pollutant or the issuance of an equivalent amount of tradable emission permits. In the following section we summarize the results of selected papers in more detail.

3.4 Results of Particular Models with Non-Renewable Resource and/or Pollution

3.4.1 Resource-Saving Technological Progress in the Presence of a Non-Renewable Resource

Grimaud and Rougé [32] draw on the model of vertical innovation by Aghion and Howitt [1]. A non-renewable resource, necessary for production, enters the production function of the final-goods sector. Since there is no pollution, the utility depends on consumption only. The authors find that positive long-run growth is always positive if the R&D sector is sufficiently productive. In the steady-state, optimal and equilibrium growth rates can be negative or positive. Without policy intervention the growth path in the decentralized market equilibrium is not optimal. Two cases may occur: too little or too much growth. In the first case, the growth rate of resource extraction is less (greater) than optimal if the elasticity of marginal utility is lower (higher) than one. Excessive growth, by contrast, occurs only under a special parameter constellation. In this case both the output and the extraction growth rate may be greater than optimal if the elasticity of marginal utility is smaller than one. Optimal growth can be restored in a decentralized economy by subsidizing (taxing) the wage in the R&D sector in the case of too little (excessive) growth.

Scholz and Ziemes [78], by contrast, build on models of horizontal innovation. A non-renewable resource enters the production function of the final-goods sector. In the decentralized economy two market imperfections occur: the intermediate good is supplied by a monopolist, and the R&D firm neglects that the knowledge is a public good and raises labor productivity. Scholz und Ziemes do not study optimal growth but rather study the market solution only which turns out to be inefficient and is characterized by a too low rate of resource extraction. Despite these market failures, per capita consumption might grow in equilibrium if certain “technological prerequisites” are met. The authors further show that there may be multiple balanced growth paths. These indeterminacies may be caused by inefficient resource extraction. A necessary condition for indeterminacies in a growing economy is that the partial production elasticity of capital must be smaller than that of the exhaustible resource.

Van Zon and Yetkiner [91] combine horizontal and vertical innovation. Energy and capital are necessary to operate intermediate goods. Technological progress arises by developing new, more productive intermediates which, however, do not crowd out the previous intermediates immediately. Thus, productivity growth at the aggregate level is the result of both preference for more variety and for higher quality. Moreover, van Zon and Yetkiner allow for substitution of capital and energy. They assume that total energy supply is exogenous and that the energy price is growing at an exogenously given rate. The authors find that the growth rate depends positively on the rate of technological change and that it exceeds the growth rate of Romer's [76] model. Continuously rising real energy prices tend to slow down growth and lower the pace of introduction of new intermediates. This may be considered as surprising since it is often argued that scarcity of energy spurs technological progress, in particular energy-saving technological progress. In fact, however, energy taxes affect R&D efforts in a negative way. The authors nevertheless do introduce energy taxes in order to collect revenues which are then used to subsidize R&D directly. This indeed leads to higher growth but only as long as R&D activities are not too high.

In a more recent paper, Bretschger [10] demonstrates that sustainable development can be generated despite seemingly unfavourable conditions: inputs are poor substitutes, population grows at a positive rate, the supply of material is limited, and the non-renewable resource is an essential input for the R&D sector. In his model labor and the non-renewable resource are the primary inputs that are used in the R&D sector as well as in the intermediates sector. Similar to Romer [76] and Grossman and Helpman [34] innovation comes through an increasing variety of intermediates. Bretschger finds that despite the above mentioned unfavourable conditions, economic growth is possible if structural change and an increasing labor force are strong enough to sustain knowledge accumulation. If, however, labor reallocation between sectors is not fast enough, which may happen due to adjustment cost, wrong expectations or both, the innovation and per-capita consumption growth rates decrease over time. Hence, Bretschger's policy conclusion is that facilitating labor reallocation is the best approach to support sustainable development when there are adjustment costs.

In an extremely complex model Bretschger and Smulders [11] study how substitution possibilities and a limited supply of physical capital affects sustainability. Their work, too, draws on the models of horizontal innovation à la Romer [76] and Grossman and Helpman [34]. Primary inputs are a non-renewable resource and both skilled and unskilled labor. Moreover, there are two types of capital, homogenous and differentiated capital. Homogenous capital is produced by skilled labor only, whereas differentiated capital is produced by means of R&D and unskilled labor. R&D is created by skilled labor and public knowledge. Finally, there are two consumption goods, a standard and a high-tech good. The household's expenditure shares are assumed to be constant with respect to these goods. The standard good is produced by the non-renewable resource and homogenous capital, whereas the high-tech good is produced by the resource and differentiated capital. Thus, there is technological progress in one final good sector only. Further, resources can be substituted by man-made factors only. The assumption of two final goods sectors allows to account for the sectors to differ in their elasticities of substitution and for substitution between sectors. In the decentralized economy the usual market imperfections exist: monopoly power for differentiated capital and R&D spillovers. As a main result the authors find that long-run growth can be sustained under free market conditions even when elasticities of substitution between capital and resources are low and supply of physical capital is limited. Surprisingly, however, poor substitutability between homogenous capital and the non-renewable resource in the standard goods sector, which competes for skilled labor with the R&D sector, turns out to be favourable for growth. By contrast, and less surprising, strong dependence on non-renewable resources in the sector that employs the innovations, i.e. the high-tech good sector, is bad for growth.

3.4.2 Pollution-Reducing Technological Progress

Hung et al. [37] belong to the first authors who applied endogenous growth theory to issues of pollution and pollution-reducing technological progress. They build on Romer's [76] model of horizontal innovation. Besides labor, the final good it produced by clean and dirty intermediate inputs, where the latter cause pollution. The authors abstract from accumulation of the pollutant. Thus, only the flow of emissions causes environmental damage and disutility to the consumers. For both intermediates there is an R&D sector with firms which try to develop a better design for the intermediate goods, whereas R&D does not affect the "cleanliness" of the dirty intermediates. R&D success is stochastic and the firms have to pay fixed research cost. Production and develpment cost of the clean and dirty intermediate may differ. In the decentralized economy the three meanwhile well know market imperfections occur: monopolistic competition on the intermediate goods sector, positive R&D spillovers, and pollution. As a main result the authors find that the balanced growth equilibrium is unstable, whereas the only stable equilibria are those of unbalanced growth where either the clean or the dirty sector is growing. Hence, the authors compare the growth rates of five different scenarios: market equilibria with the clean or with the dirty sector growing, social optima with clean or with the dirty sector growing, and finally socially optimal growth without environmental concern ("second best solution"). The authors show that the market equilibrium growth rate might be lower than the first best growth rate. Thus, pollution control is not necessarily detrimental to growth. Pittel [65] (p. 78) criticizes that whether or not research will or should take place in the clean, in the dirty, or even in both sectors, is completely independent of consumer preferences for the environment. Rather, specialization in clean or dirty R&D is entirely due to initial cost differentials in the R&D sectors.

Verdier [92] also considers horizontal innovation, drawing on Grossman and Helpman. [34]. However, more variety arises in the final goods sector rather than at the intermediate goods level. It is also the final goods that cause the pollution: each variety of a final good is characterized by a certain constant emissions-per-output ratio. Pollution affects the consumers' utility. R&D firms create new products and also choose their emissions-per-output ratio. At this end cleaner products are more costly to develop. However, as the stock of knowledge increases, it becomes less costly in terms of labor to develop a new product with a certain emissions-per-output ratio. Thus, there is a trade-off between growth of product variety and “cleanliness” of the products to be developed. In the decentralized economy Verdier introduces an R&D-subsidy and either an emission tax or a performance standard (fixed emissions-per-output ratio).[18] The authors show that, while emission taxes need not be detrimental to economic growth, a performance standard has a negative effect on growth. Comparing the two regimes, the authors find that the performance standards are less cost effective than emission taxes and that under emission taxes less resources are used for production and thus more resources are available for R&D whereas more resources are used in production under performance standards. First-best can be implemented by combining an R&D subsidy with either an emission tax or a performance standard, where the subsidy is higher in the latter case. When the regulator is not able to pay an R&D subsidy and the emission tax and performance standard are set to implement a fixed emission level, the ranking of the instruments is not that clear-cut.

Elbasha and Roe [23] analyze the link between innovation, trade, growth, and environmental quality. They also draw on horizontal innovation in the tradition of Grossman and Helpman [34], Romer [76], and Rivera-Batiz&Romer [74] where the range of intermediates is expanded. Elbasha and Roe consider a Heckscher-Ohlin like model with capital and labor as primary input factors and two traded goods. They distinguish two scenarios with respect to pollution: emissions are either proportional to aggregate output of the final good or they are generated when using intermediate inputs. The flow of emissions affects utility of consumers in a negative way. The authors find that long-run growth increases with the country’s endowments, -the productivity of R&D, the elasticity of intertemporal substitution, with a smaller rate of time preference, and a smaller elasticity of substitution between the intermediates. Further they find that consumer’s care about environment might slow down, promote, or might not affect growth. The effects of trade on both environmental quality and welfare are ambiguous. Moreover, the growth rate in the decentralized economy can be smaller or greater than the optimal growth rate. In the balanced growth equilibrium, however, the decentralized growth rate is below the optimal rate. If emissions are proportional to aggregate output, environmental quality decays at a constant rate along the balanced growth path. For the alternative approach: environmental quality may decay, stay constant or improve at a constant rate. In the case where emissions are proportional to aggregate output and where a decentralized growth path is below the optimal path, the authors derive the second best levels of different growth enhancing policy instruments such as an R&D subsidy and an output subsidy. By contrast to other papers cited above, the authors do not focus on sustainability. Hence, in the long run optimal growth may be associated with a decrease in welfare. In a numerical application of the model the authors allow for an abatement technology which becomes more effective with a higher stock of knowledge. Here they find that trade promotes growth but worsens environmental quality and that the decentralized growth path is below the optimal one. If the more capital-intensive sector, which is an importer, has to pay an emission tax, then growth increases. If the other sector has to pay an emission tax, the reverse holds true.

Grimaud [30] disaggregates the model by Aghion and Howitt [2] and focuses on policy instruments in order to implement the first best sustainable growth path. Grimaud, too, identifies the usual three distortions: the intermediate goods are produced by monopolists, knowledge is a public good, and pollution in production causes an externality on consumers, and he proposes a subsidy on the purchase of intermediates, an R&D subsidy, and a free allocation of tradable emission permits in order to restore efficiency. He finds that for each triplet of instruments there exists a balanced growth path. The different paths generated by the different levels of instruments display exhibit a trade-off between environmental quality and growth. For the socially optimal growth path the number of permits decrease progressively. Therefore pollution decreases, while the price of permits increases. The impact of environmental policy on growth is as we would expect it to be: reducing the number of permits has a negative impact on the growth of output since the production sector must cope with less amounts of the polluting inputs. Moreover, the value of patents decreases by depressing demand for intermediate goods whereas the marginal cost of R&D falls. Note, that the final effect hinges on the assumption that pollution is caused by output. Hence, no substitution from dirty to clean inputs is possible.

Grimaud and Ricci [31] compare the decentralized economy in the model of horizontal innovation à la Romer [76] to the one in the model of vertical innovation à la Grossman and Helpman [34] and Aghion and Howitt [1]. In both models an accumulating pollutant is an implicit input to production with an elasticity of substitution equal to one. The utility function is additively separable in consumption and environmental amenities that depends on the stock of pollution and the natural rate of assimilation. As usual the set of policy tools is given by a subsidy to the monopolistic supplier of the input, an R&D subsidy, and instead of permits, an emission tax to cope with pollution. Among the different growth paths generated by different levels of the policy instruments, we again face a trade-off between economic growth and environmental quality, i.e. a higher growth rate of output is associated with a higher growth rate of the pollution stock. Moreover, along a balanced growth path, subsidies are constant and emission taxes increase at a constant rate. For equal levels of the policy tools, the growth rate of output is higher in the vertical innovation than in the model of horizontal innovation. The optimal R&D subsidy with respect to strong sustainability is greater in the model of horizontal innovation than in the model of vertical innovation. The same results hold if the regulator issued free permits instead of levying emission taxes.

3.4.3 Pollution-Reducing cum Resource-Saving Technological Progress

Schou [80] also draws on Romer's model of horizontal innovation and combines the issues of resource extraction and pollution. Research improves productivity and growth. A non-renewable resource enters the production function of the final-goods sector, but extraction of the resource causes pollution. The author abstracts from both accumulation of physical capital and accumulation of the pollutant which as a flow variable negatively affects the consumer's utility. The assumption of constant elasticity of marginal utility of both consumption and pollution is a necessary condition for balanced growth paths to be optimal (see Bovenberg and Smulders [8]). Schou finds that although positive growth is optimal, consumption on the optimal balanced growth path either grows or declines as utility improves even though consumption declines. The reason is that environmental improvements compensate for the decline in consumption. Pollution necessarily diminishes over time (since it is generated by a non-renewable resource). In the market economy knowledge and consumption growth rates are suboptimal and growth may be negative even though positive growth is feasible. There are the familiar three sources of market failure: monopolistic supply of the intermediate good, knowledge spill-over through R&D, and pollution. An R&D subsidy together with a subidy for the purchase of intermediates implements the optimal path. The pollution externality has no distortionary effect as it is always optimal to extract all of the resource stock, and therefore, the rate of change of the resource price over time is not distorted. Thus, an environmental policy like emission taxes is unnecessary. If the marginal utility of consumption is greater than one, there will be a "win-win" situation when subsidies are used as described above: knowledge and consumption growth rise and long run environmental conditions are improved.

4 Conclusions

We have surveyed the literature on pollution-reducing and resource-saving technological progress. The literature can be divided into two branches, the microeconomic partial equilibrium models which focus on the timing and commitment of regulation, on the comparison of different policy instruments, and on the impact of different market structures whereas the second branch focuses on growth and technological progress in the framework of endogenous growth theory. Concerning the microeconomic models the main conclusion is that instruments which provide incentives through the price mechanism by and large perform better than command and control policies. Even though, it is important that the regulator either anticipates the new technologies to a certain extent or that he reacts in an optimal way on invention and adoption of new technology. Under competitive conditions and perfect foresight, different authors established the result that ex ante commitment and ex post optimal policies generate equivalent or at least similar allocations. Under imperfect market conditions, the policy conclusions are less clear cut. Under myopic environmental policies or long term commitment to the levels of policy instruments, by contrast, emission taxes tend to provide a stronger incentive to invest in both R&D and adoption of new technology as compared to permits. The reason is that the permit price falls if new technology diffuses, providing a lower incentive for firms with old technology to invest in pollution-reducing technology.

With respect to the growth models the bottom line is that the bulk of models shows that, unless pollution affects productivity in a negative way, a policy which improves environmental conditions lowers the growth rate of physical consumption/capital goods at the same time. Moreover, the different market imperfections can be treated separately by three instruments: a subsidy on skilled labor in R&D in order to account for positive R&D spillovers, an output subsidy on intermediate, innovative products in order to cope with market power on new products which are subject to patent protection, and either pollution taxes or tradable permits to deal with pollution.

The issue of timing and interaction between the regulator and the innovator is generally not studied in the growth literature. Usually the implicit assumption on timing in the growth literature is that the regulator acts like a Stackelberg leader by committing to a whole path of tax or subsidy rates. Dynamic interaction between innovators and a regulator, as studied in detail in the static, or restrictedly dynamic microeconomic models, is much more difficult to analyze since it calls for dynamic game theoretical concepts for models with infinite time horizon. Nevertheless such analysis is important and will hopefully be subject of further research.

Notes

Obviously, this distinction is not sharp since new production processes also require new products and vice versa.

We abstract from traditional market failures such as monopoly and monopsony power on markets for primary resources.

Among economists there is no general agreement about the gap between social and private discount rates and thus on the claim that non-renewable resources are under-estimated by market prices. Our view on this dispute is that the first two issues, the common pool problem and pollution, are at least more severe than the problem of discrepancy between the social and the private discount rate.

In reality, the MAC function is in general piecewise linear. E.g. a scrubber might be able to abate 70%-80% of SO_2 emissions, whereas a cheaper technology might be able to abate 60%-70%. In the literature it is mostly assumed that there are sufficiently many pollution-reducing technologies, such that a firm´s real abatement cost function can be approximated by a continuous function.

To become a bit more formal we denote by $C(q,e)$ the joint costs which a typical firm incurs to produce q units of output with no more than e units of emissions. For this definition it is not relevant, whether the firm has an end-of-pipe or an integrated technology. The firm's profit is then given by $\pi(q,e) = pq - C(q,e)$. In the absence of regulation the competitive firm chooses q and e such that $C_q(q,e) = p$ and $C_e(q,e) = 0$, providing a maximal profit $\pi_{\max}$ and an emission level $e_{\max} = e(q)$. It is plausible to assume $C_q > 0$, $C_{qq} \geq 0$, $-C_e(q,e) < 0$ for $e < e(q)$ and $C_{ee} > 0$. We refer to $-C_e(q,e)$ as the marginal abatement costs. If now the firm is constrained to emit no more than e units of the pollutant, the rule $C_q(q,e) = p$ induces some output $q(e)$ and a reduced profit $\tilde{\pi}(e) = pq(e) - C(q(e),e)$. The full abatement cost can then be defined as $C(e) = \pi_{\max} - \tilde{\pi}(e)$, which is the forgone profit resulting from reducing emissions from $e_{\max}$ to e. It is easy to show that the reduced abatement cost function $C(e)$ has the same properties as $C(q,e)$ with respect to e.

The above formula refers to a system of auctioned permits. In case of free permits we would have $C_I(e_I) + p[e_I - \hat{e}] + F < C_0(e_0) + p[e_0 - \hat{e}]$ where $\hat{e}$ is the initial endowment of permits. If the adopting firms cannot influence the price of permits, this last relationship is equivalent to (1).

The shift of the marginal abatement cost function through new technology needs, of course, not necessarily be a parallel one.

If the phases of R&D and adoption can be separated, there is also the possibility of interim regulation. Requate [71] considers such a scenario.

In a second scenario Requate and Unold [73] study ex ante and ex post regulation, where the regulator anticipates and takes the new technology into account.

Although the authors use the term „precommitment“, we prefer to talk about ex ante commitment.

In earlier papers also Hahn [35] and Requate [66], [67], [68] allow for imperfectly competitive permit markets. They do not, however, focus on innovation and technological progress.

In a recent comment on Montero[53], Bruneau [12] holds the view that performance standards generate a greater incentive to innovate than permits even under perfect competition. Moreover, he extends Montero's analysis to the case of increasing marginal costs and argues that in this case both auctioned and free permits dominate performance standards. Bruneau, however, neither carries out a complete equilibrium analysis nor a welfare comparison, and thus does not rank the instruments with respect to total social costs or welfare. Since performance standards lead to inefficient abatement levels in the static case, it cannot be ruled out that they lead to inefficiently high investment.

Trading of permits thus implies that the buyer (seller) of a permit buys (sells) a whole stream of emissions over time. Such a scheme may discourage trade if there is uncertainty about the future value of permits and if traders are risk averse.

The authors refer to the regulator's commitment after R&D but before adoption as ex post regulation.

The interested reader is referred to Pezzey and Toman [63].

We adopted this classification from Pittel [65].

The term "AK model", or "A-times-K-model" refers to the assumption that the aggregate production function is linear in the stock of capital, and thus, by contrast to the famous Solow model, does not exhibit decreasing returns to scale.

Besides the usual knowledge spillovers there are two more imperfections through R&D in this model: first the "consumer-surplus effect" since innovators do not fully take into account the increase of consumer surplus coming from creation of new products, secondly, the "profit destruction effect" since the innovator does not consider the destructive effect on the profits of other firms. By the special assumption of Dixit-Stiglitz-CES preferences the two effects cancel out and the regulator has to correct for only two market failures.

5 References

1. Aghion, P. and P. Howitt (1992) ‘A Model of Growth Through Creative Destruction’, *Econometrica*, Vol. 60, No. 2, pp. 323-351.

Aghion, P. and P. Howitt (1998) *Endogenous Growth Theory*, MIT Press.

Amacher, G.S. and A.S. Malik (2002) ‘Pollution Taxes When Firms Choose Technologies’, *Southern Economic Journal*, Vol. 68, No. 4, pp. 891-906.

Baranzini, A. and F. Bourguignon (1995) ‘Is Sustainable Growth Optimal?’, *Internatinoal Tax and Public Finance*, Vol. 2, No. 2, pp. 341-356.

Barro, R.J. (1990) ‘Government Spending in a Simple Model of Endogenous Growth’, *Journal of Political Economy*, Vol. 98, No. 5, pp. 103-125.

Biglaiser, G. and J.K. Horowitz (1995) ‘Pollution Regulation and Incentives for Pollution-Control Research’, *Journal of Economics and Management Strategy*, Vol. 3, No. 4, pp. 663-684.

Bovenberg, A.L. and R.A. de Mooij (1997) ‘Environmental Tax Reform and Endogenous Growth’ *Journal of Public Economics*, Vol. 63, No. 2, pp. 207-237.

Bovenberg, A.L. and S.A. Smulders (1995) ‘Environmental Quality and Pollution-Augmenting Technological Change in a Two-Sector Endogenous Growth Model’, *Journal of Public Economics*, Vol. 57, No. 3, pp. 369-391.

Bovenberg, A.L. and S.A. Smulders (1996) ‘Transitional Impacts of Environmental Policy in an Endogenous Growth Model’, *International Economic Review*, Vol. 37, No. 4, pp. 861-893.

Bretschger, L. (2003) ‘Sustainable development under seemingly unfavourable conditions’, *ETH Zurich, Economics Working Paper Series, Working Paper* 03/29.

Bretschger, L. and S. Smulders (2003) ‘Sustainability and Substitution of Exhaustible Natural Resources: How Resource Prices Affect Long-Term R&D Investments’, *Tilburg University, CentER, Discussion Paper* 71.

Bruneau, J.F. (2004) ‘A note on permits, standards, and technological innovation’, forthcomin in: *Journal of Environmental Economics and Management*.

Byrne, M.M. (1997) ‘Is Growth a Dirty Word? Pollution, Abatement and Endogenous Growth’, *Journal of Development Economics*, Vol. 54, No. 2, pp. 261-284.

Carraro, C. and A. Soubeyran (1996) ‘Environmental Policy and the Choice of Production Technology’, in: Carraro, C., Y. Katsoulacos and A. Xepapadeas (eds.), *Environmental policy and market structure*, Kluwer Academic Publishers, pp. 151-180.

Chevé, M. (2000) ‘Irreversibility of Pollution Accumulation: New Implications for Sustainable Endogenous Growth’, *Environmental and Resource Economics*, Vol. 16, No. 1, pp. 93-104.

Dasgupta, P.S. and G.M. Heal (1974) ‘The Optimal Depletion of Exhaustible Resources’, *Review of Economic Studies, Symposium*, pp. 3-28.

Dasgupta, P.S. and G.M. Heal (1979) *Economic Theory and Exhaustible Resources*, Cambridge University Press.

den Butter, F.A.G. and M.W. Hofkes (1995) ‘Sustainable Development with Extractive and Non-Extractive Use of the Environment in Production’, *Environmental and Resource Economics*, Vol. 6, No. 4, pp. 431-358.

Denicolò, V. (1999) 'Pollution-reducing innovations under taxes or permits', *Oxford Economic Papers*, Vol. 51, No. 1, pp. 184-199.

Dixit, A. and R. Pindyck (1994) *Investment under Uncertainty*, Princeton University Press.

Doraszelski, U. (2001) 'The Net Present Value Method versus the Option Value of Waiting: A Note on Farzin, Huisman, and Kort (1998)', *Journal of Economic Dynamics and Control*, Vol. 25, No. 8, pp. 1109-1115.

Downing, P.B. and L.J. White (1986) 'Innovation in Pollution Control', *Journal of Environmental Economics and Management*, Vol. 13, No. 1, pp. 18-29.

Elbasha, E.H. and T.L. Roe (1996) 'On Endogenous Growth: The Implications of Environmental Externalities', *Journal of Environmental Economics and Management*, Vol. 31, No. 2, pp. 240-268.

Farzin, Y.H. (1996) 'Optimal pricing of environmental and natural resource use with stock externalities', *Journal of Public Economics*, Vol. 62, No. 1-2, pp. 31-57.

Farzin, Y.H., K. Huisman, and P. Kort (1998) 'Optimal Timing of Technology Adoption', *Journal of Economic Dynamics and Control*, Vol. 22, No. 5, pp. 779-799.

Fischer, C., I.W.H. Parry and W.A. Pizer (2003) 'Instrument Choice for Environmental Protection When Technological Innovation Is Endogenous', *Journal of Environmental Economics and Management*, Vol. 45, No. 3, pp. 523-545.

Gersbach, H. and A. Glazer (1999) 'Markets and Regulatory Hold-Up Problems', *Journal of Environmental Economics and Management*, Vol. 37, No. 2, pp. 151-164.

Gersbach, H. and T. Requate (2004) 'Emission Taxes and Optimal Refunding Scheme', *Journal of Public Economics*, Vol. 88, No. 3-4, pp. 713-725.

Gradus, R. and S. Smulders (1993) 'The Trade-Off Between Environmental Care and Long-Term Growth: Pollution in Three Prototype Growth Models', *Journal of Economics*, Vol. 58, No. 1, pp. 25-51.

Grimaud, A. (1999) 'Pollution Permits and Sustainable Growth in a Schumpeterian Model', *Journal of Environmental Economics and Management*, Vol. 38, No. 3, pp. 249-266.

Grimaud, A. and F. Ricci (1999) 'The Growth-Environment Trade-Off: Horizontal vs Vertical Innovations', *FEEM, Nota di Lavoro* 34/99.

Grimaud, A. and L. Rougé (2003) 'Non-renewable resources and growth with vertical innovations: optimum, equilibrium and economic policies', *Journal of Environmental Economics and Management*, Vol. 45, No. 2S, pp. 433-453.

Groth, C. and P. Schou (2002) 'Can Non-Renewable Resources Alleviate the Knife-Edge Character of Endogenous Growth?', *Oxford Economic Papers*, Vol. 54, No. 3, pp. 386-411.

Grossman, G.M. and E. Helpman (1991) *Innovation and Growth in the Global Economy*, MIT Press.

Hahn, R.W. (1984) 'Market Power and Transferable Property Rights', *Quarterly Journal of Economics*, Vol. 99, No. 4, pp. 753-765.

Hofkes, M.W. (1996) 'Modelling Sustainable Development: an Economy-Ecology Integrated Model', *Economic Modelling*, Vol. 13 ,No. 3, pp. 333-353.

Hung, V.T.Y., P. Chang and K. Blackburn (1994) 'Endogenous Growth, Envrionment and R&D', in Carraro, C. (ed.), *Trade, Innovation, Environment*, Kluwer Academic Publishers, pp. 241-258.

Innes, R. and J.J. Bial (2002) 'Inducing Innovation in the Environmental Technology of Oligopolistic Firms', *Journal of Industrial Economics*, Vol. 50, No. 3, pp. 265-287.

Jaffe, A.B., R.G. Newell and R.N. Stavins (2002) 'Environment Policy and Technological Change', *Environmental and Resource Economics*, Vol. 22, No. 1-2, pp. 41-69.

Jung, C., K. Krutilla and R. Boyd (1996) 'Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives', *Journal of Environmental Economics and Management*, Vol. 20, No. 1, pp. 95-111.

Katsoulacos, Y. and A. Xepapadeas (1996) 'Environmental Innovation, Spillovers and Optimal Policy Rules', in: Carraro, C., Y. Katsoulacos and A. Xepapadeas (eds.), *Environmental policy and market structure*, Kluwer Academic Publishers, pp. 143-150.

Kemp, R. (1997) Environmental Policy and Technical Change: A Comparison of the Technological Impact of Policy Instruments, Edward Elgar.

Kennedy, P.W. (1999) 'Learning about environment damage: implications for emissions trading', *Canadian Journal of Economics*, Vol. 32, No. 5, pp. 1313-1327.

Kennedy, P.W. and B. Laplante (1999) 'Environmental Policy and Time Consistency: Emission Taxes and Emissions Trading', in: Petrakis, E., E.S. Sartzetakis and A. Xepapadeas (eds.): *Environmental regulation and market power: Competition, time consistency and international trade*, Edward Elgar, pp. 116-144.

Laffont, J.-J. and J. Tirole (1996a) 'Pollution Permits and Compliance Strategies', *Journal of Public Economics*, Vol. 62, No. 1-2, pp. 85-125.

Laffont, J.-J. and J. Tirole (1996b) 'Pollution permits and environmental innovation', *Journal of Public Economics*, Vol. 62, No. 1-2, pp. 127-140.

Ligthart, J.E. and F. van der Ploeg (1994) 'Pollution, the Cost of Public Funds and Endogenous Growth', *Economic Letters*, Vol. 46, No. 4, pp. 339-349.

Ligthart, J.E. and F. van der Ploeg (1995) 'Environmental Quality, Public Finance and Sustainable Growth' in: Carraro, C and J.A. Filar (eds.), *Control and Game-Theoretic Models of the Environment*, pp. 141-173.

Malueg, D.A. (1989) 'Emission Credit Trading and the Incentive to Adopt New Pollution Abatement Technology', *Journal of Environmental Economics and Management*, Vol. 16, No. 1, pp. 52-57.

Michel, P. and G. Rotillion (1995) 'Disutility of Pollution and Endogenous Growth', *Environmental and Resource Economics*, Vol. 6, No. 3, pp. 279-300.

Milliman, S.R. and R. Prince (1989) 'Firm Incentives to Promote Technological Change in Pollution Control', *Journal of Environmental Economics and Management*, Vol. 17, No. 3, pp. 247-265.

Mohtadi, H. (1996) 'Environment, Growth, and Optimal Policy Design', *Journal of Public Economis*, Vol. 63, No. 1, pp. 119-140.

Montero, J.-P. (2002a) 'Permits, Standards, and Technology Innovation', *Journal of Environmental Economics and Management*, Vol. 44, No. 1, pp. 23-44.

Montero, J.-P. (2002b) 'Market Structure and Environmental Innovation', *Journal of Applied Economics*, Vol. 5, No. 2, pp. 293-325.

Musu, I. (1994) 'Sustainable Economy and Time Preference', *Structural Change and Economic Dynamics*, Vol. 5, No. 1, pp. 81-86.

Musu, I. and M. Lines (1995) 'Endogenous Growth and Environmental Preservation' in: Boero, G. and A. Silberston (eds.), *Environmental Economics: Proceedings of the European Economic Association at Oxford 1993*, St. Martin's Press, pp. 273-286.

Nielsen, S.B., L.H. Pedersen and P.B. Sørensen (1995) 'Environmental Policy, Pollution, Unemployment, and Endogenous Growth', *International Tax and Public Finance*, Vol. 2, No. 2, pp. 185-205.

Parry, I.W.H. (1995) 'Optimal pollution taxes and endogenous technological progress', *Resource and Energy Economics*, Vol. 17, No. 1, pp. 69-85.

Parry, I.W.H. (1998) 'Pollution Regulation and the Efficiency Gains from Technological Innovation', *Journal of Regulatory Economics*, Vol. 14, No. 3, pp. 229-254.

Parry, I.W.H., W.A. Pizer and C. Fischer (2003) 'How Large are the Welfare Gains from Technological Innovation Induced by Environmental Policies?', *Journal of Regulatory Economics*, Vol. 23, No 3, pp. 237-255.

Petrakis, E. and A. Xepapadeas (1999) 'Does Governmental Precommitment Promote Environmental Innovation?', in: Petrakis, E., E.S. Sartzetakis and A. Xepapadeas (eds.): *Environmental regulation and market power: Competition, time consistency and international trade*, Edward Elgar, pp. 145-61.

Petrakis, E. and A. Xepapadeas (2003) 'Location Decisions of a Polluting Firm and the Time Consistency of Environmental Policy', *Resource and Energy Economics*, Vol. 25, No. 2, pp. 197-214.

Pezzy, J.C.V. and M.A. Toman (eds.) (2002), *The Economics of Sustainability*, Ashgate.

Phaneuf, D.J. and T.Requate (2002) 'Incentives for Investment in Advanced Pollution Abatement Technology in Emission Permit Markets with Banking', *Environmental and Resource Economics*, Vol. 22, No. 3, pp. 369-390.

Pittel, K. (2002) Sustainability and Endogenous Growth, Edward Elgar.

Requate, T. (1993a) 'Pollution Control in a Cournot Duopoly via Taxes or Permits', *Journal of Economics*, Vol. 58, No. 3, pp. 255-91.

Requate, T. (1993b) 'Pollution Control under Imperfect Competition: Asymmetric Bertrand Duopoly with Linear Technologies', *Journal of Institutional and Theoretical Economics*, Vol. 149, No. 2, pp. 415-442.

Requate, T. (1993c) 'Equivalence of Effluent Taxes and Permits for Environmental Regulation of Several Local Monopolies', *Economics Letters*, Vol. 42, No. 1, pp. 91-95.

Requate, T. (1995) 'Incentives to Adopt New Technologies under Different Pollution-Control Policies', *International Tax and Public Finance*, Vol. 2, No. 2, pp. 295-317.

Requate, T. (1997) 'Green Taxes in Oligopoly If the Number of Firms is Endogenous', *Finanzarchiv*, Vol. 54, No. 2,pp. 261-280.

Requate, T. (2004) 'Commitment and Timing of Environmental Policy, Adoption of New Technology, and Repercussions on R&D', forthcoming in: *Environmental and Resource Economics*.

Requate, T. and W. Unold (2001) 'On the Incentives Created by Policy Instruments to Adopt Advanced Abatement Technology If Firms Are Asymmetric', *Journal of Institutional and Theoretical Economics,* Vol. 157, No. 4, pp. 536-554.

Requate, T. and W. Unold (2003) ‘Environmental Policy Incentives to Adopt Advanced Abatement Technology: Will the True Ranking Please Stand Up?’, *European Economic Review*, Vol. 47, No. 1, pp. 125-146.

Rivera-Batiz, L.A. and Romer, P.M. (1991) ‘Economic Integration and Endogenous Growth’, *Quarterly Journal of Economics*, Vol. 106, No. 2, pp. 531-556.

Romer, P.M. (1986) ‘Increasing Returns and Long-Run Growth’, *Journal of Political Economy*, Vol. 94, No. 5, pp. 1002-1037.

Romer, P.M. (1990) ‘Endogenous Technological Change’ *Journal of Political Economy*, Vol. 98, No. 5, pp. 71-102.

Rosendahl, K.E. (1996) ‘Does improved environmental policy enhance economic growth?’, *Environmental and Resource Economics*, Vol. 9, No. 3, pp. 341-364.

Scholz, C.M. and G. Ziemes (1999) ‘Exhaustible Resources, Monopolistic Competition, and Endogenous Growth’, *Environmental and Resource Economics*, Vol. 13, No. 2, pp. 169-185.

Schou, P. (2000) ‘Polluting Non-Renewable Resources and Growth’, *Environmental and Resource Economics*, Vol. 16, No. 2, pp. 211-227.

Schou, P. (2002) ‘When Environmental Policy is Superfluous: Growth and Polluting Resources’, *Scandinavian Journal of Economics*, Vol. 104, No. 4, pp. 605-620.

Smulders, S. (1995) ‘Environmental Policy and Sustainable Economic Growth: An Endogenous Growth Perspective’, *De Economist*, Vol. 143, No. 2, pp. 163-195.

Smulders, S. (1998) ‘Technological Change, Economic Growth and Sustainability’ in: van den Bergh, J.C.J.M. and M.W. Hofkes (eds.) *Theory and Implementation of Economic Models for Sustainable Development*, Kluwer Academic Publishers, pp. 39-65.

Smulders, S. and R. Gradus (1996) ‘Pollution Abatement and Long-Term Growth’ *European Journal of Political Economy*, Vol. 12, No. 3, pp. 505-532.

Solow, R.M. (1974) ‘Intergenerational Equity and Exhaustible Resources’, *Review of Economic Studies, Symposium*, pp. 29-45.

Stiglitz, J.E. (1974) ‘Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths’, *Review of Economic Studies*, *Symposium*, pp. 123-137.

Stokey, N.L. (1998) ‘Are there Limits to Growth?’, *International Economic Review*, Vol. 39, No. 1, pp. 1-31.

van der Ploeg, F. and J.E. Ligthart (1994) ‘Sustainable Growth and Renewable Resources in the Global Economy’, in: Carraro, C. (ed.), *Trade, Innovation, Environment*, Kluwer Academic Publishers, pp. 259-280.

van Ewijk, C. and S. van Wijnbergen (1995) ‘Can Abatement Overcome the Conflict between Environment and Economic Growth?’, *De Economist*, Vol. 143, No. 2, pp. 197-216.

van Soest, D.P. (2003) ‘The Impact of Policy Instruments on the Adoption of Energy Saving Technologies under Uncertainty’, *mimeo*.

van Soest, D.P. and E.H. Bulte (2001) ‘Does the Energy-Efficiency Paradox Exist? Technological Progress and Uncertainty’, *Environmental and Resource Economics* Vol. 18, No. 1, pp. 101-112.

van Zon, A. and I.H. Yetkiner (2003) ‘An endogenous growth model with embodied energy-saving technical change’, *Resource and Energy Economics*, Vol. 25, No. 1, pp. 81-103.

Verdier, T. (1995) 'Environmental Pollution and Endogenous Growth: A Comparison Between Emission Taxes and Technological Standards', in Carraro, C. and J.A. Filar (eds.), *Control and Game Theoretic Models of the Environment*, Birkhäuser, pp. 175-200.

Withagen, C. (1995) 'Pollution, Abatement and Balanced Growth', *Environmental and Resource Economics*, Vol. 5, No. 1, pp.1-8.

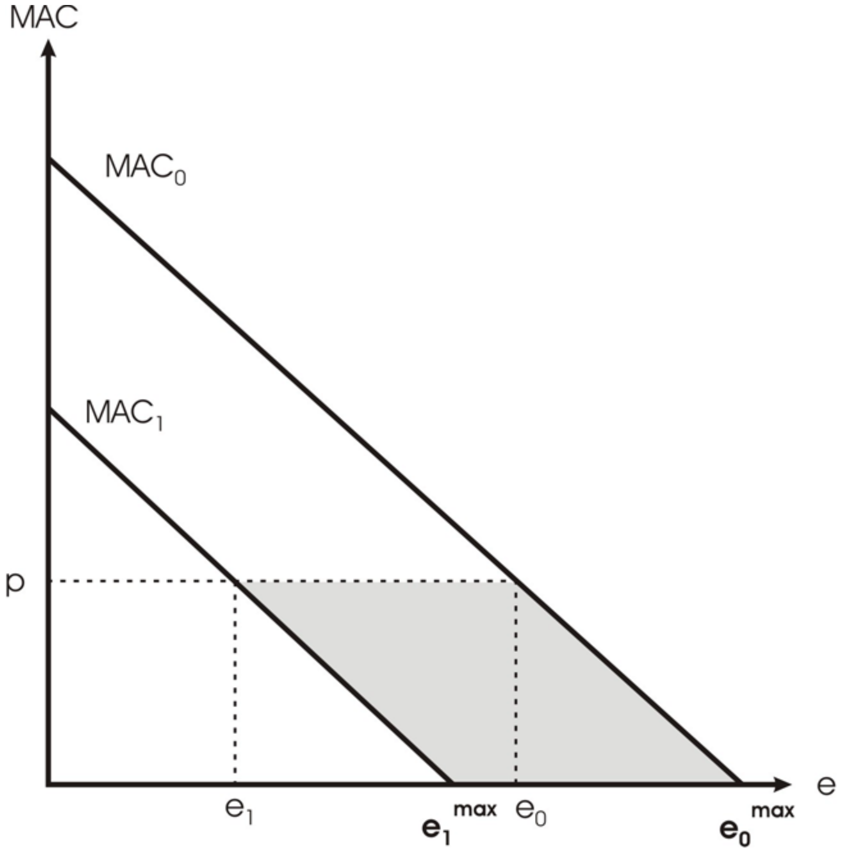

Figure 1: Change of an Adopting Firm’s Compliance Costs under Emission Taxes

Authors	Policy Instruments	Timing of Game/ Behavior of Regulator	Special Attention to Output Market	Special Other Features
Amacher & Malik (2002)	Emission Taxes	Ex Ante, Ex Post	No	Single Firm Only; Two New Technologies
Carraro &Soubeyran (1996)	Adoption Subsidies and Discriminatory Emission Taxes	Ex Ante	Yes	Two New Technologies; (Un)limited Supply of Clean Plants
Downing&White (1986)	Emission Taxes, Abatement Subsidies, Emission Standards, Free Permits	Myopic	No	
Jung et al. (1996)	Emission Taxes, Abatement Subsidies, Emission Standards, Auctioned Permits, Free Permits	Myopic	No	
Gersbach & Glazer (1999)	Free Permits	Ex Post	Yes	Imperfect Competition on Output Market; Hold-Up Problem
Kennedy (1999)	Free/Auctioned Permits and Adjustment Rule	Ex Ante	No	Uncertainty about Damage; Permits Do Not Expire
Kennedy & Laplante (1999)	Emission Taxes, Permits	Ex Ante, Ex Post	No	
Laffont & Tirole (1996a)	Permits, Permits and Futures, Permits and Price Support Policy/Options	Ex Ante	No	Shadow Cost of Public Funds Included; Uncertainty about Firms' Valuation of Emitting
Milliman & Prince (1989)	Emission Taxes, Abatement Subsidies, Auctioned Permits, Free Permits, Emission Standards	Myopic	No	
Malueg (1989)	Permits	Myopic	No	
Montero (2002a)	Auctioned Permits, Free Permits, Emission Standards, Performance Standards	Exogenous Emission Target	Yes	(Im)perfect Competition on Output and Permit Market; Continuum of New Technologies
Petrakis & Xepapadeas (1999)	Emission Taxes	Ex Ante, Ex Post	Yes	Monopoly on Output Market; Continuum of New Technologies
Phaneuf & Requate (2002)	Permits and Banking of Permits	Ex Ante	No	Aggregate Uncertainty about Abatement Costs; Continuum of New Technologies
Requate & Unold (2001)	Emission Taxes, Abatement Subsidies Auctioned Permits, Free Permits	Myopic, Ex Ante, Ex Post	No	Asymmetric Firms
Requate & Unold (2003)	Emission Taxes, Abatement Subsidies, Auctioned Permits, Free Permits, Emission Standards	Myopic, Ex Ante, Ex Post	No	Symmetric Firms
Van Soest (2003)	Emission Taxes, Emission Standards	Ex Ante	Yes	Technology Follows Stochastic Jump Process
Van Soest & Bulte (2001)	-	-	Yes	Technology Follows Stochastic Jump Process

Table 1: Models of Adoption and Diffusion.

Authors	Policy Instruments	Timing of Game/ Behavior of Regulator	R&D Stoch-astic	Marginal Damage	Special Attention to Output Market	Additional Special Features
Biglaiser & Horowitz (1995)	Emission Taxes and Technological Standard	Interim, Ex Ante	Yes	Constant	No	Stochastic Innovation Size
Denicolò (1999)	Emission Taxes, Auctioned/Free Permits	Ex Post, Ex Ante	No	Increasing	Yes	Endogenous Innovation Size
Fischer et al. (2003)	Emission Taxes, Auctioned Permits, Free Permits	Myopic, Ex Post	No	Increasing	No	Endogenous Innovation Size; (Im)perfect Costless Imitation
Katsoulacos & Xepapadeas (1996)	Emission Taxes and R&D Subsidies	Ex Ante	No	Increasing	Yes	Imperfect Competition on Output Market; Endogenous Innovation Size; Spillovers
Innes & Bial (2002)	Emisson Taxes and Emission Standards	Ex Ante	Yes	Increasing	Yes	Imperfect Competition on Output Market
Laffont & Tirole (1996b)	Permits, Advanced Allowances, Incentive Contract, Permits and Securities and Licensing Tax	Interim, Ex Ante	Yes	Increasing	No	Shadow Cost of Public Funds Included
Montero (2002b)	Emission Taxes, Emission Standard, Auctioned Permits, Free Permits	Exogenous Emission Target	No	-	Yes	Imperfect Competition on Output and Permit Market; Spillovers
Parry (1995)	Emission Taxes	Ex Ante	Yes	Constant, Increasing	No	(Im)perfect Costless Imitation
Parry (1998)	Emission Taxes, Free Permits, Performance Standards and Output Quota	Myopic, Interim	Yes	Constant	Yes	(In)complete Diffusion; (Im)perfect Costless Imitation
Parry et al. (2003)	Not Specified	Ex Post	No	Constant, Increasing	No	
Requate (2004)	Emission Taxes, Auctioned Permits	Ex Ante, Interim, Ex Post	Yes	Increasing	No	Imperfectly Competitive R&D Sector

Table 2: Models of Innovation and Diffusion.

Author	Resource (Input of Sector x) Pollution (Dependent on)	Horizontal, Vertical Innovation	Substitutability	Decentralized, Centralized Economy	Instruments	Other Special Features
Bretschger (2003)	Non-Renewable (R&D and Intermediates)	H	Intermediates Sector: EoS* btw. Labor and Resource Constant, Lower than Unity; R&D Sector: Unitary EoS* btw. Labor and Resource	D		Positive Population/Labor Force Growth; Limited Supply of Materials
Bretschger & Smulders (2003)	Non-Renewable (Both Final Goods)	H	Constant EoS* btw. Capital and Resource; Different Substitution Conditions are Analyzed	D		Two Final Goods Sectors; Two Types of Physical Capital and Labor; Variety of Only One Type of Capital Expands; Limited Supply of Physical Capital
Elbasha & Roe (1996)	Flow Pollution (Aggregate Output Final Goods Sector or Usage of Intermediates)	H	EMU** of Environmental Quality: Constant, Smaller/Greater than Unity; Constant EMU** of Consumption; Unitary Elasticity of Marginal Rate of Substitution btw. Consumption and Environmental Quality w.r.t Consumption	D, C	R&D Subsidies; Import Subsidies; Export Subsidies; Capital Taxes; Output Subsidies to Intermediates Sector; Emission Taxes	Small Open Economy Characterized by Labor/Capital Endowment; Two Final Goods Sectors with Different Capital Intensities
Grimaud (1999)	Flow Pollution (Aggregate Output Final Goods Sector)	H	Unitary EoS* btw. Emissions and Output; EMU** Higher Unity w.r.t Consumption	D, C	Pollution Permits, R&D Subsidy, Subsidy to the Demand of Monopolies	Emissions Enter Production Function As Inputs; Isoelastic Utility Function; Environmental Quality depends on Pollution and Regeneration Rate
Grimaud & Ricci (1999)	Pollution Stock (Aggregate Output Final Goods Sector and Assimilation Rate)	H,V	Unitary EoS* btw. Emissions and Output; EMU** w.r.t. Consumption Higher Unity	D, C	R&D Subsidy, Subsidy to Monopolists, Emission Taxes	Emissions Enter Production Function As Inputs; Utility Function Separable in Consumption and Pollution Stock; Strong Sustainability
Grimaud & Rougé (2003)	Non-Renewable (Final Goods)	V	Unitary EoS* btw. Capital and Resource	D, C	R&D Subsidies/Taxes	
Hung et al. (1994)	Flow Pollution (Usage Dirty Intermediates)	H		D, C		Clean and Dirty Intermediates; Two Research Sectors; TFP of Final Goods Sector Rises with Varieties of Intermediates; No environmental R&D;
Scholz & Ziemes (1999)	Non-Renewable (Final Goods)	H	Unitary EoS* btw. Capital and Resource	D	Pigou Subsidy to Capital and Knowledge Formation	Indeterminacies of Equilibria May Arise
Schou (2002)	Non-Renewable (Final Goods Sector) Flow Pollution (Resource)	H	Unitary EoS* btw. Capital and Resource; Constant EMU** of Consumption and Pollution	D, C	R&D Subsidies, Subsidies on Purchase of Intermediates	Constant Elasticity of Pollution Function; No Capital Accumulation; Pollution Externality Does Not Distort Economy

Van Zon & Yetkiner (2003)	Available at Any Quantity (Final Goods)	V, H	Unitary EoS* btw. Raw Capital and Energy; Unitary EoS* btw. Labor and Aggregate Effective Capital; EoS* of Different Intermediates Greater One	D	Energy Taxes, R&D Subsidies	Resource Price Rises Continuously at Given Rate; Intermediates Differ w.r.t. Energy Intensity; Intermediates Gradually Become Obsolete
Verdier (1995)	Flow Pollution (Aggregate Output Final Goods Sector)	H	Consumers' EoS* btw. Any Two Products Greater Unity	D, C	Emission Taxes; Performance Standards; R&D Subsidy and Emission Taxes; R&D Subsidy and Performance Standard	Labor Is Only Input; Differentiated Products with Different Emission-Output-Ratios

Table 3: Disaggregated Multi-Secotor Models with Resources/Pollution Incorporated.

*EoS = Elasticity of Substitution
**EMU = Elasticity of Marginal Utility