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On the Optimal Timing of Reductions of CO_2 Emissions

An economists' perspective on the debate on 'when flexibility'

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Abstract

Reducing the emission of greenhouse gases to reduce climate change is high on the policy agenda. Discounted costs of reduction are estimated to be substantial. They depend on the employment of various flexibility mechanisms that affect these costs. One of these flexibility mechanisms is the so-called when-flexibility stressing the timing of policy measures aimed at reducing CO_2-emissions. This paper surveys the arguments in favour of early and late reduction. By means of an illustration of some of the key-mechanisms, we discuss an applied analysis of optimal timing performed with the applied general equilibrium model DICE.

JEL-codes: Q43, Q48
Key words: climate change, when-flexibility, optimal timing of abatement activity

1 Introduction

It is by now commonly agreed upon that global warming will have serious economic and environmental consequences. Man-made greenhouse gas emissions significantly contribute to global warming (as explicitly expressed by the Intergovernmental Panel on Climate Change). Recent concerns on the negative impacts of global warming have resulted in the Kyoto protocol (agreed upon in December 1997) that sets emission standards for participating countries. These standards are strict and boil down to reductions of CO_2 emissions of about 20-40%, as compared to emissions that would have been reached without any action being undertaken. More specifically, developed countries have committed themselves to reducing greenhouse gases to on average 5.2% below their 1990 levels in the period 2008-2012. The annual discounted economic costs of applying to these standards have been estimated to be in the range of 0.5 to 2% of GDP (OECD, 1999), depending on how countries will conform to the standards. However, even if these reductions would be achieved, they are far from sufficient to reach stabilisation of greenhouse gases in the atmosphere in 2100 at levels that are currently thought to be acceptable. Additional measures than those agreed upon in Kyoto will thus be required to achieve stabilisation of concentrations of greenhouse gases. In this sense, despite the costs and difficulties of achieving consensus about the Kyoto protocol, it is only a small step into the right direction.

Over the past 10 years, there has been an intense debate in both the academic and the political domain over the risks of climate change and the appropriate policy responses. We refer to Toman (1998) for an excellent overview of what has been reached in this field to date, as well as for an overview of new challenges in the research on the economics of climate change. Important for all these analyses is that there is huge uncertainty with respect to the effects of climate change on natural and human systems, the costs and benefits of curbing it, the effectiveness of proposed policies, the working of the carbon cycle, etc. (see, for example, Lave, 1991). Despite these uncertainties, many economic analyses have been pursued where the essential question relates to the balancing of costs and benefits associated with curbing climate change or, alternatively, the minimisation of costs of emission reduction needed to achieve emission paths and levels of concentration at some future date. Basically, four types of flexibility can be distinguished that provide countries with possibilities to influence total discounted costs by diversifying reduction activities over space, time, instruments, or type of emission (OECD, 1999). The first refers to the possibilities for diversification over space and is usually labelled 'where flexibility'. The basic notion is that (marginal) costs of reduction vary substantially between regions or countries, costs tending to be low in non-OECD countries. From an economic optimality point of view, reductions should be achieved in countries with the lowest abatement costs. Emission trading, Joint Implementation and the Clean Development

Mechanism[2] are proposed as instruments to operationalise 'where flexibility'. An important (political) problem in the employment of this flexibility mechanism is that poor countries are sometimes reluctant to co-operate given the fact that the mass of emissions and the principle cause of high concentrations can be traced back to the currently rich countries.[3] The second type of flexibility relates to the choice of instruments and is often referred to as 'how flexibility'. Although countries have some freedom in deciding which instruments to apply, the Kyoto protocol specifies that countries should engage in policies aimed at further removing market imperfections. In particular, this requires the phasing out of the instrument of subsidies, which is applied in especially many formerly communist countries. Third, flexibility in choosing which emissions to cut is known as 'what flexibility'. The Kyoto protocol deals with six greenhouse gases. Countries are free to substitute reductions in emissions of one gas with equivalent increases in emissions in another gas. This is a relevant flexibility mechanism since marginal abatement costs may differ significantly between the various emissions. Finally, there is flexibility in deciding when to start reducing emissions, the so called 'when flexibility'. The discussion on the optimal timing of emission reduction was especially triggered by an influential paper by Wigley et al. (1996) that was published in *Nature* in which the authors suggested that to postpone abatement might well be an optimal policy strategy. Since then, many arguments have been put forward as to why it may be optimal to either start reducing emissions early or to adopt a wait and see strategy (see Azar, 1998, for a review).

The literature so far has mainly been concerned with the issue of how much and where emissions should be reduced from an optimality point of view. The issue of 'when flexibility' has been less addressed. It is the aim of this paper to give an overview of the various arguments that have been put forward in the debate on 'when-flexibility'. This is done by describing and discussing the various cons and pros of early action in the Sections 2 and 3, respectively. As we argue, crucial issues in this debate are the perception of technological knowledge and the relevance of various kinds of uncertainties. In Section 4, we illustrate some of the mechanisms by discussing insights obtained with the application of a simple applied general equilibrium models, namely DICE (Nordhaus, 1994). The DICE model is used to illustrate the relevance of the inter-temporal elasticity of substitution, the discount rate and the modelling of technological progress for the optimal paths of emission abatement. Furthermore, the model is used to

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[2] The instruments of Joint Implementation and the Clean Development Mechanism both allow countries to fulfil their required reductions in emissions by sponsoring projects in other countries. The difference between the two mechanisms is that Joint Implementation applies to projects sponsored by Annex I countries in other Annex I countries while the Clean Development Mechanism applies to projects sponsored by Annex I countries in non-Annex I countries.

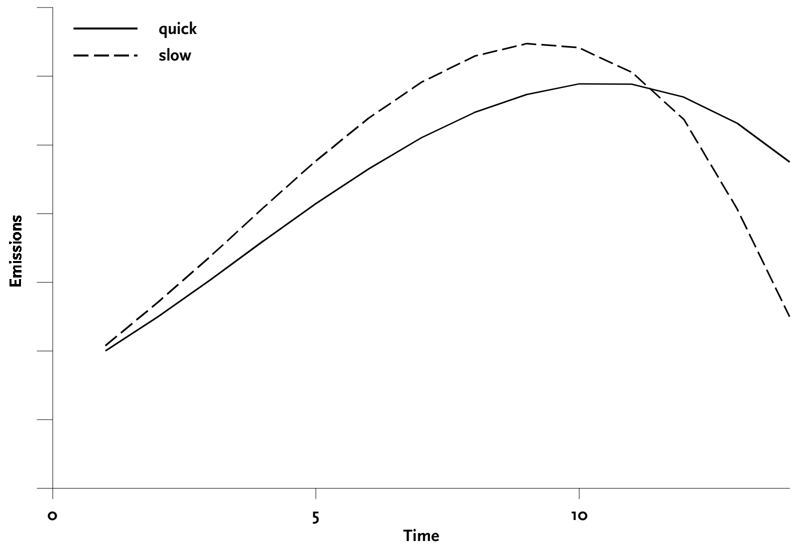
[3] This argument plays an important role in the policy debate. The ratification of the Kyoto protocol will to an important extent hinge on an acceptable resolution of this issue. Theoretical models to assess the costs and benefits and the importance of distributional issues can be found in Eyckmans et al. (1998).

illustrate the welfare consequences of delaying the introduction of optimal policies. This exercise provides a slightly different and more concrete perspective on the issues at stake when dealing with the issue of timing of abatement activities. Section 5 concludes with an evaluation and roads for further research.

2 Arguments in favour of delaying action

Before turning to a discussion of the arguments that have been offered in the debate on timing of abatement activity, it is important to be clear and specific about what exactly we mean with 'timing'. Probably the best way to study the issue of timing is to envisage a world in which a constraint on the concentration of greenhouse gases is imposed at some future point in time. This constraint can not be reached without a change in the current path of development (the business as usual). Action is hence required. This action should result in lower macroeconomic growth, a lower carbon-intensity of production or a shift in production patterns towards less carbon-intensive sectors (or a combination of the three). Applying the logic of the carbon cycle, there are infinitely many emissions paths that allow the world to reach the imposed target. Some are characterised by relatively strong and immediate reductions of emissions in the near future whereas others follow business as usual paths for long periods in order to cut back emissions only at the end of planning period. The debate on 'when-flexibility' therefore not (only) deals with the question *when* to perform action, but with the question *when* to act at what *intensity*.

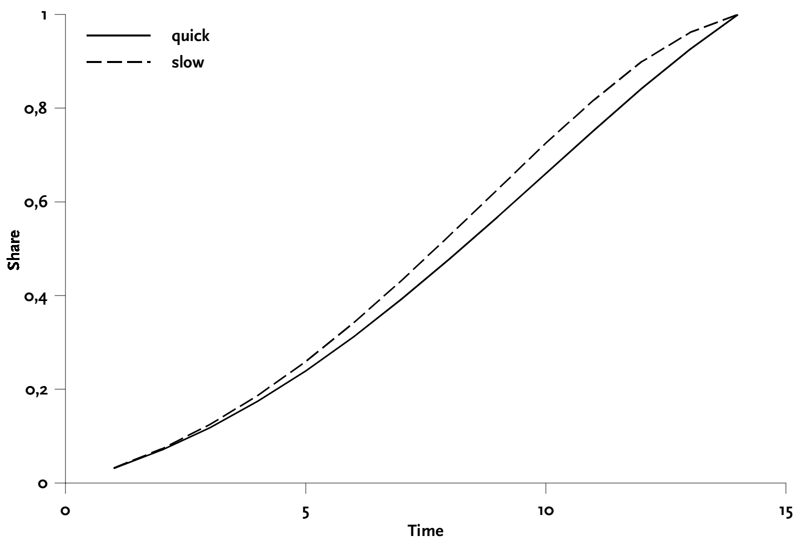
Figure 2.1 Different time paths of emissions resulting in stabilisation



The timing of abatement activities can be depicted in various ways. The first and most direct one is to study the emission paths over time that are consistent with reaching the targets that have been set. This is graphically illustrated in Figure 2.1. The figure presents two emission paths that both result in stabilisation of the concentration of greenhouse gases at one unique level, but along two different time paths. Using relatively little emissions early in the planning period (and relatively much later on) can be labelled as a situation of (relatively) early action. The surface below the curves is equal to total accumulated emissions.[4]

A second method for the illustration of timing is to determine the total amount of allowable emissions that is consistent with stabilisation of concentrations at the predetermined level and to consider the development over time of the fraction of allowable emissions that has been 'used'. This method is illustrated in Figure 2.2, which is closely related to Figure 2.1. It depicts the development over time of the percentage of total allowable emissions that is used at a certain point in time. A 45-degree line would imply that allowable emissions are linearly spread over time. The further the actual emission-profile deviates from this 45-degree line, the higher is the burden that is put on current generations in achieving the required reductions in emissions. This can be translated in the statement that action required to stabilise concentrations is done relatively early in time.[5] We refer to Section 4 for an application of this method to illustrate the timing of abatement activity and its optimality in the context of the DICE-model.

Figure 2.2 Cumulative emissions as fraction of total allowable emissions



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[4] This is almost equal to the concentration. A minor difference exists due to the 'depreciation' of concentrations in the atmosphere. In the case of slow action, relatively much of the concentration that was accumulated at early stages has already been 'depreciated'. The room that is left for emissions due to this depreciation mechanism implies that total accumulated emissions can be slightly higher in case of slow action than in case of quick action.

[5] Note the similarity between this representation of inequality of activity over time and the Lorenz curve that is commonly used to illustrate the inequality of income distribution in a population. A Lorenz curve is based on an ordering of people on the basis of their income. It enables to draw conclusions on what percentage of total income is earned by a certain fraction of the population that is ordered on the basis of income (from poor to rich).

In the discussion of the various arguments that have been put forward in the debate on 'when-flexibility' that follows, we interpret timing as it was just explained. So when we talk about early action, we mean that relatively much of the abatement activity that is required to stabilise concentrations at predetermined levels is done in early periods of the planning horizon. In the remainder of this section, we discuss four arguments that have been proposed in favour of delayed action. These are discussed in four subsequent subsections.[6]

2.1 Discounting

The probably most often used argument to defend postponing investments to the future relies on the 'logic of discounting'. The argument relies on the fact that in the presence of discounting, the present is important relative to the future. When considering the stabilisation of greenhouse-gases as an investment project with certain costs, it is optimal to shift those costs as far into the future as possible and therefore to delay action as much as possible.

Despite the logic of the argument of discounting, the relevance of the argument for favouring delayed action is disputed. First, the appropriateness of discounting climate damage at the same rate as abatement costs has been questioned in, for example, Hasselmann et al. (1998). Their basic argument emphasises the extremely long delay with which the effects of climate change will be felt. As a consequence, economic cost-benefit analyses that discount the damages associated with climate change yield outcomes in which optimal emission paths are only slightly below business as usual scenarios and in which climatic warming becomes very large and sustainable development is not achieved. This is caused by the fact that due to discounting, the benefits associated with current action occur far in the future and are thus basically neglected in the cost-benefit analyses. They therefore conclude that the only way in which economic cost-benefit analyses can yield outcomes in which sustainable development is achieved is to apply relatively low discount rates for climate damage.[7] A second argument relies on the fact that the application of discounting in exercises aimed at establishing cost-effective abatements implicitly implies that costs of fighting climate change are to a relatively large extent shifted to future generations. Essentially, this brings us to an ethical discussion (see, for example, Broome, 1992, and Nordhaus, 1991b) about the appropriateness of discounting the weights of future

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[6] As will become clear, various arguments can both be used as a justification for early action and as a justification for delayed action. For expositional clarity, we will separate the arguments as much as possible.

[7] They justify the use of a low discount rate for climate damage with the argument that the present discount value of a 'habitable planet for future generations' cannot be objectively determined by market transactions, but should be ascertained on the basis of willingness-to-pay criteria. The prior that the authors have is that once this would be done, the implied discount rate for climate damage would indeed be very low.

generations.[8] Stated alternatively, by applying the logic of discounting, future generations count less in determining optimal policies than current generations. Furthermore, in the optimally derived strategies it is implicitly assumed that possibilities exist for capital transfers in order to (partly) alleviate the negative welfare consequences for future generations. As shown in Tol (1999), loosening these assumptions would result in higher current expenditures to fight climate change.

2.2 Cheaper and better future technologies

Technologies tend to become better or cheaper over time. Under such circumstances it tends to pay to wait until new or improved versions of technologies become available. The validity of this argument relies on two (implicit) assumptions, namely the irreversibility of investments and the improvement of the technology without own action being needed. Regarding the first assumption, it is important to be aware of the fact that the validity of the argument of better future technologies as an argument to defend waiting (implicitly) relies on the assumption that - once installed - firms are stuck with the technology for a non-negligible period of time. If firms would continuously update their technologies anyway, the costs of installing a currently available technology for which an improved version will become available in the future are limited. The second assumption of technologies improving or becoming cheaper over time without any own action being undertaken may well apply for a small and open economy; it can well be an optimal strategy for a small country to wait for technologies that will be developed elsewhere and that can later be applied by firms in the country. This reasoning illustrates that free-rider problems are likely to arise.[9] For the world as a whole, this argument is unlikely to be relevant. Substantial investments are likely to be needed (and action to stimulate these investments) in order to improve the quality of current technologies and to learn how to use them. Some convincing empirical evidence for this can be derived from the empirical literature on 'learning curves'. OECD/IEA (2000) provides an overview of estimates of learning rates with respect to energy-saving technologies. The study reveals that roughly 10-20% of the costs of a technology is reduced with doubling of the installed capacity of that technology. Investing and starting to act is, in this view, a prerequisite for learning and cost reductions to take place. We return to these

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[8] Gerlach (1998) proposes a theoretically elegant way of overcoming these problems with specifying a discount rate by endogenising the discount rate by means of explicitly introducing a sustainability constraint that takes care of satisfying the needs of future generations in an Overlapping Generations Model. Practically, this could be operationalised by setting up a trust fund by means of which future generations acquire a claim over a 'clean environment'.

[9] We only talk here about free riding in terms of not investing in and contributing to technology development. It is in the nature of the problem of climate change that free-riding is a problem in that the benefits of reducing concentrations as well as the contributions to the problem are unevenly distributed among countries.

issues on technological development in Section 3 when we discuss the potential relevance of insights of endogenous growth theories with their emphasis on learning, technology development and the building of comparative advantages.

2.3 Spreading costs of adoption over time

A third reason for delaying action is related to the fact that changes in the production process require time. Quick action and strict goals can put a high cost burden on firms that have to satisfy the strict requirements within a short period of time. This argument is relevant given the often large costs of reorganisation and the huge costs of replacing the existing capital stock with a new one and integrating new technologies within the existing production process.[10] The importance of these adjustment costs has been assessed in a theoretical study by Jacoby and Wing (1999). They derive how the costs of implementing the Kyoto protocol dependent on the malleability of the capital stock (that is, the ease with which the existing capital stock can be replaced). Not surprisingly, the more rigid the capital stock is, the more costly the fast introduction and strict appliance of the Kyoto protocol will be. As a consequence, spreading efforts aimed at reducing emissions tends to be the least-cost option of reducing emissions (a conclusion which is, for example, also obtained by applying the OECD's GREEN-model which has a putty-clay vintage structure implying costs of quickly replacing existing capital stocks; see, for example, Lee et al., 1994). From a slightly different perspective, but relevant for the issue at hand, Jovanovic (1997) has estimated the relevance of adoption costs. He argues that adoption costs are a factor 20 or 30 larger than invention costs. They are an important reason for the long periods that often exist between the invention of new technologies and the large-scale application of these technologies as they are observed in practice.[11] These problems are explicitly recognised in the Kyoto-protocols. One of the arguments put forward to justify the gradual reduction over time is that it does not force firms to quickly replace existing capacity. A problem with this approach resides, however, in the credibility of such 'wait-and-see' policies; an issue to which we return in Section 3.5.

In a slightly different but strongly related context, Lecocq et al. (1998) further explore the consequences of this argument for the optimality of policy in a multi-sector context in which one sector is flexible (that is, it has high turnover rates of existing capital stocks) and the other is rigid (that is, it has low turnover rates of the capital stock). Not surprisingly, they show that once

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[10] When we assume that a predetermined level of concentration of greenhouse gases is to be achieved at a certain point in time in the future, this same argument calls for early action in order to give firms sufficient time to adjust and to reduce their emissions in order to satisfy the concentration standards.

[11] Based on a recent survey among firms in the Netherlands, de Groot et al. (1999) conclude that indeed the prime motive for firms not to adopt readily available cost-effective technologies is that the current capital stock first needs to be replaced.

allowance is made for economies with heterogeneous capital stocks, optimal policy rules become more complex. They therefore suggest that in determining the optimal timing, the composition of the capital stock needs to be taken into account (which of course not only applies to the debate on when-flexibility but also to the debate on where-flexibility).

2.4 High option values of waiting due to uncertainties and irreversibilities

It has convincingly been shown that uncertainty about costs and benefits of investment projects that are to some extent irreversible can give rise to substantial option values of waiting. These theories have been made accessible by, most notably, Dixit and Pindyck (1994). The relevance of uncertainties and irreversibilities (in the context of environmental problems) was already established by Arrow and Fischer (1974). The insights of the theory of investing under uncertainty have been used to explain, for example, the energy-efficiency paradox according to which many cost-effective technologies are not applied by firms. The explanation for this paradox relies on the fact that traditional estimates of cost effectiveness which calculate the (expected) net present value of investing in a certain project do not appropriately take into account that often firms have an opportunity to wait one period and see whether new information becomes available that is valuable in deciding whether or not to invest. By waiting, the firm can avoid investing in a project that ex-post turns out to be unprofitable and cannot be reversed. In the case of investments aimed at climate change, there are many uncertainties that may indeed justify the delay of investments. To mention a few, there may be uncertainty about future technologies which may strongly improve or become significantly cheaper over time, future energy prices and the resulting savings on the energy bill may be uncertain, damage resulting from the accumulation of greenhouse gases in the atmosphere is notorious for being highly uncertain, etc. All these uncertainties can make it optimal - both from an individual and a society's point of view - to wait for new information before deciding whether to invest. We refer to, among others, Ghosal and Loungani (2000), Price (1995), Federer (1993) and Huizinga (1993) for empirical evidence on the relevance of theories of investment under uncertainty.

These insights have been formally modelled in the context of climate change by, among others, Pindyck (1993), Ha-Duong (1998), and Xepapadeas (1998). Pindyck (1993) and Ha-Duong (1998) emphasise the relevance of two types of irreversibilities, namely economic and environmental irreversibilities. The relative importance of these irreversibilities has serious consequences for the effects of uncertainties that surround the issue of climate change and the desirability of quick versus slow action. Economic irreversibilities in combination with uncertainty about the consequences of climate change imply that early action is undesirable. The basic idea being that one wants to avoid that firms are pushed to invest in technologies by stricter environmental policies that ex-post turn out to be unnecessary once the consequences of climate change turn out to be minor. This is the basic argument derived from uncertainty that we discussed before. On the other hand, environmental irreversibilities may also be present in that damage done to the environment may be (partly) irreversible. In this case, early action has a benefit component which is not accounted for in usual cost-benefit analyses. What one basically 'buys' by acting early is the possibility to reduce greenhouse gas concentrations at still relatively low costs as compared to the future. This argument to which we return in Section 3.4 asks for early action.[12]

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[12] Xepapadeas (1998) considers the optimal policy response in a multi-country model. He argues that the optimal (timing of) policy depends on the way emission targets are decided upon. In a cooperative setting in which countries simultaneously decide upon optimal emissions, each country emits less than in a non-cooperative setting.

3 Arguments in favour of early action

Having discussed the broad classes of arguments in favour of the adoption of a 'wait-and-see' strategy, we now turn to the arguments in favour of early action. These arguments can roughly be classified in five categories, which are discussed in five subsequent subsections.

3.1 Learning effects and other insights from new growth theories[13]

Many of the studies assessing the optimal timing of reductions of greenhouse gases take the neo-classical model of growth as a starting point. They, in other words, take the rate of technological progress as exogenously given. In the mid 1980s, an alternative to this approach was developed. This new or endogenous growth theory resulted out of dissatisfaction with 'neo-classical practice' of explaining growth by simply exogenously postulating it (see Romer, 1986, and Lucas, 1988 for the seminal contributions that spurred the revival of growth theory and, among others, Grossman and Helpman, 1991, and Aghion and Howitt, 1992, for important further developments). This new or endogenous growth theory is obviously better suited for modelling issues related to sustainable development since the question whether growth can be sustained is central in this theory (cf. Aghion and Howitt, 1998).

A basic lesson from the new theories of economic growth relevant for environmental economics is that economic growth can, under conditions, be sustained in the long-run (for example, Aghion and Howitt, 1998, and Bovenberg and Smulders, 1995). What is characteristic of all endogenous growth models is that reproducible factors can be reproduced with reproducible factors alone with constant returns to scale (the so-called 'core property' cf. Rebelo, 1991). Important weight is attached to innovations and ideas in these models. In the context of environmental economics, one can think of abatement technologies that become more productive over time.

The importance of these theories in the context of the debate on the optimal timing of abatement activities relates to several factors. First, the new theories of economic growth emphasise that technological progress and the development of innovations required to sustain economic growth in the long run do not fall like manna from heaven. On the contrary, they require the employment of scarce resources that may contribute to enhanced technological opportunities, building on existing knowledge. Given the often significant spillovers that tend to

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[13] We discuss this issue of learning from a neo-classical perspective by focussing on insights from the new or endogenous growth theory. We are well aware that arguments emphasizing the importance of learning (and technological lock-ins associated with or resulting from learning) have been made in evolutionary economics as well (often earlier). We refer to, for example, Nelson and Winter (1982) and Dosi et al. (1988) for an extensive discussion of the importance of learning and technological lock-ins for understanding technological progress. The importance of these ideas in the debate on Climate Change has been stressed by, for example, Janssen (1996).

result in under-investments in new technologies, policies aimed at fostering R&D may well be conducive to economic growth. Furthermore, the emphasis in the theory of endogenous growth on building on knowledge accumulated in the past explicitly recognises that technologies can improve over time. By investing in new technologies now, future costs of reducing greenhouse gases can be lower due to, for example, learning by doing (see, for example, Grübler and Messner, 1998). This argument can be used to defend early policies aimed at developing emission-reducing technologies as these may reduce future costs of satisfying future emission reductions and concentration targets, where of course these investments have to be weighted against other investment projects. Also, stricter policies can be defended, as they will induce firms to adopt and develop new technologies at an earlier stage (see, for example, Goulder and Mathai, 1998, in their paper on the optimal CO_2 abatement in the presence of induced technological change). A second argument that may favour early action is that learning to use currently employed technologies can result in 'lock-ins' (Arthur, 1989). Early policy action can then be a means to avoid an economy to become 'locked-in' into a sub-optimal 'techno-economic paradigm'. In this case, learning results in such a strong competitive advantage with using one particular technology that it is no longer attractive (or feasible) to switch to another technology. This kind of argument is strongly emphasised in the evolutionary theories of technological change, but also fits closely with the new theory of endogenous growth (see Mulder et al., 2000).[14]

3.2 'Developing' a comparative advantage: The Porter/Van der Linde Hypothesis[15]

The so-called Porter hypothesis basically extends the argument developed in the previous section to an international multi-country context. In contrast with the commonly held belief, it emphasises that '[s]trict environmental regulations do not inevitably hinder competitive advantage against foreign rivals, they often enhance it' (Porter, 1991, p. 162). The validity of this argument strongly depends on a particular notion of technology and innovation. This is emphasised in Porter and van der Linde (1995, p. 98) when they state that '[b]y stimulating innovation, strict environmental regulations can actually enhance competitiveness'. In other

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[14] This kind of argument has intensively been explored in the historical literature describing technological change (for example, Mokyr, 1990, Olson, 1982). This literature emphasizes the relevance of vested interests that may give rise to economies being stuck with inferior technologies due to the unwillingness of producers or workers to switch to new technologies. This kind of ideas has recently been formalized in, for example, Holmes and Schmitz (1994), Helpman and Rangel (1998), and Canton et al. (1999).

[15] We refer to Withagen (1999) for an overview of the literature on (the status of) the Porter hypothesis. One of his basic conclusions is that at date there is no systematic empirical evidence on the validity of the hypothesis. What is crucially needed is this evidence. We add here that what is then basically needed is a good insight into the question of the degree of tacitness of technological knowledge.

words, by adopting a strict policy, a comparative advantage can be created. What is meant here is that innovation is triggered by strict policy and may in the end result in a situation in which firms in a particular country can operate at relatively low costs and thereby more easily compete on the world market. This view exemplifies a new perspective on comparative advantages based on knowledge that can be created and shaped by explicit policies. An important condition that needs to be satisfied for the Porter hypothesis in its pure format to apply is that technological knowledge should contain important elements of tacitness. Once technological knowledge would flow and be applicable without any regard to boundaries (be it firm or country boundaries), the Porter-hypothesis cannot hold. This again brings us to the relevance of understanding the nature of technological knowledge.

3.3 Existence of many non-exploited but cost-efficient technologies

Engineers often claim that there exist many technologies that can significantly contribute to reducing emissions, that can cost-effectively be applied by firms, but which nevertheless are not introduced by firms. These technologies tend to be called low hanging fruits. This paradoxical evidence is known in the literature as the energy-efficiency paradox (see, for example, Jaffe and Stavins, 1994). We refer the reader to the concepts of bounded rationality and 'satisficing behaviour' for interesting potential explanations for this paradox. These concepts loosen the assumption of rational behavior of firms deciding on whether or not to invest in technologies and go back to the seminal work of Simon (1955). They cast doubt on the possibilities of firms to acquire and process all relevant information regarding current and future possible states of the world that are needed to rationally decide about the adoption of a technology. Instead, they propose that firms often behave according to a 'satisficing principle', where they look for 'satisfactory profits' instead of maximum profits associated with an investment choice, and apply rules of thumb and routines. This approach has been elaborated upon in the evolutionary theory (for example, Nelson and Winter, 1982). If indeed low hanging fruits are so prevalent as suggested by the before-mentioned engineers and firms do not exploit these technologies, immediate implementation of stricter policies is likely to be desirable. It can be a means to attract the attention of firms to technologies they did not consider before simply because they are forced to do so by the regulations.[16]

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[16] Some evidence on the relevance of such theories is provided in, for example, Jaffe and Stavins (1995) and Hassett and Metcalf (1995). They show that adoption subsidies that are granted upon adoption of the technology, are a factor three to eight more effective than 'equivalent' energy taxes which accrue to the firm over the lifetime of the technology. Financial analysis building on the rational-behavior hypothesis would suggest that they should be the same. The results reveal that adoption decisions are more sensitive to up-front cost-benefit considerations than to longer-term benefits (Jaffe et al., 2000). Non-rational behavior is clearly the most logical candidate to explain this result.

3.4 Ecological arguments

We have already seen that uncertainty is one of the important factors that affect the optimal timing of stricter policies. One aspect of uncertainty that so far was only mentioned in passing is uncertainty with respect to the existence, location and effect of environmental thresholds that, once surpassed, result in irreversible damage. Especially with respect to the location and the effects of thresholds very little is known, despite the fact that this information is crucial. The uncertainty is neatly expressed by the IPCC (1996) when it states that climate models will become more and more unreliable as the concentration of greenhouse gases in the atmosphere rises beyond the boundaries of empirical knowledge and that at high concentrations it becomes more likely that actual outcomes will include surprises and unanticipated rapid changes.

Relatively little attention has been paid in the literature to thresholds (which is likely to be related to the analytical intractability of models that include thresholds due to damage being non-convex). Perrings and Pearce (1994, p. 13) put it as 'There is generally considerable uncertainty about the threshold values of either populations or organisms or bio-geochemical cycles for many of the most important ecosystem types, and there is often fundamental ignorance about the implications of crossing a threshold'. A notable exception to this is Aalbers (1999). He shows that in the presence of thresholds a good case can be made for prudent behaviour and economic policy, provided that the damage of passing the threshold is large, there is uncertainty about the location of the threshold, and crossing the threshold is an irreversible event.[17] More in particular, it is shown that the optimal level of consumption is inversely related to the level of uncertainty, both with respect to uncertainty about the impact and the location of a threshold. The author therefore concludes that 'Given that there is, at least to my opinion, little prospect to learn anything about the location and impact of thresholds, risk and ambiguity are likely to be high. Consequently, the level of consumption should, compared to the case in which there is no uncertainty or ambiguity, be reduced'. So in the presence of thresholds, irreversibilities and uncertainty a case can be made for early action aimed at reducing greenhouse gas emissions in order to keep society away from catastrophic events (see also Ha-Duong et al., 1997, Ha-Duong, 1998, and Gjerde et al., 1999, for similar conclusions).

A second argument for early action in this context that has not explicitly been mentioned before is related to the low rate at which concentrations of greenhouse gases dissolve once being

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[17] A similar conclusion was already drawn by Nordhaus (1991a) when he considers the effects of a steep rising damage function on optimal policy (although he did not consider the effects of uncertainty). He concludes that both the tax and control rate rise sharply in coming decades to keep society away from the threshold' (p. 115).

accumulated (half-year times being around 265 years[18]). Concentrations are therefore to a large extent irreversible. This aspect of greenhouse gas concentrations exacerbates the before mentioned effects. If, for example, new information becomes available on the (negative) health effects of high concentrations of greenhouse gases which may already have been surpassed, enormous efforts will be required to reduce emissions (and thereby concentrations) at as fast a rate as possible with huge associated costs. Put somewhat differently, early action allows for a 'safe landing' (Kreileman and Berk, 1997) and increases future flexibility by extending the range of emission paths that will be consistent with stabilisation of greenhouse gases in the atmosphere.[19]

A final argument in this context is that climate experts have pointed out that damages of climate change do not only depend on the change in temperature, but also on the rate of change. Faster climate change tends to have larger negative impacts than more gradual change. As a consequence, flat emission paths are more preferable than spiky ones and emission reductions should start relatively early (for example Tol, 1998, for an analysis of this issue).[20]

3.5 Political arguments

Finally, we can distinguish arguments in favour of early action that are politically related. The first is prevalent in the negotiations on the division of the burden of reducing emissions and concentrations. The argument here goes that early action by OECD countries is required to overcome the reluctance of non-OECD countries to engage in reductions. The argument here basically is that non-OECD countries are not willing to reduce their emissions as long as OECD-countries - which add significantly more to the problem - are not willing to act themselves. This may hold true despite the optimality of doing so given that costs of reducing emissions in non-OECD countries are often far below those in OECD countries. An often used

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[18] According to the OECD (1999; Annex 3), a factor 0.247 of emissions that are emitted at time t=0 are still in the atmosphere after 535 years. Assuming linear depreciation, this corresponds to an annual rate of depreciation of 0.261% or a half-life value of 265 years. Note, however, that there are various models circulating for modeling the amount of CO_2 remaining in the atmosphere after it has been emitted (see Hasselmann et al., 1998, for a survey and discussion).

[19] At RIVM (National Institute of Public Health and the Environment, The Netherlands), a tool of analysis has been developed that allows one to determine corridors of emissions that are safe in that they are consistent with predefined targets (on emissions, concentrations, temperature, sea level rise, etc.). These corridors are determined on the basis of the integrated climate change model IMAGE 2 (see Leeman et al., 1997, and Kreileman and Berk, 1997).

[20] There is a trade-off to be faced here, however, since gradual climate change prevents optimal use of the so-called 'carbon cycle premium' which is based on a specific feature of natural processes. These processes are such that the goal of stabilization of concentrations of greenhouse gases can be achieved with relatively many emissions, provided that these emissions take place in a relatively short period of time.

argument of 'fairness' to defend this position is that after all the majority of the current greenhouse gas concentrations are the resultant of activities performed in OECD regions. A second argument is based on credibility problems. Even if postponement of action would be desired from a purely economic point of view, credibility or time-consistency problems may arise. The problem here is that the promise of future strict policy does not induce the desired change in actual behaviour since the public does often not believe these promises. This argument countervails, for example, the argument in favour of late adoption that was based on giving firms sufficient time to adjust their behaviour.

3.6 Summarising the arguments

We have so far seen a wide range of arguments that has been proposed as relevant for judging whether early action or delayed response is desirable. Some of these arguments could even be used to defend both early action and delayed response. Table 3.1 attempts to summarise the arguments and their implications for the optimality of early action or delayed response. Reference is made to the section in which the argument is more elaborately discussed.

Table 3.1 Summary of the arguments

	Favouring early action	Favouring delayed response
Discounting	–	Section 2.1
Technological progress	Section 3.1: if progress is endogenous	Section 2.2: if progress is exogenous
Spreading costs	–	Section 2.3
Uncertainty and irreversibility	Section 3.4: if environmental damage is irreversible	Section 2.4: if installed capital/technology are irreversible
Developing comparative advantage	Section 3.2	–
Existing low-hanging fruits	Section 3.3	–
Political arguments	Section 3.5	–

4 A model application to the debate on 'when flexibility': experiments with DICE

The discussion so far was restricted to a theoretical discussion of potentially relevant mechanisms that can affect the assessment of the optimality of timing of environmental policy. This section turns the attention to a simple applied general equilibrium model that can be applied to the optimality of timing. We do not intend to assess the relevance of the theoretical arguments by providing an empirical assessment. Instead, we take an existing model - the DICE model - as a starting point in order to illustrate the relevance of some of the arguments, obviously within the context of that particular model. The DICE model was developed by Nordhaus. It will be used to assess the relevance of the discount rate and the inter-temporal elasticity of substitution for the optimal distribution of efforts aimed at stabilising CO_2 concentrations at a pre-determined level. Furthermore, we introduce some insights from the endogenous growth theory in the model - in an admittedly stylised way - in order to illustrate the relevance of understanding the nature of technological progress for a good assessment of the optimality of timing. Finally, we consider the consequences of (deliberately) delaying action for the possibilities and efforts required to reach stabilisation (in the relatively short remaining period of time).

DICE is a simple *D*ynamic *I*ntegrated model of *C*limate and the *E*conomy. It is essentially a neo-classical model of economic growth with Ramsey-type of optimal savings behaviour, extended with feed backs of the economy on the climate and vice-versa. The feed backs that are modelled between climate and the economy are twofold. First, production is associated with emissions that in their turn affect the accumulation of greenhouse gases in the atmosphere resulting in changes in temperature. Second, these temperature changes affect the 'total factor productivity' (as explained below) of the economy and thereby affect production. The remainder of this section is devoted to two issues. We first briefly describe and discuss the basic equations that constitute the DICE model. Next, we discuss in Section 4.2 the steady-state characteristics of the model. Section 4.3 discusses the comparative static characteristics of the model with respect to the discount rate and the inter-temporal elasticity of substitution in relation to the optimal time profile of reduction efforts. Section 4.4 studies the issue of optimal timing from a slightly different angle by assessing the costs of delaying action - that is imposing the rate of emission abatement to be exogenously equal to zero for a certain number of periods. Section 4.5 concludes by showing the consequences of endogenising technological progress in DICE for the timing of reduction efforts.

4.1 The basic structure of DICE

The following description of DICE is based on Nordhaus (1994, chapter 2). The model is formulated as a standard planner's inter-temporal optimisation problem with the objective of maximising the present discounted utility of all future consumption streams.[21]

$$\max \sum_{t=0}^{\infty} \frac{U[c_t, L_t]}{(1+\rho)^t} \quad \text{where} \quad U(c_t, L_t) = \frac{L_t[c_t^{1-\alpha} - 1]}{1-\alpha} \quad .$$

In this equation, L represents population, c is per capita consumption (C/L), U is the instantaneous utility function, ρ is the planner's discount rate and $1/\alpha$ is the inter-temporal elasticity of substitution. The social planner solving this optimisation problem has two instruments at his disposal, namely the savings rate (that is, the fraction of output to be used for the accumulation of capital) and the rate of emission abatement (that is, the fraction of production to be used for reducing emissions). Production takes place according to a Cobb-Douglas production function using labour (L) and capital (K)

$$Q_t = \Omega_t A_t K_t^{\gamma} L_t^{1-\gamma} .$$

This equation reveals that 'total factor productivity' consists of two components. The term A represents 'standard' Hicks-neutral technological progress known from basic neo-classical growth models (Nordhaus assumes the exogenous rate of technological progress to decline (exogenously) and to converge to zero in the long run). The term Ω can best be interpreted as a feedback factor on total factor productivity that is related to the environment. Nordhaus assumes

$$\Omega_t = \frac{1 - b_1 \mu_t^{b_2}}{1 + \theta_1 T_t^{\theta_2}} ,$$

This feedback term can be understood as follows. Let us consider $A\ K^{\gamma}\ L^{1-\gamma}$ as gross output. Part of this output is spent on abatement of emissions. Nordhaus assumes that in order to reduce

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[21] Note that the environment does not enter the utility function. The only way in which the environment affects the economy is through the (negative) effect of increased temperature on total factor productivity as explained below. In part, this way of modeling is chosen to simplify the analysis and the calibration of the model. Allowing the environment to feature in the utility function would make the analysis more difficult and realistic but would not add to the basic insights that can be obtained with the current setup of the model.

emissions with a fraction μ, abatement outlays are required equal to a fraction $b_1 \mu^{b2}$ of gross output. This fraction can be seen as the investments in the environment.[22] Hence, a share equal to $1\text{-}b_1 \mu^{b2}$ is left as gross output after abatement. Marginal costs of abatement are assumed to be increasing in the level of abatement activity (b_2>1). Stated alternatively, there are diminishing returns to abatement activity. An important notion is that these investments are completely depreciated after one period (that is, then years). Abatement activity in the model can therefore best be seen as the installation of an end of pipe technology with a lifetime of one period. A second correction is made on gross output associated with climate change (or - to be more precise - with temperature). This correction is captured in the denominator of Ω.[23] As will be indicated below, emissions result in the accumulation of greenhouse gases which in their turn result in changing temperature. Higher temperature is modelled as having a negative impact on output for consumptive or investment purposes. Net output (*Q*) can be used for consumption and investment

$$Q_t = C_t + I_t ,$$

in which *I* are investments in physical capital. This is essentially the core of the DICE model. The remainder of the model describes the accumulation of physical capital, the relationship between emissions and production, the relationship between emissions and greenhouse gas concentrations, and the relationship between greenhouse gas concentrations and temperature. The development of physical capital is modelled in the standard fashion as

$$\Delta K_t = I_t - \delta K_t ,$$

in which δ is the depreciation rate of physical capital. Emissions (*E*, expressed in billion tons of CO_2 equivalents) are linked to output in the following way

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[22] The parametrisation of the model chosen by Nordhaus implies that emissions can be reduced to zero by investing 6.9% of GDP in the reduction of emissions.

[23] Nordhaus (1994) is not clear on the precise way of modelling the correction on total factor productivity. On p.19, he claims abatement costs to be a fraction of net output (*Q*), while damage resulting from higher temperature is also a fraction of net-output *Q*. One then would expect that adding the two cost components to net-output would result in gross-output. This is inconsistent with the formulation of the productivity parameter as it is formulated. In order to end up with the correction on total output as is modelled by Nordhaus, the costs of abatement should be modelled as a fraction of gross-output.

$$E_t = [1 - \mu_t]\sigma_t Q_t .$$

In this expression, μ represents the fraction of emissions that is being reduced due to abatement activities ($0<\mu<1$), while σ captures an exogenous part of the emission intensity of output. Nordhaus assumes that this emission intensity falls permanently, ultimately reaching a constant. This can be defended by arguing that over time consumption patterns shift towards less carbon-intensive goods like services (de-carbonisation of the society) or by assuming exogenous (biased) technological progress that lowers the emission intensity of output in an exogenous manner (that is, without abatement activities).

Finally, four climate equations are needed in order to link emissions to GHG concentrations (M, expressed in billions of tons of CO_2 equivalent concentrations)[24] and to link these to temperature change (T).

$$M_{t+1} = 590 + \beta E_t + (1 - \delta_M)(M_t - 590) ,$$

$$T^*_{t+1} = T^*_t + \frac{1}{R_1}\left[\frac{R_2}{\tau_{12}}(T_t - T^*_t)\right] ,$$

$$T_{t+1} = T_t + \frac{1}{R_1}\left[F_t - \lambda T_t - \frac{R_2}{\tau_{12}}(T_t - T^*_t)\right] ,$$

$$F_t = 4.1\left[\frac{\log(M_t/590)}{\log(2)}\right] + O_t .$$

In these expressions, δ_M stands for the depreciation rate of concentrations accumulated in the atmosphere, T is the atmospheric temperature in excess of the temperature in 1965 (in degrees C), T^* is the temperature of the lower ocean in excess of its 1965 level (in degrees C), and F are radiative forcings (in W per square meter). The other parameters are transformation parameters; we refer to Nordhaus (1994) for details. These equations reveal that:

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[24] These concentrations can be translated into the more common unit of measurement of parts per million volume (ppmv) by dividing by 2.12.

- GHG concentrations are equal to some predefined (pre-industrial) level of 590 (corresponding to 280 ppmv) plus a fixed percentage of accumulated emissions in the past, taking into account a fixed depreciation rate of accumulated GHG's;
- radiative forcings that lead to temperature change are a (weighted) sum of GHG's plus other radiative forcings (*O*) which are assumed to be exogenous;
- atmospheric temperature increases (relative to the base temperature) with radiative forcings and decreases as long as temperature exceeds the temperature of the ocean (T^*);
- the temperature of the ocean increases (relative to the base temperature) as long as the atmospheric temperature exceeds the temperature of the ocean.

4.2 The steady state of the model

This section presents the transition path and the steady-state characteristics of the DICE model in order to give a sense for the numbers involved in the model and the short and long run characteristics of the base-line of the model as developed and calibrated by Nordhaus (1994). DICE has been parametrised in such a way that the steady state is characterised by absence of growth of population and total factor productivity. This is due to the assumed (exogenously imposed) convergence of productivity, population and the emission intensity of final output to constants. In the steady state, the model is therefore characterised by constant consumption, investment and capital stock. The climate block of the model is such that the steady state is characterised by constant and equal atmospheric and ocean temperature, a constant concentration of GHGs and constant emissions.

An analytical solution of the steady state of the model is difficult to obtain. We therefore rely on a numerical (iterative) procedure using GAMS (technical details are available upon request from the author).[25] The atmospheric CO_2 concentration and temperature that apply in the steady state turn out to far exceed concentrations and temperature reported by Nordhaus (due to the fact that he only reports values in the period 1965-2105). The steady-state temperature increase (as compared to the pre-industrial level) is 7.3° C, while the steady-state concentration is 2649 billion tons of carbon dioxide (which corresponds to 1245 ppmv). This is obviously the result of the long transition periods that characterise the model (in combination with the relatively short period over which Nordhaus reports his simulation results). A summary of the results is

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[25] We put all parameters of the model at their steady-state values. Subsequently, we changed the initial capital stock, the initial level of CO_2 concentrations in the atmosphere, the initial temperature changes and the corresponding shadow prices until these values remained constant along the transitional path. Constancy along the transition path indicates that the initial values correspond to the steady-state values of the corresponding stock variables and their corresponding shadow prices. These shadow prices obviously also correspond to the theoretically correct transversality coefficients. Details of the procedure and the GAMS-program used to determine the steady state are available upon request.

contained in Table 4.1, which mimics the Base-line scenario of Nordhaus, but now including the steady-state values.

Table 4.1 Transition of some key variables in Base line scenario and steady-state values

	1965	2025	2095	Steady State
Output	9	47	103	166
Capital	16	100	240	414
Consumption	7	38	85	139
Savings rate	0.22	0.18	0.17	0.16
Interest rate	0.07	0.05	0.04	0.04
Emission control rate	0.06	0.11	0.14	0.162
Emissions	41	130	207	268
CO_2 concentration	677	896	1356	2649
Temperature atmosphere	0.2	1.4	3	7.3
Temperature oceans	0.1	0.2	0.4	7.3

Several interesting results appear from the table. First, during the time period reported by Nordhaus, the model has only partly converged to its steady state. Economic variables like consumption, capital and output have closed about 60% of the initial gap to the steady state in the first 130 years, while the greenhouse gas concentrations and temperature increases have only closed about 40%. Most slow in its transition is the temperature increase of the lower ocean, which has only closed 4.5% of the initial gap, illustrating the long transitional periods of especially the natural processes. An important consequence of the difference in transition periods is that the benefits of action aimed at reducing emissions (that is, a lower increase in temperature) are only felt after a relatively long period of time. The costs therefore tend to be relatively dominant in deciding on investments in the environment, which is another way of explaining the rationality of delaying investments in the abatement of emissions. Second, the temperature increase resulting in the steady state is high, but falls within the ranges currently argued to be potentially relevant (see, for example, IPCC, 2001). Finally, a technical remark is in place. With the discount rates used in the DICE-model, the optimal path is hardly affected by whatever transversality condition is imposed on the system. This is useful information when analyzing the short and medium term behavior of models like this. It implies that in doing the comparative-static analysis, one is justified in neglecting the steady-state characteristics of the model since these do not affect the optimal paths anyway. We will in the remainder of the analysis use this characteristic of the model.[26]

4.3 Optimal timing, discount rates and the desire to smooth consumption

Starting from this basic integrated model, various simulation exercises can now be performed. In this section, we simulate the model under two different scenarios.[27] In the first scenario, we determine the optimal time path in the absence of any constraint. This is the BASE-scenario as it is also discussed by Nordhaus. In the second scenario, we impose a constraint on greenhouse-gas concentrations in 2095. More specifically, we impose the concentration to be below 1150 billions of tons carbon equivalents (which roughly corresponds to 550 ppmv). We label this scenario as STAB referring to stabilisation. The latter comes close to the 'constant-climate' scenario presented by Nordhaus in which he puts a constraint on temperature increase.[28] The imposition of a constraint of GHG concentrations in 2095 effectively puts a maximum on total accumulated emissions.[29] The STAB scenario essentially describes the division of the allowable emissions over time.

The time paths of consumption are given in Table 4.2.[30] Not surprisingly, the results reveal that consumption paths get steeper when the discount rate (ρ) declines and when the inter-temporal elasticity of substitution ($1/\alpha$) declines. A higher discount rate means that less importance is attached to the future. Current consumption will therefore be relatively large, going at the expense of capital accumulation and future consumption. Translated to average annual growth rates, an increase of the discount rate from 0.025 to 0.035 results in a decrease of the average annual growth rate over the period 1965-2095 from 2.00% to 1.97%. A relatively high inter-temporal elasticity of substitution implies that consumers are willing to accept a

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[26] We have experimented with various transversality conditions, including the true steady state values, but the transition dynamics for the first ten periods of the model are virtually not affected. This is a basic reflection of the turnpike theorem, indicating that it is optimal for the economy to move to the transition path as soon as possible and only to deviate from this path close to the final period if the transversility conditions require this.

[27] In Section 5, we will discuss two alternative scenarios in which we allow for learning effects associated with investing in emission abatement.

[28] Details on how to perform scenario and sensitivity analysis with GAMS are available upon request from the author.

[29] This is not exactly true since the total allowable emissions that are constant with stabilization of concentrations at a certain level depend on the timing of emission. Relatively early emission results in relatively high allowable emissions, since relatively much of the emissions can be 'depreciated' over time. This 'premium' associated with early emission is also known as the carbon cycle premium.

[30] Note that consumption and investment differ in the various regimes from the first period onwards. This is due to the calibration strategy in which physical capital and labor are given in the first period, fixing output, but not fixing the allocation of output over consumption and investments which is optimally chosen from the first period onwards.

relatively steep consumption path (that is, they are relatively willing to offer current consumption in exchange for increased future consumption). The optimal consumption path is relatively steep in such a case. This is evident when considering the average annual growth rates of consumption which are 1.97% in the case with the low inter-temporal elasticity of substitution and 1.99% in the case with the high inter-temporal elasticity of substitution. These comparative static results obviously apply in both the BASE and the STAB scenario.

Table 4.2 **Time paths of consumption 1965-2095 in BASE and STAB scenario**

	1965	1985	2045	2095
Base	6.65	14.27	52.6	85.45
High discount (ρ=0.035)	6.78	14.23	52.39	85.16
Low discount (ρ=0.025)	6.52	14.29	52.95	86.1
Low intert. subst. (α=1.1)	6.7	14.25	52.49	85.34
High intert. subst. (α=0.9)	6.6	14.3	52.7	85.56
STAB	6.65	14.27	52.53	83.06
High discount (ρ=0.035)	6.78	14.23	52.34	82.76
Low discount (ρ=0.025)	6.52	14.3	52.87	84.36
Low intert. subst. (α=1.1)	6.7	14.25	52.42	82.98
High intert. subst. (α=0.9)	6.6	14.3	52.63	83.14

Note: in the base scenario, parameters values are equal to those used by Nordhaus (the GAMS-listing with all parameter values is available upon request). For the key-parameters, this implies ρ=0.03 and α=1.

The implications for emission profiles and CO_2 concentrations are presented in Tables 4.3 and 4.4. Several remarks need to be made here. First, Table 4.3 reveals that the effects of changes in the inter-temporal elasticity of substitution and the discount rate are similar as their effect on the consumption path. The most important reason for this is that at high discount rates (or low inter-temporal elasticities of substitution), optimal consumption paths are relatively flat requiring investments aimed at reducing greenhouse gases (which go at the expense of consumption possibilities) to be postponed to the future. In addition, the marginal benefits of capital accumulation relative to the marginal benefits of emission reduction are relatively large in early periods causing total investments being biased towards the accumulation of physical capital. As a consequence, concentrations rise relatively quickly in early stages. Second, in the stabilisation scenario, emission reductions are postponed to later periods. This is related to various characteristics of the model. First, as we already indicated, the marginal benefit of an additional unit of capital as compared to the marginal benefit of emission reduction is relatively high initially. This results in a bias of total investments towards physical capital. Second, achieving stabilisation can be considered as sort of an investment project with mainly costs. The 'logic of discounting' as discussed in Section 2 than tends to result in delay. In a growing economy, this holds *a fortiori* given the desire of consumers to smooth their consumption over

Table 4.3 Time paths of emission 1965-2095 in BASE and STAB scenario

	1965	1985	2045	2095
Base	41.6	69.4	157.1	207.4
High discount (ρ=0.035)	41.9	69.1	156.4	207.6
Low discount (ρ=0.025)	41	69.5	156.7	206.4
Low intert. subst. (α=1.1)	41.7	69.1	156.8	207.3
High intert. subst. (α=0.9)	41.4	69.6	157.3	207.6
STAB	41	67.7	127.8	72.9
High discount (ρ=0.035)	41.6	67.6	129.5	72.9
Low discount (ρ=0.025)	40.3	67.3	125.5	72.9
Low intert. subst. (α=1.1)	41.2	67.5	128	72.9
High intert. subst. (α=0.9)	40.9	67.8	127.7	72.9

Note: see Table 4.2.

time. The reason that not all investments are made in the final period only is related to the fact that (i) maximum emission reduction in the last period is likely to be insufficient to reach stabilisation and (ii) the costs of emission reduction are convex in the rate of emission reduction tending to result in smoothing of abatement efforts.[31] Third, we would like to remark that the accumulated emissions that are allowable in the stabilisation case are higher in case the emission profile gets flatter. This is due to the fact that a flat emission profile implies relatively large emissions in early days which can - subsequently - to a relatively large extent be 'removed' by the natural system.

Table 4.4 Time paths of CO_2 concentrations 1965-2095 in BASE and STAB scenario

	1965	1985	2045	2095
Base	677	723.6	1015.5	1355.8
High discount (ρ=0.035)	677	722.7	1014.3	1355.6
Low discount (ρ=0.025)	677	722.3	1015.4	1354.1
Low intert. subst. (α=1.1)	677	722.6	1014.7	1354.7
High intert. subst. (α=0.9)	677	722.6	1016.4	1357
STAB	677	721.7	985.9	1150
High discount (ρ=0.035)	677	722.2	988.3	1150
Low discount (ρ=0.025)	677	721	982.2	1150
Low intert. subst. (α=1.1)	677	721.7	986	1150
High intert. subst. (α=0.9)	6.77	721.6	985.9	1150

Note: see Table 4.2.

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[31] These statements can be illustrated by performing further comparative-static exercises with respect to the inter-temporal elasticity of substitution and the curvature of the costs of emission abatement. Details on these exercises are available upon request from the author.

A common way to summarise the effects discussed before is to determine the (implicit) carbon taxes that are required in a decentralised equilibrium to follow the optimal path.[32] These taxes are given in Table 4.5 and can be interpreted as measures of the optimal strictness of environmental policy. Evidently, the results show a similar picture as the one presented before. The higher the discount rate and the lower the inter-temporal elasticity of substitution, the less restrictive (optimal) environmental policy should be at early stages. The taxes needed to stabilise concentrations at levels currently argued to be acceptable (550 ppmv) are extremely high if compared to the (optimal) taxes in the unrestricted version of the model.

Table 4.5 Time paths of (optimal) taxes 1965-2095 in BASE and STAB scenario

	1965	1985	2045	2095
Base	1.9	3.9	13.4	20.4
High discount (ρ=0.035)	1.4	2.8	10.4	19.5
Low discount (ρ=0.025)	2.7	5.4	17.8	27.1
Low intert. subst. (α=1.1)	1.8	3.6	12.9	20.1
High intert. subst. (α=0.9)	2.1	4.2	13.9	20.8
STAB	2.7	6.3	65.3	424.7
High discount (ρ=0.035)	1.9	4.6	55.1	423.3
Low discount (ρ=0.025)	3.9	8.8	77.9	433.9
Low intert. subst. (α=1.1)	2.4	5.8	63.6	423.8
High intert. subst. (α=0.9)	2.9	6.9	67.1	425.4

Note: see Table 4.2.

We have just seen how the (optimal) emission time path is affected by the imposition of a constraint on concentration levels. These stabilisation scenarios are now commonly used by the IPCC and are - as discussed in Section 2 - useful to illustrate the key mechanisms that arise in the debate on timing of abatement activity. It will be evident from the discussion so far that optimal timing is not a simple issue of whether or not to delay action with, say, ten years. It is a complex decision on how much to do at what period in time. Still, most studies have focused on the consequences of delaying action with, for example, ten years and have computed the cost-consequences of such a delay. These cost estimates have subsequently been used as indications for the desirability of early action.

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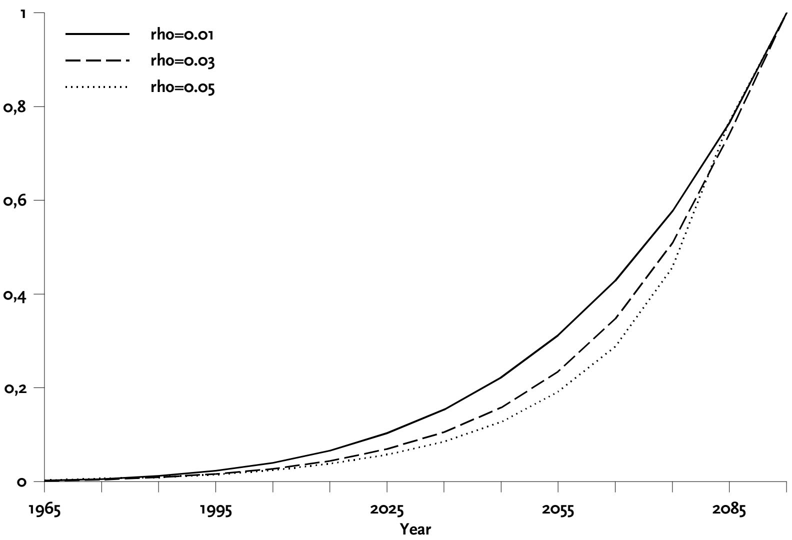
[32] In optimal control models like DICE, these taxes are implicitly determined. Essentially, the carbon tax is a dual variable of the optimal control problem. Formally, the tax rate should be defined as the ratio between the marginal utility of an extra unit of emissions and the marginal utility of an additional unit of consumption. In his applications, Nordhaus uses (for technical reasons) the ratio between the marginal utility of emissions and the marginal utility of capital. The tax rate is then defined as -1000 times this ratio. For reasons of comparability, we also use this measure.

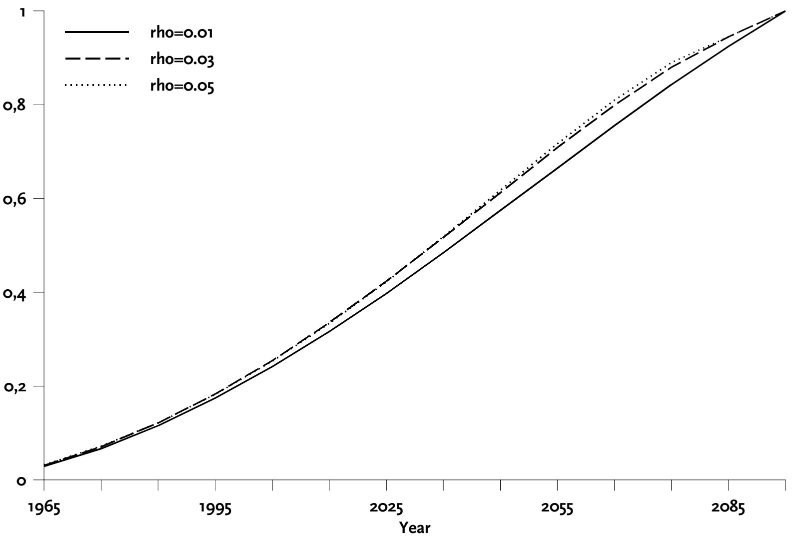
In the reminder of this section, we apply the method to illustrate the optimal timing of abatement activity as discussed and developed in the introduction of Section 2. The illustration starts from the idea that the basic question at hand is how much of total abatement activity has to be performed in a certain period of time to satisfy (exogenously determined) constraints. We therefore determine the total activity (either in terms of emissions or abatement costs) and subsequently determine the (cumulative) amount of activity that has been performed after a certain number of periods. The development of the (cumulated) activity over time gives a good impression of the timing of activity.

Figure 4.1 Timing and cumulative costs at different discount rates



Figures 4.1 and 4.2 illustrate the timing of activity using the method just discussed. It is evident that the dependence of timing on the discount rate in the comparative-static exercises chosen here is numerically limited. However, the figures illustrate that in terms of costs, high discount rates tend to make it optimal to shift abatement efforts to the future. Not surprisingly, the same conclusion is drawn when considering the cumulative emissions; they are relatively large in early periods when the discount rate is relatively large.

Figure 4.2 Timing and cumulative emissions at different discount rates



4.4 The costs of delayed action

The analysis so far assumed that - apart from the constraint that the CO_2 concentrations should be stabilised in the STAB-scenarios - the social planner was fully free to determine the optimal policy (that is, the optimal rates of investment in physical capital and the environment). Much of the debate on optimal timing has - however - been phrased in terms of the costs of delaying action (that is, the costs of not reaching an agreement on how to fight climate change resulting in longer periods of in-action). The aim of this subsection is to exactly address this question. This is done by determining the costs of constraining the rate of emission abatement to be equal to zero for a certain number of decades. In model terms, we exogenously impose $\mu=0$ for a certain number of periods and allow it to be optimally chosen afterwards. This exercise is done in the context of stabilisation scenarios. More specifically, we assess the costs of delay in two scenarios in which we impose the constraint that the CO_2 concentration does not exceed 450 and 550 ppmv, respectively from 2095 onwards.[33]

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[33] The optimal investment rate in physical capital does take into account the effects of the presence of the constraint on CO_2 concentrations from the outset. In that sense, environmental concerns are (indirectly) taken into account.

Figure 4.3 Emission profiles with delayed action

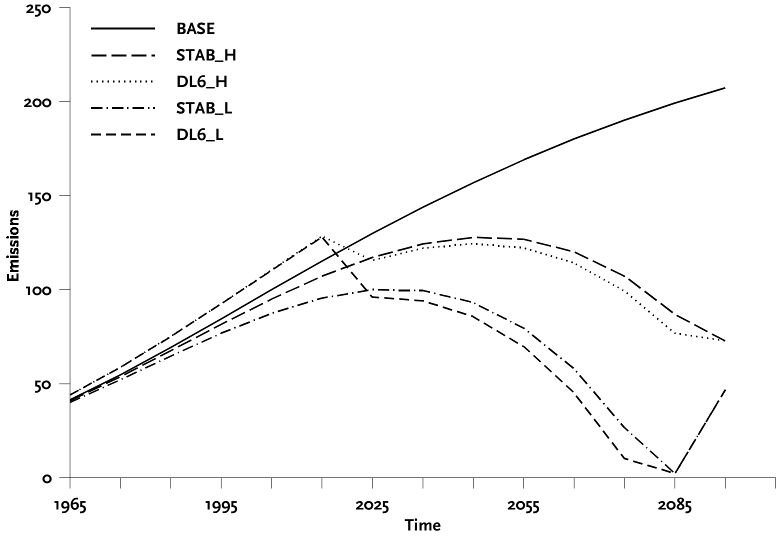
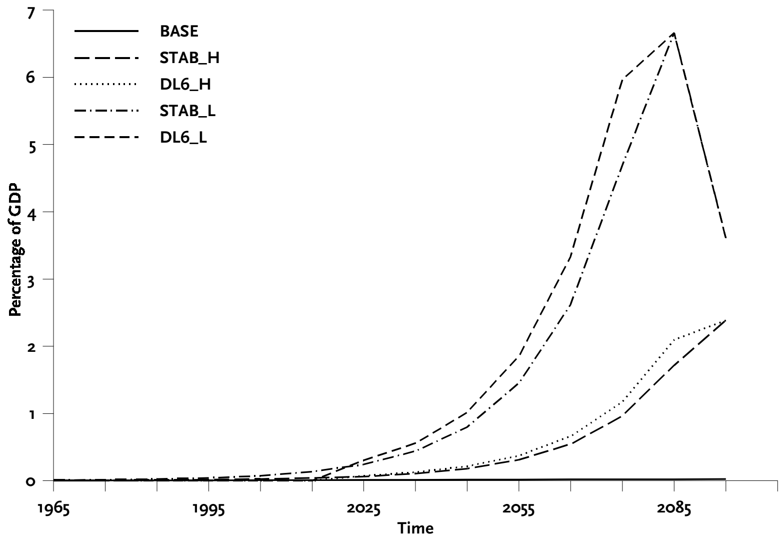


Figure 4.3 depicts the emission profiles for five scenarios. The first is the fully unconstrained scenario (BASE) in which no stabilisation is required and investments are optimally chosen in all periods. Next, there are two stabilisation scenarios resulting in stabilisation of CO2 concentrations from 2095 onwards at 450 and 550 ppmv respectively (STAB_L and STAB_H) in which investments are still optimally chosen in all periods. The deviation from the BASE-scenario is therefore purely due to the imposition of the stabilisation constraints. We see the typical pattern that we already saw in the previous section of initially rising emissions that are only cut back at the end of the planning period in order to assure satisfaction of the stabilisation constraint. This result is the outcome of various mechanisms of which discounting, the desire to smooth consumption, benefits of curbing emissions that fall relatively far into the future and convex costs of emission reductions are most important as discussed in the previous section. Finally, we have two cases in which emission abatement is restricted to be absent in the first 60 years (that is, until 2025). In the absence of short-run abatement, emissions rise relatively fast initially (even faster than in the BASE-case). After the planner is free to optimally choose emission reductions, emissions drop immediately to a level slightly below the level in the STAB-case (reflecting the working of the turnpike theorem; see footnote 26). Emissions subsequently remain slightly below those in the STAB-case in order to ultimately reach a stable level of CO_2 concentrations.

Figure 4.4 **Investment rates in the environment**



The abatement investment rates are depicted in Figure 4.4. In the scenarios resulting in stabilisation at 550 ppmv they gradually increase, always remaining below 3% of GDP. Relatively small investments are thus needed to achieve stabilisation of CO_2 concentrations in this model. The picture is slightly different in the case in which stabilisation is required at 450 ppmv from 2095 onwards. There we also see the tendency to delay investments in the environment (for reasons explained above), but now we see that in the last but one period, investments are at their maximum (that is, emissions are brought back to zero). This at first sight strange result can only be understood by recognising the fact that the DICE-model assumes that it is technically feasible to reduce emissions to zero at relatively small costs (slightly less than 7%). Combining this with the very low benefits of curbing emissions due to the long transition periods of the climate system, corner solutions in which maximum abatement effort is optimal with stringent standards can occur.[34]

Finally, we turn to the costs of stabilisation and delay. Our measure of costs is as follows. We first determine the present discounted value of utility (PDVU) in the unconstrained world (UNC). Next, we determine the PDVU in the worlds of stabilisation (in the absence of delay). Finally, to get a monetary measure of costs, we determine the consumption level in the first period that would be required in the stabilisation worlds to make the PDVU equal to the PDVU

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[34] In our view, these results are not realistic and suggest the need for a different calibration of the model in order to avoid these corner solutions. This could be done by increasing the costs of emission reduction, increasing the convexity of the cost function and reducing the technical possibilities to bring emissions back to very low levels. Results on this are available upon request from the author. By increasing b_2, the result of extremely strong reductions in emissions at the end of the planning horizon indeed disappears.

in the unconstrained world. This consumption level is then related to the consumption level in the unconstrained world. This exercise is repeated for the situations in which optimal environmental policy is delayed. The results of this exercise are numerically illustrated in Figure 4.5.

Figure 4.5 Costs of stabilisation and delayed action

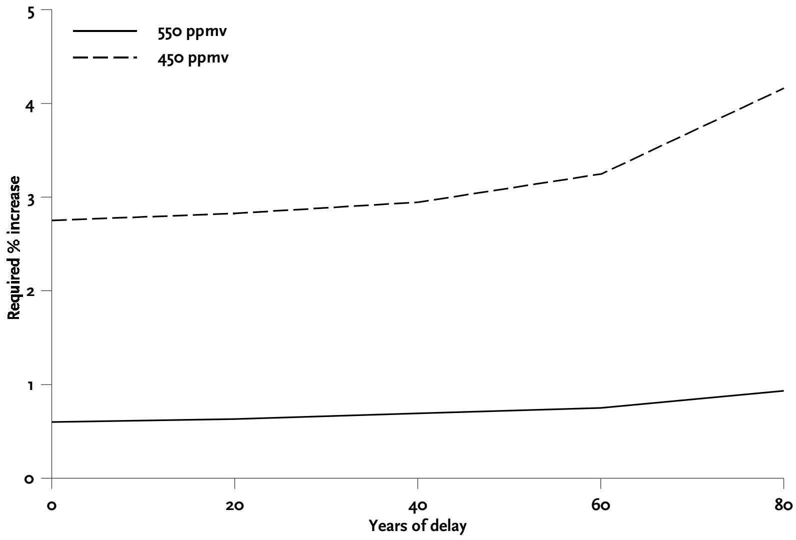


Figure 4.5 reveals the following. With otherwise optimal policies, stabilisation results in a consumption loss of, respectively, 0.6 and 2.8% of consumption in the unconstrained world. In other words, in the stabilisation world, consumers should receive 0.6 (2.8%) more consumption in the first period than in the unconstrained world in order to be equally well of in terms of their present discounted value of utility over the time period 1965-2095. The figure further reveals that delay increases the welfare costs. Delaying action with 80 years (until 2045) increases welfare costs with a factor of approximately 1.5. Still, the welfare costs are relatively minor, essentially reflecting the relatively low costs of bringing emissions back to zero assumed in the DICE-model.

4.5 Endogenising emission-saving technological progress and the implications for timing

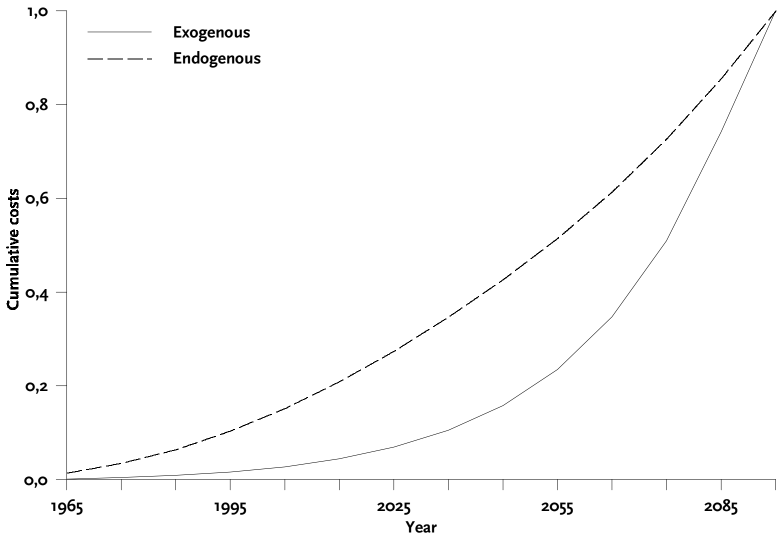
In the DICE model, abatement activity is modelled as only affecting the current flow of emissions. In other words, abatement activity in the model is like installing an end of pipe technology with a lifetime of one period (that is 10 years in DICE). Endogenous improvements in abatement technology (for example, as the resultant of learning by doing or learning by using) are thus not taken into account. In the context of the debate on optimal timing of abatement activity, this is a serious shortcoming of the model. As we discussed in Section 3.1, the endogeneity of technological progress is one of the prominent factors that tend to make early action optimal. Neglecting the endogeneity of technological progress in other words biases the results of modelling exercises with DICE towards delayed response. The remainder of this section discusses a simple attempt to incorporate an element of endogenous technological progress and considers the consequences for the optimal timing of abatement activities.

Let us be somewhat more precise on the modelling of emission saving in DICE. The emission intensity of production (*E/Q*) can be reduced by investing in abatement activity (see Section 2.1). A first obvious way to endogenise the emission intensity is to allow the intensity to depend not only on instantaneous abatement activity, but also on past abatement activity. More formally, we propose to change the relationship between emissions and output as follows

$$E = \sigma h Q \quad \text{where} \quad h_t = 1 - \mu_t - (1 - \delta_h)(1 - h_{t-1})$$

So the emission-output ratio depends negatively on current abatement activity and a weighted average of abatement activities in the past, where activities performed long ago have a relatively limited impact due to depreciation of 'knowledge' on how to produce in an emission extensive way. The special case with $\delta_h=1$ (depreciation of knowledge is immediate) results in the DICE-model. The other extreme in which 'knowledge does not depreciate at all ($\delta_h=0$) results in $h_t=h_{t-1}-\mu_t$. In the more general case in which $\delta_h<1$, the emission intensity depends negatively on both current abatement activities and accumulated abatement activities in the past. The implications of this change in the model can easily be understood by considering a stationary situation in which h is constant. The emission intensity of production is then straightforwardly derived as $[\sigma(\delta_h-\mu)]/\delta_h$. It is evident that this stationary emission intensity negatively depends on the investment rate and positively on the rate of depreciation of technological knowledge (or, stated alternatively, the rate at which knowledge becomes obsolete or useless for the development of better technologies).

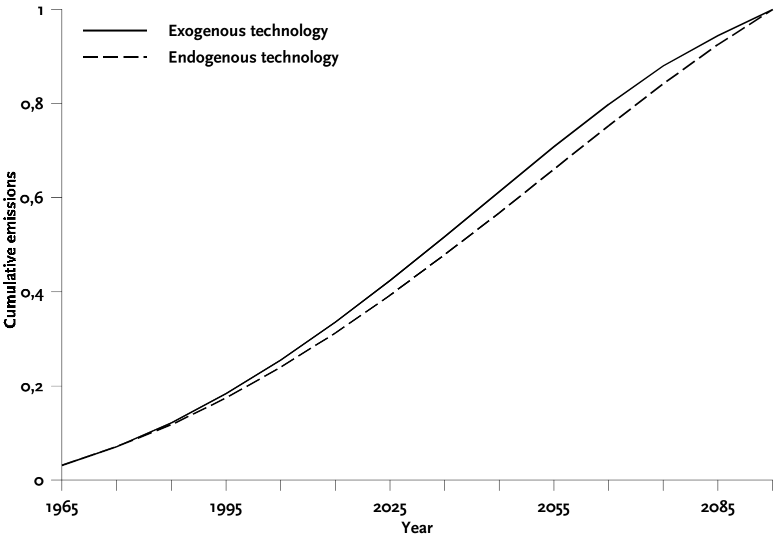
Figure 4.6 Timing and endogenous technology



In order to illustrate the impact of endogenising technological progress, we use the STAB-scenario discussed previously with stabilisation at 550 ppmv. In order to illustrate the implications for the timing of climate policy of endogenising technological progress, we perform a comparative-static exercise with respect to the depreciation rate of knowledge (δ_h). More specifically, we consider the following two cases: (i) the depreciation rate is unity, that is technological progress is exogenous as in the standard DICE-model, and (ii) the depreciation rate is equal to a half (δ_h=0.5). The latter value implies that 50% of the knowledge generated becomes obsolete after 1 period. On an annual basis, it corresponds to a rate of depreciation of knowledge of 6.7%.

The results of this comparative-static exercise are illustrated in Figures 4.6 and 4.7. They clearly illustrate the impact of endogenising technological progress. Figure 4.6 reveals that it becomes optimal to make a relatively large share of the total costs needed to stabilise the CO_2 concentrations early in time. The intuition for this result is simple. As part of the returns to investing in a clean environment (still) accrue in the future, early action becomes relatively advantageous. The implications for the optimal path of emissions are illustrated in Figure 4.7. This figure reveals that the attractiveness of early action translates into relatively little emissions in early years and more in later years.

Figure 4.7 Timing and Endogenous technology



This subsection has shown that the introduction of endogenous technological progress increases the attractiveness of early abatement. The reason for this is simple. Reducing emissions now by developing technologies to combat emissions adds to the knowledge on how to combat emissions in the future. Put alternatively, the presence of an inter-temporal knowledge spill-over urges for early action. Associated with this optimal emission pathway is a development of concentrations that initially rises relatively slowly in order to increase relatively fast at the end of the period. These results are based on a 'new' perspective on technological progress as advocated in the 'new' or 'endogenous' growth theory. These new theories drop the neo-classically oriented perspective on technological progress and were already discussed in Section 3.1. Future modelling efforts should further be devoted to satisfactorily incorporating the (endogenous) process of technological progress. This will unavoidably require more emphasis on (integration of) bottom-up approaches in the modelling efforts. Recently, some first steps have been made. In an interesting study, Dowlatabadi (1998) discusses the sensitivity of estimates of mitigation costs to assumptions about technological change. In particular, he considers the effects of allowing for (i) a link between technological change and policy intervention and (ii) endogenous technological progress by modelling learning processes. Although he admits that he is 'not in a position to specify models of endogenous technical change with great accuracy' (p. 491), he concludes that the incorporation of mechanisms of endogenous technological change are far-reaching and often tend to favour early action. We also refer to very recent studies by Buonanno et al. (2000) and Gerlagh and van der Zwaan (2000) for comparable conclusions.

5 Evaluation and conclusion

The issue of the optimal timing of starting to reduce CO_2 emissions is a complex one. Many of the arguments explicitly rely on relatively new concepts in economic theory that have to do with uncertainties, irreversibilities and the nature of technological progress. We have argued that these concepts are indeed of crucial importance for providing a good answer to the question on the optimal employment of 'when flexibility'. The influence of these factors on the optimal timing is ambiguous and hence from a purely theoretical point of view, both early and delayed action can be defended. Therefore, we are left with a problem that can only be resolved on an empirical basis.

The deployment of calibrated applied general equilibrium models can in principle give a feeling for the quantitative relevance of the various arguments in favour of early and delayed action, respectively. Some examples of such applications were provided in Section 4. However, the currently available applied general equilibrium models are only to a limited extent able to serve this goal because they only incorporate some of the mechanisms that influence the optimal timing of emission reductions. In particular, they often have a neo-classically oriented perspective on technological progress (that is, technological progress is exogenous), and they often do not explicitly deal with uncertainties, irreversibilities and their consequences for decision making processes. Future efforts should thus be devoted to satisfactorily incorporating uncertainties, irreversibilities and the (endogenous) process of technological progress in order to reveal the complex trade-offs that policy makers face in designing robust policies aimed at a sustainable future. This will unavoidably require more emphasis on (integration of) bottom-up approaches in the modelling efforts.

A second and related issue that arises in modelling exercises is related to the time horizon of the models. This time-horizon is in most economically oriented models restricted to about at most a century ahead. Good reasons can be put forward for not going beyond such a time scale because uncertainties about technological developments, consumption patterns, population growth, development patterns of less developed countries, etc. become so large that hardly any reasonable analysis can be made. Nevertheless, for the issue of Climate Change, this is problematic given the very long-term dynamics of carbon cycles (several hundreds of years).[35] For these reasons, new scenario analyses in which the (economic) uncertainties are resolved as much as possible, but at some stage also taken for granted and made explicit, may contribute to our understanding of future possible developments and the working of crucial dynamic mechanisms (without claiming that reliable forecasts are being made). We expect that current

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[35] We refer to, for example, Hasselmann et al. (1998) and Jacoby et al. (1996) for an extensive discussion about the need to consider long time horizons given the 'long memory' of the climate system and the problems of the mismatch in time-horizon between climate models and economic models that need to be integrated to study climate change.

efforts devoted to these issues will increase our understanding on the relevance of the factors that determine the optimal timing of abatement efforts. But it should also be emphasised that many of the uncertainties that characterise the problem of climate change are fundamental and unlikely to be resolved in a fully satisfactory way by more research, at least not in the near future. The best that researchers can do in such a world is to try and reveal the wide range of potentially relevant trade-offs in determining whether it is better to act immediately or to adopt a wait-, see- and learn strategy.

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