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Optimal CO_2-abatement with socio-economic inertia and induced technological change

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Abstract

The impact of induced technological change (ITC) in energy/climate models on the timing of optimal CO_2-abatement depends on whether R&D or learning-by-doing (LBD) is the driving force. Bottom-up energy system models employing LBD suggest strong increases in optimal early abatement. In this paper we extend an existing top-down model supporting this view according to the notion that socio-economic inertia interferes with rapid technological change. We derive analytical results concerning the impact of inertia and ITC on optimal initial abatement and show a wide range of numerical simulations to illustrate magnitudes. Inertia now dominates the timing decision on early abatement, such that LBD might even have a negative effect on early abatement and the impact of R&D is limited. However, ITC still reduces costs of stabilizing atmospheric CO_2-concentrations considerably.

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1. Introduction

Scenarios of energy use and CO_2-emissions as well as the costs of limiting climate change depend crucially on technological change. Many (older) energy/climate models assume exogenous technological progress, usually called autonomous energy efficiency improvements (AEEI). Results are very sensitive to the AEEI. Modelers have been well aware that energy technology does not fall "like manna from heaven", but rather results from R&D or learning-by-doing (LBD). Therefore, researchers have implemented methodological advancements of new growth theory into energy/climate models. Endogenizing technological change has significant effects on the cost of stabilizing atmospheric CO_2-concentration and on the optimal timing of abatement efforts. Since we can accelerate technological change, the option to induce technological change provides more degrees of freedom in decision-making. Therefore, it is not surprising that the majority of models reveals drastic reductions in compliance costs, particularly in case of LBD, as learning is basically for free (Azar and Dowlatabadi, 1999; Grubb et al., 2002; Löschel, 2002). Most LBD models suggest increased near term abatement to realize learning potentials (Rasmussen (2001), and Manne and Richels (2004) are exceptions[1]). More diverse results can be found in the case of R&D. Goulder and Schneider (1999) show that the impact of R&D on total abatement costs depends on assumptions about potential crowding out and spillovers between environmental and non-environmental R&D (similarly Popp (2004)). Furthermore, including R&D seems to have a rather negligible effect on optimal timing decisions.

Most models with induced technological change (ITC) are rather complex and lack analytical tractability. Goulder and Mathai (2000) – from here on referred to as GM – use an analytical model, which also allows for comparing R&D and LBD. They show that induced technological change necessarily reduces total costs of stabilizing the atmosphere at any given level. Moreover, initial abatement is always lower with R&D than without. On the other hand, the effect of LBD on initial abatement is ambiguous in theory, although a wide range of numerical simulations show that LBD has a strong increasing effect on early abatement.

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[1] Rasmussen (2001) reports a slight negative impact of LBD on optimal near term abatement in a multi sector model. LBD cost reductions only occur in the renewable energy sector and follow a knowledge accumulation function similar to the one used in the model to be presented here. Manne and Richels (2004) implement LBD in the bottom-up energy system model *MERGE*. They basically find no impact of LBD on the optimal path but major cost reductions.

This paper demonstrates that GM's results on the optimal timing of abatement are biased by their assumption that there is no inertia in the energy system. GM neglect that there are barriers that slow the diffusion of new energy technologies. Sathaye et al. (2001) identify missing markets, distorted prices, financial market imperfections, tariffs on imported equipment preventing international diffusion, transaction costs, distorted incentives, public goods nature of information, but also social, cultural, and behavioral norms and aspirations as the main barriers.[2] However, these barriers are difficult to quantify and modeling them would overload the analytic framework of the GM model, which requires perfect market assumptions. But GM also ignore that energy consumption is partly determined by the capital stock, which turns over only slowly. *Figure 1* shows the typical turnover times for energy producing and consuming equipment. On the lower end, refrigerators and cars run for at least ten years, whereas energy generating and distributing infrastructure lies in a range of 30 to 50 years. Moreover, the building stock and transport patterns are likely to remain unchanged for decades if not centuries.[3] Thus, significant emission reductions in a short time imply expensive premature capital turnover costs. Taking into consideration the other barriers to diffusion, the use of turnover costs seems to be a conservative estimate of the costs of socio-economic inertia.

In order to keep the analytical lucidness of GM's model, inertia is included in the simplest way, i.e. by penalizing rapid changes in the level of abatement from one period to the next (Ha-Duong et al., 1997). GM identify that major gains from ITC result from the option to accelerate abatement efforts when they have become cheaper due to previous R&D or LBD. Thus, it seems reasonable to assume that inertia might offset some of the gains from ITC. However, we show here that the cost reducing effect of ITC in GM's model is robust to the inclusion of inertia. Furthermore, numerical simulations demonstrate that even an inert path can show considerable acceleration of emission reduction. This is mainly caused by discounting.

Ha-Duong et al. (1997) observe an upward shift of optimal initial abatement efforts due to inertia. Their study neglects LBD but they hypothesize that a model incorporating both inertia and LBD would call for even higher early abatement. Already GM's analytical model cannot prove them unambiguously right. But inertia even aggravates ambiguity, so that in contrast to

[2] See also Jaffe et al. (2002).

[3] Similar time spans are reported by Hammitt et al. (1992) and Grubb (1997).

GM's numerical simulations and the large majority of LBD studies to date, the model presented here shows a small, perhaps even negative influence of LBD on early abatement. This can be explained by the notion that inertia shifts initial abatement significantly upward, so that decreasing returns from LBD prevent additional gains from more pronounced early actions. The paper further shows that ITC reduces the costs of stabilizing atmospheric CO_2-concentrations, but also that its effects on optimal timing have been overstated. Inertia seems to be a much more important determinant of the optimal abatement path than is ITC.

We restrict our analysis to the stabilization of CO_2-concentrations at a given target. GM also explore a cost-benefit setting with a damage function relating CO_2-concentration levels to economic costs. In such a setting one could measure the impact of inertia on the optimal target, which equals marginal costs and benefits. As inertia adds to abatement costs, higher inertia would therefore imply a less strict target. However, inherent in a cost-benefit approach of climate change is the problem that (high) current abatement costs are weighted against future benefits from avoided climate change, which are discounted over several decades. Consequently, as can also be observed in GM's model, less initial abatement is justified and the optimal atmospheric CO_2-concentration is rather high. In such a framework, costs to overcome inertia as part of the total abatement costs are expected to have only a minor impact on optimal abatement.[4]

The paper is organized as follows: In the next section, a simple analytical model of ITC via LBD or R&D and inertia is introduced and analyzed particularly with respect to the behavior of optimal initial abatement. *Section 3* describes the functional forms and parameter values chosen for numerical simulations, before *Section 4* is devoted to the extensive presentation of results, including sensitivity analyses. Finally, *Section 5* summarizes and discusses the main insights.

2. The model

The main assumptions and the structure underlying the treatment of technological change follow GM, whereas inertia is modeled as in Ha-Duong et al. (1997). The model can be considered as

[4] In a cost-benefit framework as in GM, the discount rate and the assumed damage function are the main determinants of optimal abatement. Restricting ourselves to a stabilization target approach avoids the issue of discounting future benefits, which implies strong ethical assumptions (see e.g. Tol, 1999). There is much wider agreement that discounting is appropriate for abatement costs, and that discount rates should reflect the (social) opportunity costs of capital (Markandya et al., 2001). Applying different discounting schemes is deferred to future research.

"top-down" given the implicit postulation that the world economy is at its optimum at first, i.e. any no-regret options due to market failures or non-optimizing behavior are completely exhausted. Now the economy faces a new constraint, namely to stabilize atmospheric CO_2-concentrations at a certain level at a certain point in time. Technological change enters the model either through R&D or through LBD, such that there are actually two different models, which use a common overall structure so as to allow for comparisons between both specifications. The following subsection describes the abatement cost function used in either mode, before the R&D and the LBD specifications are explored separately.

2.1. The abatement cost function

Following basically GM's notation, $C^A(A_t, H_t, E_t^0)$ is the aggregate abatement cost function of a competitive economy, in which producers minimize costs. The superscript A indicates that costs refer to the direct level of abatement, compared to the costs of change that are described down below. A_t denotes the level of abatement at time t, H_t refers to the level of technology (or knowledge), and E_t^0 are the baseline emissions allowing the cost function to depend on the relative rather than the absolute level of abatement.[5] The function is assumed to have increasing marginal abatement costs ($C_A^A > 0$ and $C_{AA}^A > 0$). Technology is supposed to reduce costs directly ($C_H^A < 0$) and also decreases marginal abatement costs ($C_{AH}^A < 0$). Finally, abatement becomes less costly the more there is to abate, thus giving $C_E^A < 0$ and $C_{AE}^A < 0$.

The costs of change are considered to be $C^R(R_t)$, where R_t is a variable reflecting the speed of change in abatement and is related to the difference between current and previous abatement, i.e. R_t might become negative. Since transition costs are likely to increase also at an increasing rate, this requires $C_{|R|}^R > 0$ and $C_{|R||R|}^R > 0$. The rather unpleasant notation of the absolute values of R takes care of the fact that not only rapid switches from low to high levels of abatement are expensive, but also rapid switches back, i.e. once our cars are running on hydrogen, it would be costly to move to carbon fuels again. For analytical simplicity, the absolute values will be replaced below by squares of R_t. The transition costs are assumed to be independent of the level

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[5] Since baseline emissions are given, one could also provide the cost function with a time index and abandon E_t^0 as an argument of the function.

of technology, because they reflect the costs of significantly speeding up installation of abatement technology, i.e. replacing equipment at a higher rate than depreciation. Installation costs themselves are included in the direct abatement costs C^A and are therefore subject to technological change. Following Ha-Duong et al. (1997) we assume that direct abatement costs and change costs are separable, i.e. total abatement costs are $C^{tot}(A_t, H_t, E_t^0, R_t) = C^A(\cdot) + C^R(\cdot)$. This formulation allows for restrictions on the functional form of the change costs, without restricting the direct cost function as well; this improves analytical tractability.[6]

2.2. Technological change through R&D

In the R&D formulation of the model the social planner has to choose an optimal abatement path together with optimal investments in R&D to accumulate knowledge. Adding the corresponding equations of motion for knowledge as well as atmospheric CO_2-concentrations and a concentration constraint the planner faces the following intertemporal minimization problem:

$$\min_{A_t, I_t} \int_0^\infty (C^A(A_t, H_t, E_t^0) + C^R(R_t) + p(I_t) I_t) e^{-rt} dt \tag{1}$$

s.t.

$$\dot{R}_t = -R_t + A_t - A_{t-1} \text{ for } t \geq 1 \tag{2}$$

$$\dot{S}_t = -\delta S_t + E_t^0 - A_t \tag{3}$$

$$\dot{H}_t = \alpha H_t + k\Psi(I_t, H_t) \tag{4}$$

$$R_0 = 0 \tag{5a}$$

$$\dot{R}_0 = 0 \tag{5b}$$

$$H_0,\ S_0 \text{ given and } S_t \leq \overline{S} \text{ for } t \geq T, \tag{6}$$

where I_t is investment into R&D, $p(I_t)$ is the real price of a unit of research, r is the discount rate, S_t is atmospheric CO_2-concentration, δ is the natural rate of CO_2 uptake, α is the rate of autonomous technological change, $\Psi(\cdot)$ is the knowledge accumulation function, k is a parameter that defines the magnitude of ITC and $\overline{S}$ is the stabilization target to be met from year T onwards.

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6 As we add costs of change to a (top-down) abatement costs function, we cannot apply this setup to analyze whether inertia might explain why top-down models tend to predict higher abatement costs than bottom-up models. After all, adding additional costs actually widens the gap even more.

Expression (1) states that the planner minimizes the discounted sum of direct abatement costs, costs of change and investment costs from now on to the infinite future. Expression (2) defines that R changes with the difference between current and previous abatement. So R can be handled as a state variable that depends on the control variable and a lagged control variable, and therefore the system is solvable as a model with delayed response following Kamien and Schwartz (1991, Part II, Section 19).[7] The choice of this setup requires some discussion. A more intuitive approach might be to set $\dot{A}_t = R_t$ with R_t as a control variable and A_t as a state variable. But this approach was dismissed for several reasons. First of all, we are interested in the optimal path of A_t rather than the change in A_t, especially at early time steps. But to derive the value of A_t from R would require an initialization of A_t, influencing results, or would require an additional control variable A_0. More importantly, results would be more difficult to interpret, as we would obtain the shadow price of the change in abatement, rather than the shadow price of abatement. The ambiguities reported below would also appear in the alternative setup. Another advantage of the approach we are using is that the GM model is fully nested in it and appears for $C^R(R_t) = 0$ ensuring the highest possible degree of comparability.

A drawback in the formulation of equation (2) is that the change costs R enter the objective function lagged by one period.[8] For large time steps, this formulation is inexact. However, in this manner we avoid the use of lead variables and introduce the costs of change nonetheless and in a simple form at that. Assuming infinitesimally small time steps the formulation does not alter the qualitative insights gained from the analytical model.

The equation of motion for S (expression 3) shows that CO_2-concentration declines through natural removal of atmospheric CO_2 and abatement, but increases through baseline emissions. According to expression (4) knowledge rises by the exogenous rate α plus induced knowledge

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[7] El-Hodiri et al. (1972) develop a growth model with lags in the employment of the optimal capital stock and Mann (1975) models the delay between advertising expenditures and their impact on sales. For an application of the technique in the context of resource economics, see Wilman and Mahendrarajah (2002).

[8] Following the delayed response setup one gets $R_2 = R_1 - R_1 + A_1 - A_0 = A_1 - A_0$, where it would be more appropriate to have $R_2 = A_2 - A_1$. This would get closer to the intuitive approach to set $R_t = \dot{A}_t$ following the setup in Grubb et al. (1995) as well as in Hourcade and Chapuis (1995). But both studies do not provide any analytical derivations; and therefore for their simulations they presumably used a similar definition of the rate as here akin to the time derivative.

accumulation. $\Psi(\cdot)$ is assumed to be positive and increasing in I_t with diminishing returns ($\Psi_I(\cdot) > 0$, $\Psi_{II}(\cdot) < 0$). Whether $\Psi_H(\cdot) > 0$ or $\Psi_H(\cdot) < 0$ depends on whether knowledge accumulation is characterized by "standing on shoulders" meaning that researchers built on successful work of their predecessors; or whether there might be a "fishing out" of opportunities assuming that there exists only a limited amount of knowledge, so that it gets more difficult to achieve additional knowledge the more is already exhausted. Analytically a decision on the behavior of knowledge accumulation with respect to H is not necessary, but it is helpful (for the later sufficiency of the solution) to ensure concavity by presuming $\Psi_{HH}(\cdot) < 0$, which seems reasonable no matter if we are in a "standing on shoulders" or "fishing out" world. The relative importance of ITC compared to autonomous technological change is defined through k, which is used in the analysis as a switch to "turn on ITC" through an increase from $k = 0$ to $k > 0$, allowing for comparative statics.

Expressions (5a) and (5b) take care of the starting point problem due to the lagged control variable in (2). Finally, condition (6) forces CO_2-concentrations not to exceed the concentration target $\overline{S}$ from period T on.

2.2.1. *Solving the problem*

As mentioned in the previous section, the model is set up with a delayed response mechanism and the first order conditions are obtained, following Kamien and Schwartz (1991). As already indicated above, it is convenient at this point to accept some loss of generality by replacing the broad form of the change cost function with a quadratic function, such that

$$C^R(R_t) = mR_t^2, \tag{7}$$

where m is a parameter that defines the magnitude of costs associated with the rate of change.[9] Plugging (7) into (1), abandoning the superscript of the direct cost function and switching signs of the objective function to obtain a maximization problem leads to the current value Hamiltonian

$$\mathcal{H}_t = -C(A_t, H_t, E_t^0) - mR_t^2 - p(I_t)I_t - \tau_t(-\delta S_t + E_t^0 - A_t) + \mu_t(\alpha H_t + k\Psi(I_t, H_t)) + \lambda_t(-R_t + A_t - A_{t-1})$$

for $t < T$,

[9] The parameter m corresponds to the "D" in Ha-Duong et al. (1997), indicating the magnitude of inertia in the economy, i.e. the higher m, the higher the penalty to rapid change.

where τ_t, μ_t and λ_t are the shadow values of S_t, H_t and R_t respectively. Following GM a negative τ_t is used, departing from the usual setup in the control literature, to clarify the positive shadow value (i.e. the marginal benefit) of abatement and the negative impact of additional (baseline) emissions.

For $t \geq T$, the concentration constraint must be satisfied, hence it is necessary to form the Lagrangian

$$\mathcal{L}_t = \mathcal{H}_t + \eta_t(\overline{S} - S_t).$$

Assuming an interior solution, and therefore ruling out negative abatement, together with costate equations, state equations and transversality conditions, a set of first-order conditions (FOCs) can be derived from the maximum principle. Since the negative of (1) and (3) as well as (4) are concave in A, R and H, the FOCs are also sufficient (Kamien and Schwartz, 1991, Part II, Section 3). The relevant necessary conditions that provide insights with respect to the optimal abatement path are

$$\frac{\partial \mathcal{H}_t}{\partial A_t} + \left.\frac{\partial \mathcal{H}_t}{\partial A_{t-1}}\right|_{t+1} = 0 \Leftrightarrow C_A - \lambda_t + \lambda_{t+1} = \tau_t \quad \text{(FOC 1)}$$

$$\dot{\lambda}_t = r\lambda_t - \frac{\partial \mathcal{H}_t}{\partial R_t} - \left.\frac{\partial \mathcal{H}_t}{\partial R_{t-1}}\right|_{t+1} \Leftrightarrow \dot{\lambda}_t = (1+r)\lambda_t + 2mR_t \quad \text{(FOC 2)}$$

and

$$-\dot{\tau} = r(-\tau) - \frac{\partial \mathcal{L}_t}{\partial S_t} \Leftrightarrow \dot{\tau}_t = (r+\delta)\tau_t - \begin{cases} 0, & \text{for } t < T \\ \eta_t, & \text{for } t \geq T. \end{cases} \quad \text{(FOC 3)}$$

For the sake of completeness we also state the remaining FOCs, which are

$$\frac{\partial \mathcal{H}_t}{\partial I_t} + \left.\frac{\partial \mathcal{H}_t}{\partial I_{t-1}}\right|_{t+1} = 0 \Leftrightarrow \frac{p'(I_t)I_t + p(I_t)}{k\Psi_I} = \mu_t \quad \text{(FOC 4)}$$

and

$$\dot{\mu}_t = r\mu_t - \frac{\partial \mathcal{H}_t}{\partial H_t} - \left.\frac{\partial \mathcal{H}_t}{\partial H_{t-1}}\right|_{t+1} \Leftrightarrow \dot{\mu}_t = \mu_t(r - \alpha - k\Psi_H) + C_H. \quad \text{(FOC 5)}$$

(FOC 1) states that in each period optimality requires the sum of the marginal costs of abatement and the value of a change in current abatement evaluated in the next period λ_{t+1} less the current value of a change in abatement λ_t to be equal to the shadow-costs of CO_2-emissions τ_t.

(FOC 2) shows that λ_t is not necessarily strictly increasing or strictly decreasing over the whole time horizon, but depends on R_t. However, an acceleration of abatement activities implies an increase of the multiplier due to increasing marginal transition costs.

To achieve a more intuitive expression of (FOC 1), a first step is solving the differential equation in (FOC 2) with respect to t, which gives

$$\lambda_t = -2m\int_t^{\infty} R_s e^{-(1+r)(s-t)} ds \, . \tag{8}$$

Using (8) for λ_t and λ_{t+1} in (FOC 1) leads to

$$C_A + 2m\left(\int_t^{\infty} R_s e^{-(1+r)(s-t)} ds - \int_{t+1}^{\infty} R_s e^{-(1+r)(s-t-1)} ds \right) = \tau_t \, .$$

Now, for incremental time steps the difference in parentheses can be simplified to get

$$C_A + 2m\left((1 - e^{1+r}) \int_t^{\infty} R_s e^{-(1+r)(s-t)} ds + e^{1+r} R_t \right) = \tau_t \, . \tag{FOC 1'}$$

GM define τ_t as the optimal carbon tax in a decentralized competitive economy, where no other market failures exist, thus being a pure Pigouvian tax that corrects the global externality associated with CO_2-emissions. In this model, the optimal tax must equal the sum of direct marginal costs of abatement and marginal costs of the difference between current and next periods discounted sum of the rates of abatement. The explanation for this is that e.g. if abatement rises over time, an addition in current abatement increases the current rate (and therefore current costs of change) but reduces the rate in the next period. We will refer to the net effect as the costs of abatement shifting.

2.2.2. Implications of ITC and inertia

The focus of this section is to analyze whether there are some indications for opposite effects of ITC and inertia on the optimal abatement path and particularly on initial abatement. Optimality requires that the FOCs are fulfilled at every point in time. Therefore, to first answer the question how the optimal abatement path reacts to the introduction of transition costs, (FOC 1') is differentiated with respect to m and evaluated at $m = 0$, which gives

$$C_{AA}\frac{dA_t}{dm} + C_{AH}\frac{dH_t}{dm} + 2\left((1 - e^{1+r}) \int_t^{\infty} R_s e^{-(1+r)(s-t)} ds + e^{1+r} R_t \right) = \frac{d\tau_t}{dm} \, ,$$

solving for dA_t/dm leads to

$$\frac{dA_t}{dm} = \frac{\frac{d\tau_t}{dm} - C_{AH}\frac{dH_t}{dm} - 2\left((1-e^{1+r})\int_t^{\infty} R_s e^{-(1+r)(s-t)} ds + e^{1+r} R_t \right)}{C_{AA}}. \tag{9}$$

The impact of m on A_t turns out to be ambiguous for $t > 0$, as can be seen from (9). The denominator is positive (marginal abatement costs by assumption increase at an increasing rate) and $d\tau_t/dm$ is clearly non-negative, because switching from $m = 0$ to $m > 0$ imposes an additional cost to abatement and therefore increases the shadow-costs of emissions. Nothing can be said about how m changes the optimal value of H_t and additionally, the sign of the third term in the numerator, defining the change in the costs of abatement shifting, is ambiguous. Matters change if the analysis is restricted to the initial period. Evaluating (9) at $t = 0$ and using the assumption that $R_0 = 0$ and H_0 is fixed, results in

$$\frac{dA_0}{dm} = \frac{\frac{d\tau_0}{dm} - 2\left((1-e^{1+r})\int_0^{\infty} R_s e^{-(1+r)s} ds \right)}{C_{AA}}. \tag{10}$$

A_0 tends upward, because the shadow-costs of carbon emissions increase with the level of inertia as stated above. In the initial period, the sign of the change in the costs of abatement shifting can be derived. The integral is non-negative, because from abatement being non-negative follows that the sum of all possible decreases in abatement cannot exceed the sum of all increases and furthermore the increases must happen before the decreases and are therefore discounted less.[10] Altogether, the change in the costs of abatement shifting is negative. The intuition behind is that if the penalty to change is increased, then the optimal abatement path will be characterized by lower changes. Now, the negative sign leads to an overall positive numerator. So we can conclude that introducing costs of change put an upward pressure on initial abatement. Therefore, the above representation of the impacts of inertia can be seen as an analytical underpinning of Ha-Duong et al.'s (1997) or Grubb's (1997) numerical analyses that higher

[10] This argumentation denies the possibility of an extremely sharp increase in abatement in the first period that is not realized in the objective function due to the starting point problem. But several simulations even with unrealistically high costs of change did not show a tendency for such behavior. The reason is presumably the continuous increase in baseline emissions during the early periods and that there is no option to "over abate" at early periods to lower future baseline emissions.

inertia shifts optimal early abatement upward. From here on the term "inertia-effect" is used to refer to this tendency.[11]

To shed some light on the impacts of ITC in the presence of inertia (FOC 1') is now differentiated with respect to k, which gives

$$C_{AA}\frac{dA_t}{dk}+C_{AH}\frac{dH_t}{dk}+2m\left((1-e^{1+r})\int_t^{\infty}\left(\frac{dR_s}{dA_{t-1}}\frac{dA_{t-1}}{dk}+\frac{dR_s}{dA_{t-2}}\frac{dA_{t-2}}{dk}\right)e^{-(1+r)(s-t)}ds\right.$$
$$\left.+e^{1+r}\left(\frac{dR_t}{dA_{t-1}}\frac{dA_{t-1}}{dk}+\frac{dR_t}{dA_{t-2}}\frac{dA_{t-2}}{dk}\right)\right)=\frac{d\tau_t}{dk}. \qquad (11)$$

Unfortunately, (11) hardly provides any insights concerning dA_t/dk, as long as there are terms containing dA_{t-1}/dk and dA_{t-2}/dk. To circumvent this problem it is necessary to consider infinitesimally small time steps, such that successive changes in abatement through ITC are basically identical, i.e. it can be assumed that

$$\frac{dA_{t-2}}{dk}\approx\frac{dA_{t-1}}{dk}\approx\frac{dA_t}{dk}.$$

This assumption might look strong at first glance but it really does not postulate anything else but a relative robustness in the sense of similar behavior of an extremely small region of the optimal path (from $t-2$ to t) towards an incremental change in k. Applying this, (11) can be solved for dA_t/dk, which gives

$$\frac{dA_t}{dk}\approx\frac{\frac{d\tau_t}{dk}-C_{AH}\frac{dH_t}{dk}}{C_{AA}+2m\left((1-e^{1+r})\int_t^{\infty}\left(\frac{dR_s}{dA_{t-1}}+\frac{dR_s}{dA_{t-2}}\right)e^{-(1+r)(s-t)}ds+e^{1+r}\left(\frac{dR_t}{dA_{t-1}}+\frac{dR_t}{dA_{t-2}}\right)\right)}. \qquad (12)$$

For sufficiently small time steps, the integral in the denominator of (12) can be approximated as a sum and at time t the term in large parentheses can be written as

$$(1-e^{1+r})\left(\frac{dR_t}{dA_{t-1}}+\frac{dR_t}{dA_{t-2}}+\frac{dR_{t+1}}{dA_{t-1}}e^{-(1+r)}\right)+e^{1+r}\left(\frac{dR_t}{dA_{t-1}}+\frac{dR_t}{dA_{t-2}}\right),$$

which uses the fact that (2) implies $R_t = A_{t-1} - A_{t-2}$, such that $dR_s/dA_t = 0$ for $s - t > 2$. Furthermore, $dR_t/dA_{t-1} = 1$ and $dR_t/dA_{t-2} = dR_{t+1}/dA_{t-1} = -1$ so that the above expression simplifies to

[11] It seems necessary to point out that the analytical result is only valid in the vicinity of $m = 0$, but simulations do not provide any indication not to believe that it holds also around other values of m.

$$(1-e^{1+r})\left(1-1-e^{-(1+r)}\right)+e^{1+r}\left(1-1\right)=(1-e^{1+r})(-e^{-(1+r)})=1-e^{-(1+r)}>0 \text{ for } t>1.$$

Assumptions (5a and b) imply that $dR_t/dA_{t-2} = 0$ for $t = 1$, such that at $t = 1$ the second last expression reduces to $2-e^{-(1+r)} > 0$. Consequently, for $t = 0$, also $dR_t/dA_{t-1} = 0$, and the whole expression becomes zero. Defining the second term in the denominator of (12) as a function $f(r, t)$ the equation can be rewritten as

$$\frac{dA_t}{dk} \approx \frac{\frac{d\tau_t}{dk} - C_{AH}\frac{dH_t}{dk}}{C_{AA} + 2mf(r,t)}, \tag{12'}$$

$$\text{with } f(r, t) = \begin{cases} 0, \text{ for } t = 0 \\ 2-e^{-(1+r)}, \text{ for } t = 1 \\ 1-e^{-(1+r)}, \text{ for } t > 1. \end{cases}$$

The starting point problem, which is inherent in the delayed response setup, introduces some weird behavior of the function $f(r, t)$ during the first two periods. But from the analytical perspective the only relevant aspect is that $f(r, t)$ is clearly non-negative, because compared to the GM result, which can be recovered for $m = 0$, the only difference is the magnitude but not the sign of the denominator. Since C_{AA} is positive the denominator in total is positive. Thus, the direction of dA_t/dk depends only on the numerator. To start with, the second term ($-C_{AH}$) is positive, because by assumption knowledge decreases marginal abatement. Together with the fact that H increases with k we end up with a positive impact on current abatement. But on the other hand the first term of the numerator ($d\tau_t/dk$) is what GM call the "shadow-cost-effect". In their model, it turns out to be less than or equal to zero for every point in time. An intuitive explanation for $d\tau_t/dk \leq 0$ is according to GM that ITC provides an instrument to lower future abatement costs, such that additional emissions become less frightening, which reduces their shadow-costs. GM also demonstrate analytically that $d\tau_t/dk$ cannot be positive. It can be easily shown that their proof is valid also in this context.[12] Consequently, for any point in time there is a trade off between the shadow-cost-effect and the "knowledge-growth-effect" ($-C_{AH}dH_t/dk$), therefore the impact of k on A_t is ambiguous. But something can be said about the change of initial abatement A_0. As H_0 is fixed, evaluating (12') at $t = 0$, such that $dH_0/dk = 0$, gives

[12] The analytical proof shows that the assumption of $d\tau_t/dk > 0$ leads to a contradiction. It basically requires the right hand side of (12') to be strictly positive for $d\tau_t/dk > 0$, which is the case here. For the detailed proof see GM's Appendix A.

$$\frac{dA_0}{dk} = \frac{\frac{d\tau_0}{dk}}{C_{AA}}, \tag{13}$$

which is the same expression as in GM, indicating that initial abatement changes in the same direction as the initial shadow-cost.[13] As stated above the shadow-cost-effect is less than or equal to zero, implying a negative impact of ITC on initial abatement (this could be called "R&D-effect" in opposite to the upward inertia-effect).

From (13) it is tempting to conclude that the change in initial abatement is independent of change costs. But the shadow-costs τ increase with additional costs of transition. Thus, in this model ITC affects initial shadow-costs at a higher level and it is reasonable to think that the magnitude of the change in shadow-costs due to ITC declines if *m* increases, i.e. the larger the share of transition costs. However, it can be noted that the basic mechanisms of the GM model with respect to ITC through R&D are still at work. Initial abatement weakly goes down, implying some deferral of abatement. But in general, as can be seen from (12'), the impact of ITC on the optimal abatement path is decreasing in *m*. The reason is straightforward: A large share of change costs within the total costs makes the optimal path to get close to the smoothest path that satisfies the constraints. Thus, the larger *m*, the more expensive it is to move away from the smoothest path by taking advantage of the ITC option. Nevertheless, even for extremely high values of *m* there will be some downward pressure on initial abatement by "turning on ITC" through increasing *k*, all else being equal. On the other hand, as shown above, *m* has (ceteris paribus) an opposite inertia-effect. Analytically there is no way to gain any information about the relative magnitude of the two impacts, but as the simulations will show, it appears that for reasonable parameters, the upward inertia-effect tends to outweigh the downward R&D-effect.

2.3. Technological change through LBD

In this section the above model will be altered, such that technological change does not depend on expenditures on R&D anymore, but rather "comes for free" just by learning from the act of abatement. So in this case, the social planner only chooses an optimal abatement path, but she is well aware of the fact that early abatement lowers the costs of later abatement by accumulating

[13] The effect on initial abatement defined by (13) is not an approximation anymore, because it can directly be derived from (11) assuming dA_{t-1} and dA_{t-2} to be zero, as they are not defined for $t = 0$.

knowledge. At this point, for simplicity the function of change costs is already specified according to equation (7) and the planner solves

$$\min_{A_t} \int_0^{\infty} (C(A_t, H_t, E_t^0) + mR_t^2) e^{-rt} dt \tag{14}$$

s.t. $\dot{R}_t = -R_t + A_t - A_{t-1}$ for $t \geq 1$ (15)

$$\dot{S}_t = -\delta S_t + E_t^0 - A_t \tag{16}$$

$$\dot{H}_t = \alpha H_t + k\Psi(A_t, H_t) \tag{17}$$

$$R_0 = 0 \tag{18a}$$

$$\dot{R}_0 = 0 \tag{18b}$$

H_0, S_0 given, and $S_t \leq \overline{S}$ for $t \geq T$. (19)

The definitions of the variables and parameters are exactly as in the R&D model. Besides the fact that investment costs drop out of the objective function, only (4) changes, since now it is abatement itself that increases knowledge accumulation ($\Psi_A > 0$, $\Psi_{AA} < 0$).[14] Solving the problem involves the same assumptions about the existence of an interior solution and necessary first order conditions. For the sake of brevity a renewed statement of the Hamiltonian is forgone and it turns out that all (relevant) FOCs derived in *Section 2.2* are the same with the exception of (FOC 1'), which now is

$$C_A - \mu_t k\Psi_A + 2m\left((1 - e^{1+r}) \int_t^{\infty} R_s e^{-(1+r)(s-t)} ds + e^{1+r} R_t \right) = \tau_t \,. \tag{FOC 6}$$

Compared to the FOC in the R&D case, here the shadow-value of abatement is equal to the marginal costs of abatement and change of abatement, reduced by the value of learning from abating.

To proceed as in the R&D specification, the impact of a change in *m* is explored by differentiating (FOC 6) with respect to *m* and evaluating it at $m = 0$, which gives

[14] The assumption of decreasing returns of learning is motivated by the empirical observation of experience curves. See e.g. Dutton and Thomas (1984), Argote and Epple (1990) or Wene (2000) in the context of carbon-free energy sources.

$$C_{AA}\frac{dA_t}{dm}+C_{AH}\frac{dH_t}{dm}+\mu_t k\Psi_{AA}\frac{dA_t}{dm}+\mu_t k\Psi_{AH}\frac{dH_t}{dm}+k\Psi_A\frac{d\mu_t}{dm}$$

$$+2\left((1-e^{1+r})\int_t^{\infty}R_s e^{-(1+r)(s-t)}ds+e^{1+r}R_t\right)=\frac{d\tau_t}{dm}. \quad (20)$$

The above expression contains several terms that are difficult if not impossible to sign. To illuminate matters a little bit, considering (20) at $t = 0$ makes the second and fourth term of the left hand side become zero, since H_0 is fixed. Taking the fifth term as given for the moment and solving for dA_0/dm leads to

$$\frac{dA_0}{dm}=\frac{\frac{d\tau_0}{dm}-2\left((1-e^{1+r})\int_0^{\infty}R_s e^{-(1+r)s}ds\right)-k\Psi_A\frac{d\mu_0}{dm}}{C_{AA}+\mu_0 k\Psi_{AA}}. \quad (21)$$

First of all it can be noted that without ITC, i.e. $k = 0$, expression (21) reduces to expression (10) of the R&D case and A_0 tends upward if m increases. But if $k > 0$, things get unclear. Since knowledge lowers abatement costs, the shadow value of knowledge μ_0 cannot be negative. Thus, by assuming decreasing returns in knowledge accumulation, the second term in the denominator is negative, so that the sign of the ratio is already ambiguous. Furthermore, it turns out to be impossible to handle the behavior of the third term in the numerator, which adds even more uncertainty.[15]

Hence, there is no definite answer to the question whether in an ITC world initial abatement tends upward or downward if the inertia of the system increases.[16] This might be a surprising result at first glance. Optimal initial abatement tends upward in the R&D specification; so one might expect such a consequence all the more if it is possible to gain learning effects from early abatement. But there is uncertainty about the impact of LBD itself as it is shown now. Following the same steps as in the R&D case, the derivative of (FOC 6) with respect to k is taken, but this time evaluated at $k = 0$. Furthermore, the same assumptions about the impact of a change of k on neighboring values of abatement is used to derive an approximation of the effect as

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[15] A derivation of the sign of the third term in the numerator would require for a start an integration of the costate equation of μ_t, which is $\dot{\mu}_t = r\mu_t - \partial H_t/\partial H_t = (r-\alpha-k\Psi_H)\mu_t + C_H$. But the integration fails, since Ψ_H is not necessarily constant over time and multiplicatively connected with μ_t.

[16] The simulations will show that within reasonable ranges of parameters (which imply an upward sloping abatement path at least over the 21st century) increased inertia shifts optimal initial abatement up to ensure a smoother path during the early periods.

$$\frac{dA_t}{dk} \approx \frac{\frac{d\tau_t}{dk} + \mu_t \Psi_A - C_{AH} \frac{dH_t}{dk}}{C_{AA} + 2mf(r,t)}, \tag{22}$$

$$\text{with } f(r,\ t) = \begin{cases} 0, \text{ for } t = 0 \\ 2 - e^{-(1+r)}, \text{ for } t = 1 \\ 1 - e^{-(1+r)}, \text{ for } t > 1. \end{cases}$$

Compared to the R&D specification, there is an additional term in the numerator, which GM call the "LBD-effect". It is the value of a marginal change in knowledge due to a change in abatement. Together with the knowledge-growth effect there is a tendency for abatement to be increased by the introduction of ITC. On the other hand, there is still a negative shadow-cost-effect working in the opposite direction, justifying postponement of abatement, since it gets cheaper over time by accumulating knowledge.[17] Unlike the R&D case opposite effects remain even in the initial period, because at $t = 0$ equation (22) reduces to

$$\frac{dA_0}{dk} = \frac{\frac{d\tau_0}{dk} + \mu_0 \Psi_A}{C_{AA}}, \tag{23}$$

which is the same expression as in GM. The LBD-effect in (23) rules out that initial abatement necessarily declines. Actually, this effect is responsible for the increase in virtually all of GM's numerical simulations. In the existence of the LBD-effect, GM see weak support for Ha-Duong et al.'s (1997) claim that besides inertia, LBD would be an additional justification for higher initial abatement.[18] But in this model, there is an inertia-effect at work that has an ambiguous impact on initial abatement. The numerical simulations will show that there is a strong upward inertia-effect that gives very little room to additional cost-effective increases through LBD.

2.4. Summary of analytical results

To sum up the key results of the section, *Table 1* provides an overview over the main impacts (ceteris paribus) of inertia and ITC on optimal initial abatement. In the R&D specification, the GM model turns out to be robust in the sense that the qualitative results are unchanged, even though the formulation of inertia allows for a wide range of different assumptions about the behavior of abatement costs. On the other hand, in the LBD case, an ambiguous result is now perturbed with additional uncertainty. It is of course not a particularly surprising outcome that by

[17] As in the R&D case GM's analytical proof of the shadow-cost-effect being weakly negative is valid also in this enhanced setting.

[18] Note that Rasmussen (2001) is an example where the shadow-cost effect outweighs the LBD-effect.

increasing the complexity of the model an already indistinct result becomes even more uncertain, but it could have created a situation in which additional forces work in the same direction as the LBD-effect.

3. Functional forms and parameterization

To get an impression of the relative magnitudes of the different effects on an optimal abatement path derived in the previous section and the corresponding costs, numerical simulations are performed. The functional forms and main parameter values with respect to direct abatement costs, knowledge accumulation and CO_2 accumulation chosen for the simulations follow GM directly to ensure that the results are comparable at least with respect to the order of magnitude. Thus, total costs evolve as follows

$$C^{tot}(A_t, H_t, E_t^0, R_t) = C^A(\cdot) + C^R(\cdot) = M_c \frac{A_t^{\alpha_{c1}}}{(E_t^0 - A_t)^{\alpha_{c2}}} \frac{1}{H_t} + m^{\alpha_{c3}} \left| R_t \right|^{\alpha_{c4}}. \qquad (24)$$

The functional form of the direct abatement costs $C^A(\cdot)$ satisfies all the assumptions of the analytical section. Furthermore, costs tend to infinity if there is complete abatement of all emissions.[19] This specification is reasonable in the sense that the model considers virtually all anthropogenic CO_2-emissions and therefore does not allow for a backstop technology, which could serve as a substitute in all cases

GM set $\alpha_{c1} = 3$, $\alpha_{c1} = 2$, and $M_c = 83$, such that costs of reducing emissions by 25% in 2020 should fall in the range between 0.5% and 4% of global GDP. Moreover, using a 5% discount rate, the net present value of all abatement costs for reaching a 550 ppmv stabilization by 2200 should be some \$600 billion. Since GM only provide a rough scheme of their baseline emission path it was impossible to reproduce these values exactly. However, the optimal abatement paths generated with this model are sufficiently close to their ones, such that the above parameter values are applied as a reference point. Baseline emissions follow IPCC IS92a (Leggett et al.,

[19] To avoid possible divisions by zero during the optimization process, the programs include an additional condition that forces A_t to be strictly less than E_t^0.

1992) until 2110, peaking slightly above 26 GtC at that time. Afterwards, baseline emissions decline so as to stabilize at roughly 18 GtC around 2200.[20]

Now, costs of change $C^R(\cdot)$ enter the numerical model basically in the same way as in the analytical part except that $R_t = A_t - A_{t-1}$ is used, which implies $\dot{R}_t = -R_t + A_{t+1} - A_t$. This has previously been avoided to achieve an analytically more convenient lag-structure instead of a lead-structure. Numerically this is irrelevant and has the advantage of gaining one more observation in the very beginning, which is of particular interest. The exponents α_{c3} and α_{c4} in equation (24) are set equal to 2 in the central case.[21] This formulation of change costs follows Ha-Duong et al. (1997), who claim that results from several modeling studies of capital stock turnover justify a nonlinear increase in costs. They interpret m as the characteristic timescale of turnover in the global energy system. From the half-life of capital for a depreciation rate of 4% they derive $m = 20 \approx ln2/0.04$ years as a lower bound for inertia, representing a realistic assumption for the average rate of replacement of appliances and cars. To incorporate typical timescales of the turnover in energy systems and additional sources of inertia, Ha-Duong et al. (1997) also analyze a value of $m = 50$. In order not to overstate the impact of inertia, in this model a rather low end value of 30 is used for the central case.

Splitting up abatement costs into direct and change costs requires a recalibration. Therefore, the parameter M_c of equation (24) is altered, such that the sum of total discounted costs (without ITC) including costs of change equals the sum in the GM central case. A reduction from 83 to 74 fulfils this requirement. Additionally, with $m = 30$ the share of the sum of discounted transition costs within total costs over the next century is approximately 33%. For $m = 20$ and $m = 50$ the according percentages are 18% and 55% respectively, which are lower but basically in line with the values of Ha-Duong et al. (1997), who report 31% and 71%.

[20] Baseline emissions are assumed to decrease (over five years) with the somewhat arbitrary logistic function

$$\frac{dE_t^0}{dt} = 0.75 \cdot \left(\frac{(E_t^0 - E^{min})}{(E^{max} - E^{min})} - 1 \right) (E_t^0 - E^{min}), \text{ with } E^{max} = 26.3\ GtC \text{ and } E^{min} = 18\ GtC.$$

[21] For the sake of simplicity, m is used instead of m^2 in the analytical part. Furthermore, in the simulations, the employment of the absolute value of R_t makes it possible to do sensitivity analyses with respect to the exponent α_{c4}.

Turning to the equations defining technological change, knowledge accumulates autonomously at a rate $\alpha = 0.005$. Furthermore, the returns from ITC in the R&D case raise knowledge according to

$$\Psi(I_t, H_t) = M_\Psi I_t^\gamma H_t^\varphi, \tag{25a}$$

with $M_\Psi = 0.0022$ and $\gamma = \varphi = 0.5$. This is a standard knowledge production function, which is widely used in the endogenous technological change literature.[22] It employs constant returns to scale and implies that knowledge generation is characterized by "standing on shoulders", but with decreasing returns. GM calibrate M_Ψ, such that direct abatement costs decline by some 30% in their R&D case. The price of investments into R&D is assumed to be $p(I_t) = I_t$, thus, via expression (1) costs of R&D increase squared. This represents the idea that there is only a limited pool of (potential) researchers and they must be drawn away from other sectors at increasing costs, i.e. there is a crowding out in the sense of Goulder and Schneider (1999) and Popp (2004). To use a consistent approach in the LBD specification knowledge increases by

$$\Psi(A_t, H_t) = M_\Psi A_t^\gamma H_t^\varphi \tag{25b}$$

with the same parameter values as before, such that there are decreasing returns in learning, mimicking the behavior of experience curves.[23]

Finally, we follow GM in using a slightly more realistic formulation of the accumulation of CO_2 in the atmosphere than the one used in the analytical section that goes back to Nordhaus (1994, chapter 3):

$$\dot{S}_t = \beta(E_t^0 - A_t) - \delta(S_t - PIL), \tag{26}$$

where β is set to be 0.64 meaning that only 64% of anthropogenic emissions actually contribute to the atmospheric CO_2-concentration and on the other hand, a natural rate of carbon uptake δ, which equals 0.008 (per annum), only reduces concentration levels above the preindustrial concentration (PIL) of 278 ppmv. The concentration level of 2000 as a starting point is assumed to be 360 ppmv.

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[22] A similar function is used by Nordhaus (2002) and goes back to Romer (1990), whose original specification would appear for $\varphi = 0$.

[23] Grubb et al. (2002) criticize the use of such a knowledge production function for modeling LBD as it would imply – as they incorrectly claim – that 50% of the LBD gained in one period dissipates exponentially in each subsequent period and hence understates LBD potentials.

In the central cases stabilization targets of 550 ppmv will be analyzed, which are to be achieved by 2200. The 550 ppmv level received great attention in the literature and therefore ensures comparability of results. It simply refers to a rough doubling of preindustrial concentration; hence it contains no further scientific foundation of being a "safe" target. The model is solved in five-year steps from 2000 until 2300. In the last period, steady state conditions require abatement and CO_2-concentrations to remain constant, to eliminate any unsmooth behavior at the very end. The model runs on GAMS 21.1 using the CONOPT3 solver.[24] Usual computational difficulties related to the path dependence of LBD that potentially runs solvers into local optima are negligible here, since only one path is chosen optimally in opposite to models of competing technologies.[25]

4. Results of numerical simulations

In this section the main results from a wide range of simulations are presented in the following way. Firstly, the behavior of the optimal abatement path in the presence of inertia but without ITC is presented for the central case parameter values stated in the previous section. Afterwards the timing of optimal abatement in the R&D and LBD modifications is presented, before changes of overall costs of stabilization and optimal CO_2-taxes are shown.

Most of the results gain their significance from a comparison with the GM study. Thus, it is necessary to redo their simulations under the baseline emission path constructed for this model.[26] It turns out that the model reproduces all their results adequately, also with respect to the responsiveness to certain parameter changes, but the impact of ITC is slightly lower within all model runs. This seems to be acceptable, because the difference is well within the same order of magnitude and the model including inertia is calibrated against the redone simulations.

Nevertheless, one important drawback of this study needs to be pointed out. In both ITC specifications (R&D and LBD) there are four cases to be considered: With or without ITC and low inertia as well as with or without ITC and high inertia. So there is no real ceteris paribus situation. As already indicated above, the results in *Sections 4.2* to *4.4* are presented in contrast

[24] The GAMS code is available from the authors upon request.
[25] For a discussion of the reliability of different solvers in the context of LBD in energy technologies see Manne and Barreto (2004).
[26] The simulations are done using $M_c = 83$ as described in *Section 3*.

to the GM situation to overcome this problem. This strategy can be defended by the fact that the two base cases, i.e. the model in the GM parameterization (M_c = *83*) and in the inertia parameterization (M_c = *74* and m = *30*) each without ITC (k = *0*), have by calibration the same NPV of total abatement. Furthermore, costs of change account for 33% of the total costs from 2000-2100, but are responsible for only some 10% of the total costs over the whole simulated time span. Additionally, it can be seen from *Figure 2* that the two cases also hardly differ in the overall behavior of the optimal abatement path. So it can be concluded that the two cases are sufficiently comparable.

4.1. Optimal abatement-paths in the presence of inertia

As mentioned right before *Figure 2* shows the similarity of the two base cases on a large time scale. Abatement is accelerating until the beginning of the next century and slowly increases for another 50 years before it turns down. Baseline emissions are already falling from 2115 but abatement remains relatively high such as to meet the concentration target by 2200. At the year 2200 the optimal path kinks down, because baseline emissions are low and the concentration level can be maintained with relatively low abatement efforts compared to the high levels that were necessary to reduce CO_2- concentrations in order to meet the target.

To get an impression of how the optimal abatement path reacts towards changes in the assumed sluggishness of the systems, *Figure 3* shows the range of several additional model runs, within the lower (m = *20*) and the upper end (m = *50*) of the Ha-Duong et al. (1997) parameters. Only the first one hundred years, which are the relevant ones from the policy point of view, are shown. *Figure 3* underlines one of the main findings of the analytical part, namely the upward pressure of inertia on initial abatement. On the other hand, the graphs prove the intuitive reasoning that higher costs of change would lead to a more smooth abatement path and therefore require higher initial abatement, to be only part of the story. Instead, an important rationale lies in the forces of discounting, which do affect costs of change in the same way as direct abatement costs. Looking at the graph for m = *50* it is clearly optimal to have a fairly flat path as long as possible and realize high transition costs from acceleration not before the second half of the century.

The high inertia case implies significantly more early abatement than the low one (about 0.3 GtC), but the picture changes, such that around 2075 some 0.5 GtC less must be abated. Part of this effect is due to the setup of the model, which incorporates the implicit assumption that the choice of the initial level of abatement is free of transition costs. Therefore, the model tends to overstate optimal initial abatement. But additional model runs with zero discounting show that due to the fact that baseline emissions are mainly increasing, the former argument of a smoother path towards the stabilization target that requires higher initial abatement is valid. This cause for an upward shift would be less dependent of assumptions regarding transition costs towards the initial period. However, it should be noted that we are not aiming at a precise estimate of initial abatement, but rather investigate how different assumptions about the inertia of the system change the reaction of optimal early abatement towards technological change.

4.2. Optimal timing in the presence of R&D

4.2.1. Central case

In this section the focus is on how an optimal path characterized by inertia is altered if technological change can be induced via R&D. Therefore, in the two base cases, the parameter *k* is switched from zero to one. Recall from the analytical analysis that early abatement is expected to go down, independent of any assumptions about the underlying inertia of the system (R&D-effect). *Figure 4* shows the optimal abatement paths of the two base cases each with and without R&D. The optimal paths without R&D are very similarly affected by introducing R&D. Due to the shadow-cost-effect, optimal abatement is reduced in the first decade and actually over the whole 21st century - slightly in the beginning but more pronounced in the last 25 years. Looking at the first two decades it becomes obvious that at least during that period the main determination of each path lies in the assumed inertia and is not much altered by introducing R&D.

4.2.2. Sensitivity of the impact of R&D on initial abatement

An extensive sensitivity analysis with respect to the assumed inertia of the system also for extreme values of *m* has been done to underpin especially the results presented in *Figure 3* and *Figure* 4. Not surprisingly, given the analytically derived insights, initial abatement always increases with *m* and decreases if the R&D situation is compared with the non-R&D situation. For the sake of brevity, these rather tedious results are not presented in detail. In contrast, the following question is more broadly examined: What if the GM model is “true” apart from a single parameter that has to be adjusted and how much would be the impact of R&D under these circumstances? This is compared with the assumption that the inertia model is the correct one aside from a certain parameter. *Figure 5* shows the percentage reduction of initial abatement due to R&D under different assumptions about the discount rate *r*, the stabilization target *S* (formerly denoted as $\bar{S}$) and parameters guiding the evolution of knowledge over time, namely the relative magnitude of ITC (M_Ψ), stronger benefits from previous knowledge ($\varphi = 0.75$) or oppositely "fishing out" ($\varphi = -0.5$), higher autonomous technological change ($\alpha = 0.01$), and finally no autonomous technological change at all ($\alpha = 0$). By comparing the two central cases it can be seen that the reduction is cut by half in the inertia-model compared to the GM model. Similar drastic declines in the impact of R&D are observable for alterations in the knowledge parameters. Reductions in the effect of R&D are still noticeable for different values of the discount rate and the stabilization target, with the extremely ambitious $S = 350$ ppmv target being the only exception, in which R&D remains powerful.

Looking at the bars, it is tempting to conclude that the downshifting R&D-effect on initial abatement in the presence of inertia is severely limited. But this view neglects the fact that in the model ITC only affects the direct abatement costs. *Figure 6* outlines the share of transition costs within total costs during the 21st century. By calibration, they amount for some 33% in the central case and therefore also in the simulations where only M_Ψ or φ are altered. The contribution of costs of change to total costs increases with the discount rate, because higher discounting implies later abatement and hence requires fast transition at some point in time. The same argument is valid for a higher stabilization target.[27] Taking *Figure 5* and *Figure 6* together it becomes obvious that the main reason for the lower impact of ITC on initial abatement lies in the fact that a smaller fraction of costs is affected by ITC. Within this smaller fraction, the R&D-effect is quite noticeably. Nevertheless, as one would have expected from the analytical part, R&D and inertia seem to interfere with each other. From the $S = 350$ case follows that a low share of transition costs gives room for an R&D-effect in the "usual" magnitude. But looking at the extreme differences in the shares of transition costs between $S = 450$ and $S = 650$ as well as between $r = 0.025$ and $r = 0.075$ it is at least remarkable to see rather similar reductions of the R&D-effect. However, it cannot be ruled out that it is mainly due to the parameterization.

[27] In both cases also costs of change are deferred into the future. However, looking at the data underlying *Figure 5* indicates that the share of change costs within total costs increases due to a stronger decline in direct costs. The opposite holds true for lower discounting or a lower stabilization target.

To complete the picture about what's going on in the initial period, *Figure 7* gives an impression of the absolute values.[28] Independent of the parameters chosen (with the $S = 350$ case being somewhat aside), initial abatement much more depends on the question whether the "true" model is characterized by inertia or not rather than the presence of R&D. Therefore with respect to the optimal timing of abatement efforts, inertia seems to be crucial. We can sum up the main results of this section as follows: If the inertia model is believed to describe the reality more adequately, optimal initial abatement is comparatively high but remains on this level relatively long, before it accelerates significantly, at even higher rates as without inertia. It is primarily the assumed magnitude of inertia in the system that determines the optimal timing in the near future. However, ITC still has a noticeable effect on initial abatement, which can be seen as support for GM's results.

4.3. Optimal timing with LBD

4.3.1. Central case

Over the whole simulated time scale the optimal abatement path in the presence of LBD follows roughly the picture in *Figure 2*. However, there are some remarkable differences in near term behavior. *Figure 8* shows the optimal abatement paths of the two central cases with and without LBD. The solid lines indicate that LBD increases initial abatement in the GM model, i.e. the LBD-effect outweighs the shadow-cost-effect before by 2030 long-term gains from enhanced learning are exploited and the difference turns negative. But in the inertia model things are quite different. Initially, abatement is at a higher level due to inertia, but it is virtually unaffected by LBD (the two graphs basically lie upon each other) until about 2025 where small reductions can be observed, which get more pronounced over time, implying a noticeable advantage for deferring action. Thus, like in the R&D specification it is the inert path that shows the fastest acceleration at the end of the century. However, the main conclusion to be drawn from *Figure 8* is that in the presence of inertia the LBD-effect and the shadow-cost-effect seem to balance each other. In the numerical part of GM's study initial abatement goes significantly up under almost all different assumptions about parameter values. The results of the sensitivity analyses of the next section reveal that GM's outcomes do not generally resist the introduction of inertia.

[28] Information about the initial period also implies similar optimal behavior in the following periods, since almost all model runs show very smooth behavior at the beginning. So it is not the aim to say that optimal abatement in the year 2000 should have been e.g. 0.5 GtC. It should rather be interpreted as "relatively high" or "relatively low" abatement within the next, say 20 years, because comparable figures could be drawn until 2020.

4.3.2. *Sensitivity of the impact of LBD on initial abatement*

To address the orders of magnitude of the change in initial abatement if knowledge accumulation is enhanced by LBD, the model is run with the same parameter changes as in the R&D sections. In the GM model, LBD increases initial abatement noticeably except for $S = 350$ and $S = 450$. But in the presence of inertia it remains almost unchanged and for $r = 0.025$, $M_{\Psi} = 0.0044$, and $\alpha = 0$ actually the sign of the impact switches, and LBD lowers initial abatement. *Figure 9* also shows the change of initial abatement under different assumptions for the exponent of the rate of change (α_{c4}) and for the characteristic timescale of the energy system (m).[29] Decreasing the exponent implies that small rates are relatively expensive and vice versa. Therefore, *Figure 9* illustrates that the more costly changes are, the lower the impact of LBD, which can be even negative.

Recall from the discussion of the analytical analysis that already GM could not rule out a negative impact of LBD. But in their sensitivity analysis, the $S = 350$ ppmv case is the only one for which they report a negative impact of LBD. In the redone analysis here a decrease by 7.49% matches quite well with the 8.88% computed by them. GM state that numerically the positive LBD-effect can be quite substantial. Thus, the $S = 350$ ppmv case looks like an "outlier" for a rather unrealistic scenario, especially as they do not provide a result for the much more reasonable 450 ppmv case, which already shows the same tendency.[30] However, the main question is why inertia almost eliminates the generally substantial positive effect on initial abatement, since this is not at all a particularly intuitive result given e.g. Ha-Duong et al.'s (1997) claim that within their analysis of inertia they have probably underestimated the value of early abatement because of neglecting the effects of LBD. As in the R&D case a point could be made about the fact that LBD primarily affects direct abatement costs and therefore the impact on initial abatement should be alleviated. But this would only explain a reduction of the effect and not necessarily a change in direction. A more relevant reason can be derived from *Figure 10,* which goes back to the absolute values for initial abatement.[31] As in the R&D simulations, the magnitude of early abatement is dominated by the assumptions with respect to the discount rate

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[29] Since the inertia model is calibrated for $\alpha_{c4} = 2$ and $m = 30$ there are no corresponding cases of the GM model.

[30] Actually, further sensitivity analyses, which are not reported here, show that if a 450 ppmv target is to be achieved and we alter the other parameters in the same way, LBD has always a negetive impact on initial abatement in the presence of inertia.

[31] Like in *Figure 9* values for the GM specification for changes of α_{c4} and m are left out due to the lack of compareability.

and the stabilization target and also whether inertia is present or not. Inertia shifts initial abatement upwards. Comparing the absolute values in *Figure 10* with the relative changes in *Figure 9* it becomes obvious that LBD has a decreasing impact exactly in those cases where initial abatement is already rather high. Then, due to decreasing returns in knowledge accumulation, the gains from additional early abatement to induce long term cost reductions are low. But on the other hand, the option to defer some more abatement efforts to the future, when they will be much cheaper because of discounting and "free" knowledge enhancements from LBD, becomes much more valuable. Consequently, this latter cost shifting potential of LBD might outweigh the former cost reduction potential.

To elaborate this reasoning further, looking at the different parameterizations of the knowledge accumulation function in *Figure 9* illustrates that in the GM specification $M_{\Psi} = 0.0044$ implies a high cost reduction potential and initial abatement shifts strongly up, whereas for $M_{\Psi} = 0.0011$ this potential is rather low and higher initial abatement does not pay off that much. But with the already high initial abatement in the inertia case, the option to lower future costs is already sufficiently exploited for $M_{\Psi} = 0.0044$, such that abatement goes down, while this is not yet the case for $M_{\Psi} = 0.0011$ leaving room for a slight increase. The fact that a higher exponent of knowledge $\varphi = 0.75$ makes additional abatement relatively less valuable compared to the central case leads to a comparatively small increase in initial abatement in the GM case. At the previously higher levels in the inertia case for $\varphi = 0.75$ additional abatement is even less valuable and the cost shifting potential can hardly offset the cost reduction potential, ending up with early abatement being almost unchanged. For $\varphi = -0.5$ the reasoning holds vice versa.

Putting together the insights gained from modeling LBD in the presence of inertia we find that like in the R&D case costs of change do not necessarily lead to a smooth path and may rather imply noticeable acceleration of abatement efforts. Furthermore, if one considers the discount rate and the stabilization target as first order determinants of the optimal path, then inertia of the system seems to be of second order before finally LBD has a rather negligible impact. While in the R&D case this has just led to a decrease in magnitude of the effect on optimal near term abatement, the qualitative results in the LBD case are not clear-cut anymore. The numerical simulations imply that if it was believed that the inertia of the system justifies substantial near term abatement then LBD potentials should only very cautiously be used as arguments for even higher efforts, because one might neglect the option to defer some abatement to the future where it would be cheaper by the very act of abating.

4.4. Reduction of stabilization costs and optimal CO_2-tax

This section explores the impact of ITC on the overall costs for achieving a stabilization of the atmospheric CO_2-concentration. R&D can be considered as an option to lower future abatement costs, which implies greater flexibility with respect to optimal timing, so that R&D has a significant cost reducing effect. The values reported in *Table 2* show that the R&D option can indeed be fairly valuable. Compared to the non-R&D costs of roughly $400 billion reductions of 17% even within rather inert systems ($m = 50$ or $\alpha_{c4} = 1$) are substantial. For those parameterizations, which allow comparisons with the GM cases, cost savings for reaching the stabilization target due to R&D seem to be hardly affected by inertia. The reduction in direct costs, i.e. abatement costs and investment in R&D are only slightly less than in the GM case. Of course, the change in total costs, which include transition costs, is further reduced, but within an order of magnitude equivalent to the share of transition costs within total costs over the whole time horizon, e.g. some 10% in the central case. Thus, the cost reducing effect of R&D seems to work as usual, so to say, but is limited to the fraction of direct costs. Given the results from *Section 4.2* this can be seen as an indication that declines in costs are mostly due to the long-term decrease in unit costs and only to a lesser extend by the option to lower early abatement.

Since with LBD cost reductions are for free[32] the decline in costs should be even more pronounced compared to the R&D specification. *Table 2* shows that this is indeed the case. Reductions of one third for the central case result in total discounted costs of only $270 billion for stabilization, which is at the very low end of the range of most cost estimates. Nevertheless, recent studies like that by van der Zwaan and Gerlagh (2002) show similarly low costs. If large LBD potentials are assumed, even further cost reductions up to 50% are observable and savings are slightly less in the more inert cases. As in the R&D simulations, reductions are limited (by construction) to the fractions of direct abatement costs. Once again, the major cost decreasing

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[32] The reductions are free since total costs would go down even if the non-ITC path was not altered. A deviation from the non-ITC path only occurs to achieve additional gains from timing. An increase in early abatement efforts could be interpreted as optimal demonstration investments that pay off in the future whereas a decline just realizes cost savings from deferring abatement.

effect of ITC is related to lower future unit costs rather than timing and therefore works independently of the assumed inertia.

It should be noted that cost savings potentials for more ambitious stabilization targets (*S = 450* and *S = 350*) are substantial, especially since they are related to higher initial values. This observation differs from the outcome of the much more complex model of Manne and Richels (2004) who get similar reduction levels for 550 ppmv and above, but almost no decline in costs for lower targets. Their explanation is that for those targets the main part of the costs is associated with premature retirement of the energy capital stock.[33] In their model, the speed of transition is constrained to a maximum rate. Here, costs of change increase with the square of change but the rate is unbounded. This opens the option for much more flexibility with respect to timing and therefore significant cost reductions. *Table 2* also gives the impression that cost savings due to LBD are rather independent of the assumed inertia of the system. This result is consistent with Rasmussen (2001) who observes that welfare effects are not significantly altered if costs of capital adjustment are changed.[34]

Finally, *Table 2* illustrates the effect on costs in a more policy orientated way. An optimal CO_2-tax generated by the model (i.e. the shadow-cost of carbon) would start at some moderate $3.9 per ton of carbon for the GM and inertia central cases, and would then increase exponentially,[35] reach approximately $13 by 2025 and hit $100 around 2060. Since there are no market failures in the model (not even in the R&D sector), setting taxes along such an optimal path would generate an abatement behavior that follows the optimal abatement timing shown in *Figure 2* (Schneider and Goulder, 1997).[36] If the agent(s) can also decide on investment in R&D to lower abatement costs, the CO_2-tax would induce optimal investment decisions with respect to timing and magnitude. But the optimal tax to do so would be lower since the ITC option decreases the

[33] A further explanation of the divergence of the results might be due to a different choice of the date of stabilization, which they unfortunately do not report.

[34] Given the similarity of the findings with respect to costs it would be interesting to see whether Rasmussen's (2001) model could confirm the responsiveness of initial abatement with respect to turnover costs, given the fact that he also observes a slight decline in initial abatement due to LBD.

[35] The rate of increase is determined by the discount rate and the natural rate of carbon uptake, as implied by (FOC 3).

[36] As stated earlier, the tax is purely Pigouvian, correcting the global externality associated with CO_2-emissions. Goulder and Schneider (1999) analyze the impact of a carbon tax if the R&D investments of non-carbon based energy providers are distorted (because they ignore knowledge spillovers). Then the tax incentive to increase R&D involves additional benefits, reducing the overall stabilization costs. Thus, ignoring such market failure might understate the optimal tax path.

optimal initial tax. This shifts the whole tax path down, because (according to (FOC 3)) if the tax rises at a constant rate, then the percentage reduction is the same over the whole time horizon. *Table 2* reveals these reductions, so e.g. in the GM central case with R&D the optimal tax at each point in time would be 26.1% less than the corresponding tax without (i.e. more than one Dollar less per ton of carbon). In almost all R&D and LBD cases these tax shifts are quite noticeable and it turns out that inertia does not alter the reductions significantly. Similarly to the argument regarding reductions in total costs the impact of ITC on optimal taxes is slightly limited by the fact that first and foremost direct costs can be changed by R&D or LBD.

To sum up the main results of this section it can be said that GM's findings with respect to the reduction of overall costs of achieving stabilization of the atmosphere and of the necessary CO_2-taxes that would lead to the optimal timing of abatement, turn out to be robust against the inclusion of inertia and remain within the same magnitude. The declines in total costs and CO_2-taxes are limited to the range of direct costs, though, but this is mainly due to the modeled independence of direct costs and transition costs.

5. Conclusion and discussion

This paper develops a model that includes two factors previously identified as crucial for determining costs and timing of a transition to a less carbon intensive energy system: ITC and inertia. The model optimizes global emission abatement over the next three centuries, so that atmospheric CO_2-concentrations stabilize by 2200. Technological change is either enhanced through R&D or via LBD. Inertia is modeled by penalizing fast increases in abatement efforts with additional costs. Analytical insights are obtained especially with respect to optimal initial abatement and numerical simulations are done mainly to evaluate the relative magnitudes of the opposite effects implied by ITC and inertia. The model confirms the widely accepted view that ITC reduces the costs of stabilizing the atmospheric CO_2-concentration at any given level considerably. The inclusion of inertia lowers this effect only slightly. The benefits from ITC are mainly due to long term cost reductions per unit of abatement rather than a different timing of major emission reduction efforts.

Nevertheless, for today's policy considerations, near term costs and therefore optimal near term abatement requirements are particularly important. The numerical model reveals that the level of inertia assumed determines early abatement to a much higher degree than does ITC. In the central case considered, inertia implies relatively high abatement over the next decades. Although analytically R&D always reduces optimal initial abatement even in the presence of inertia, the numerical model shows that the option to do R&D and lower current abatement is limited, because at early stages the relatively high share of transition costs dominates optimal timing.

In the case of LBD, the model challenges the notion that potential gains from learning justify pronounced early abatement. Two interrelated effects are responsible for the fact that the model shows even negative impacts for not at all unrealistic parameter values. As inertia already implies relatively high initial abatement, additional upward pressure from LBD is limited because of decreasing returns from learning. Therefore, if learning potentials are sufficiently exhausted, optimality calls for a deferral of some abatement efforts as future actions are less costly due to the very act of learning together with discounting.

The model cannot be used for detailed policy considerations because of its high aggregation. However, the simplicity provides the insights into the different effects, particularly in the context of LBD. More complex models would disguise these effects, but they should at least show similar overall behavior with respect to parameter changes. Therefore, the results obtained in the present study can also be used for testing the plausibility of optimal solutions derived in disaggregated models. Furthermore, models showing an increase in optimal near term abatement due to LBD should be checked for their representation of inertia.

There are several limitations of the present model. The empirical base for the parameters that describe the endogenous change of technology is weak. The stabilization target is assumed to be known, while uncertainty about the target is only addressed via sensitivity analysis. The implications of uncertainty in optimal timing of abatement are not clear-cut. There might be benefits from waiting given the sunk cost character of abatement (Pindyck, 2000, 2002), but there are also irreversibilities in the climate, calling for early action (Kolstad, 1996).

Although the merits of the model lie in its simplicity, the high level of aggregation is another drawback. A promising compromise would be to break down the economy into two sectors, as in

Lecocq et al. (1998). The two sectors would differ in inertia, and therefore also in the effects of R&D and LBD. Additionally, knowledge spillovers between the two sectors could be incorporated. Similarly, instead of two sectors, two countries could be modeled, which have different starting positions for achieving a common emission reduction target. Since distributional effects are likely to have an important impact on climate targets and policies to achieve them, such a setting may provide valuable insights into burden sharing. Our model cannot address possible interactions between inertia and market imperfections, either in R&D or by LBD; for example, a slow turnover of the capital stock may limit demonstration effects of new technologies. We lump all inertia together, ignoring that there are different reasons why change is slow in the energy sector, and that this may affect the optimal emission reduction path. These issues are deferred to future research.

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References

Argote, L. and Epple, D. (1990). "Learning Curves in Manufacturing." Science 247: 920-924.

Azar, C. and Dowlatabadi, H. (1999). "A Review of Technical Change in Assessment of Climate Policy." Annual Review of Energy and the Environment 24: 513-544.

Dutton, J.M. and A. Thomas (1984). "Treating Progress Functions as a Managerial Opportunity." Academy of Management Review 9 (2): 235-247.

El-Hodiri, M.A., E. Loehman, and A. Whinston (1972). "An Optimal Growth Model With Time Lags." Econometrica 40 (6): 1137-1147.

Goulder, L.H. and K. Mathai (2000). "Optimal CO_2 Abatement in the Presence of Induced Technological Change." Journal of Environmental Economics and Management 39: 1-38.

Goulder, L.H. and S.H. Schneider (1999). "Induced technological change and the attractiveness of CO_2 abatement policies." Resource and Energy Economics 21: 211-253.

Grubb, M., T. Chapuis, and H. Ha-Duong (1995). "The economics of changing course - Implications of adaptability and inertia for optimal climate policy." Energy Policy 23 (4/5): 417-432.

Grubb, M., J. Köhler, and D. Anderson (2002). "Induced Technical Change in Energy and Environmental Modeling, Analytic Approaches and Policy Implications." Annual Review of Energy and the Environment 27: 271-308.

Grubb, M. (1997). "Technologies, energy systems and the timing of CO_2 emissions abatement." Energy Policy, 25 (2): 159-172.

Ha-Duong, M., M.J. Grubb, and J.-C. Hourcade (1997). "Influence of socioeconomic inertia and uncertainty on optimal CO_2-emission abatement." Nature 390: 270-173.

Hammitt, J.K., Lempert, R.J., and Schlesinger, M.E. (1992). "A sequential-decision strategy for abating climate change." Nature 357: 315-318.

Hourcade, J.-C., and T. Chapuis (1995). "No-regret potentials and technical innovation." Energy Policy 23 (4/5): 433-455.

International Energy Agency (2000). World Energy Outlook 2000. Paris: OECD Publications.

Jaffe, A.B., R.G. Newell, and R.N. Stavins (2002). "Environmental Policy and Technological Change." Environmental and Resource Economics 22: 41-69.

Kamien, Morton I. and Nancy L. Schwartz (1991). Dynamic Optimization - The Calculus of Variations and Optimal Control in Economics and Management, 2nd Edition. New York: North-Holland.

Kolstad, C.D. (1996). "Learning and Stock Effects in Environmental Regulation: The Case of Greenhouse Gas Emissions." Journal of Environmental Economics and Management 31: 1-18.

Lecocq, F., J.-C. Hourcade, and H. Ha-Duong (1998). "Decision making under uncertainty and inertia constraints, sectoral implications of the when flexibility." Energy Economics 20: 539-555.

Leggett, J.A., W.J. Pepper, and R.J. Swart (1992). "Emission scenarios for the IPCC: An update." In: J.T. Houghton, B.A. Callander, and S.K. Varney, eds. (1992). Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment. Cambridge and New York: Cambridge University Press: 69-95.

Löschel, A. (2002). "Technological change in economic models of environmental policy: a survey." Ecological Economics 43: 105-126.

Mann, D.H. (1975). "Optimal Theoretic Advertising Stock Models: A Generalization Incorporating the Effects of Delayed Response from Promotional Expenditure." Management Science 21 (7): 823-832.

Manne, A.S. and L. Barreto (2004). "Learn-by-doing and Carbon Dioxide Abatement." Energy Economics 26: 621-633.

Manne, A.S. and R. Richels (2004). "The Impact of Learning-By-Doing on the Timing and Costs of CO_2 Abatement." Energy Economics 26: 603-619.

Markandya, A., K. Halsnaes, A. Lanza, Y. Matsuoka, S. Maya, J. Pan, J. Shogren, R. Seroa de Motta, and T. Zhang (2001). "Costing Methodologies." In B. Metz, O. Davidson, R. Swart and J. Pan (eds): *Climate Change 2001: Mitigation*. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change: 455-498.

Nordhaus, W.D. (1994) Managing the Global Commons: The Economics of Climate Change. Cambridge, MA: MIT Press.

Nordhaus, W.D. (2002). "Modeling Induced Innovation in Climate-Change Policy." In: A. Grübler, N. Nakicenovic, and W.D. Nordhaus, eds. (2002). Technological Change and the Environment Washington, DC: Resources for the Future Press: 259-290.

Pindyck, R.S. (2000). "Irreversibilities and the timing of environmental policy." Resource and Energy Economics 22: 233-259.

Pindyck, R.S. (2002). "Optimal timing problems in environmental economics." Journal of Economic Dynamics & Control 26: 1677-1697.

Popp, D. (2004) " ENTICE: endogenous technological change in the DICE model of global warming." Journal of Environmental Economics and Management 48: 742-768.

Rasmussen, T.N. (2001). "CO_2 abatement policy with learning-by-doing in renewable energy." Resource and Energy Economics 23: 297-325.

Romer, P.M. (1990). "Endogenous Technological Change." The Journal of Political Economy 98 (5): 71-102.

Sathaye, J., D. Bouille, D. Biswas, P. Crabbe, L. Geng, D. Hall, H. Imura, A. Jaffe, L. Michaelis, G. Peszko, A. Verbruggen, E. Worrell, and F. Yamba (2001). "Barriers, Opportunities, and Market Potential of Technologies and Practices." In B. Metz, O. Davidson, R. Swart and J. Pan (eds): *Climate Change 2001: Mitigation*. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change: 345-398.

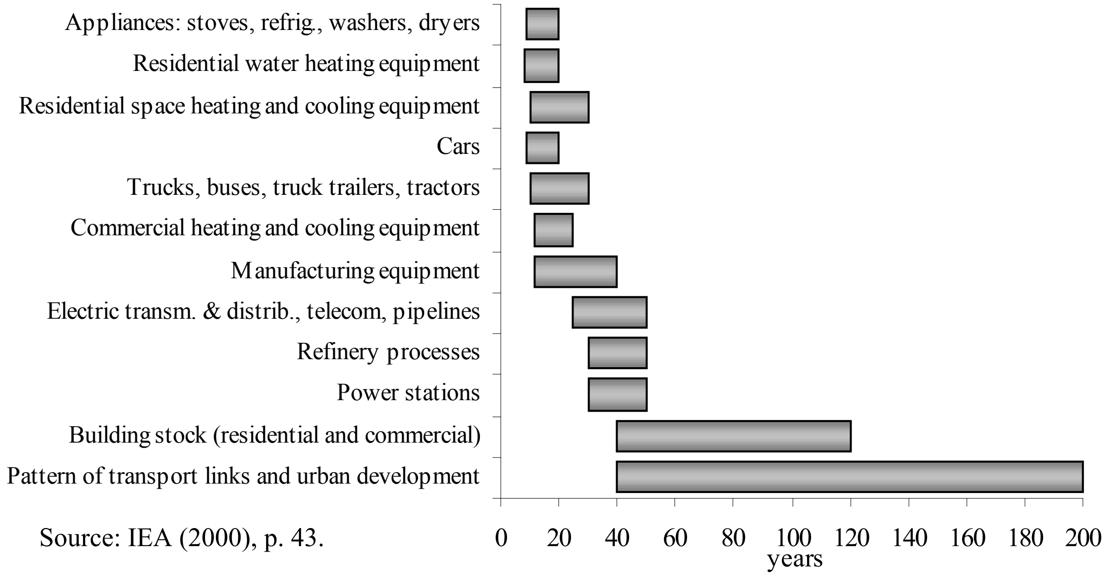
Schneider, S.H. and L.H. Goulder (1997). "Achieving low-cost emission targets." Nature 389: 13-14.

Tol, R.S.J. (1999). "Time Discounting and Optimal Control of Climate Change: An Application of FUND." Climatic Change 41 (3-4): 351-362.

van der Zwaan, B.C.C. and R. Gerlagh (2002). "A Sensitivity Analysis of Timing and Costs of Greenhouse Gas Emission Reductions under Learning Effects and Niche Markets." Energy research Centre of the Netherlands, Paper presented at the International Energy Workshop, 18-20 June 2002, Stanford University, CA, ECN-C-02-067.

Wene, C.-O. (2000). Experience Curves for Energy Technology Policy, International Energy Agency. Paris: OECD Publications.

Wilman, E.A. and M.S. Mahendrarajah (2002). "Carbon Offsets." Land Economics 78 (3): 405-416.



Source: IEA (2000), p. 43.

Figure 1 **Typical time spans for capital-stock turnover**

Table 1 **Analytical results**

	Higher Inertia (m↑)	**Presence of ITC (k↑)**
R&D	A_0 increases (inertia–effect)	A_0 decreases (R&D–effect)
LBD	A_0 increases for $k = 0$ (inertia–effect), otherwise ambiguous effect on A_0	Ambiguous effect on A_0

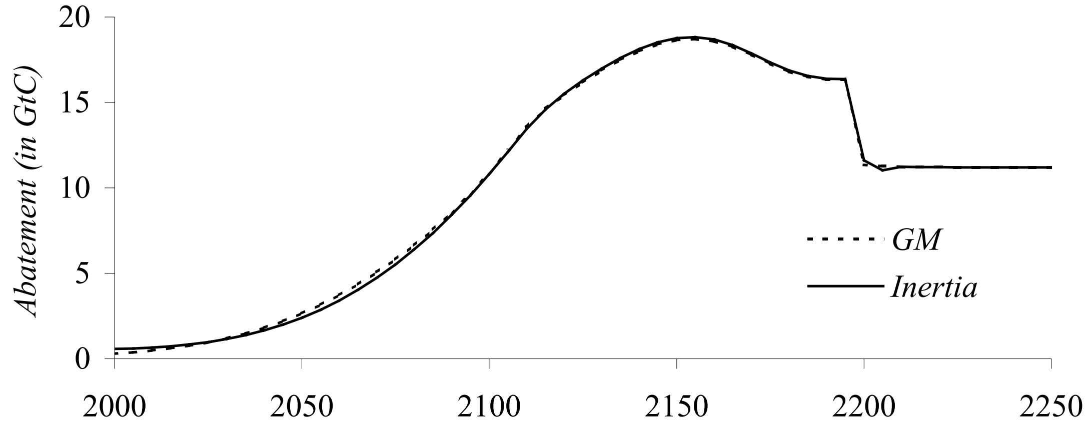


Figure 2 **Optimal abatement paths of the central cases**

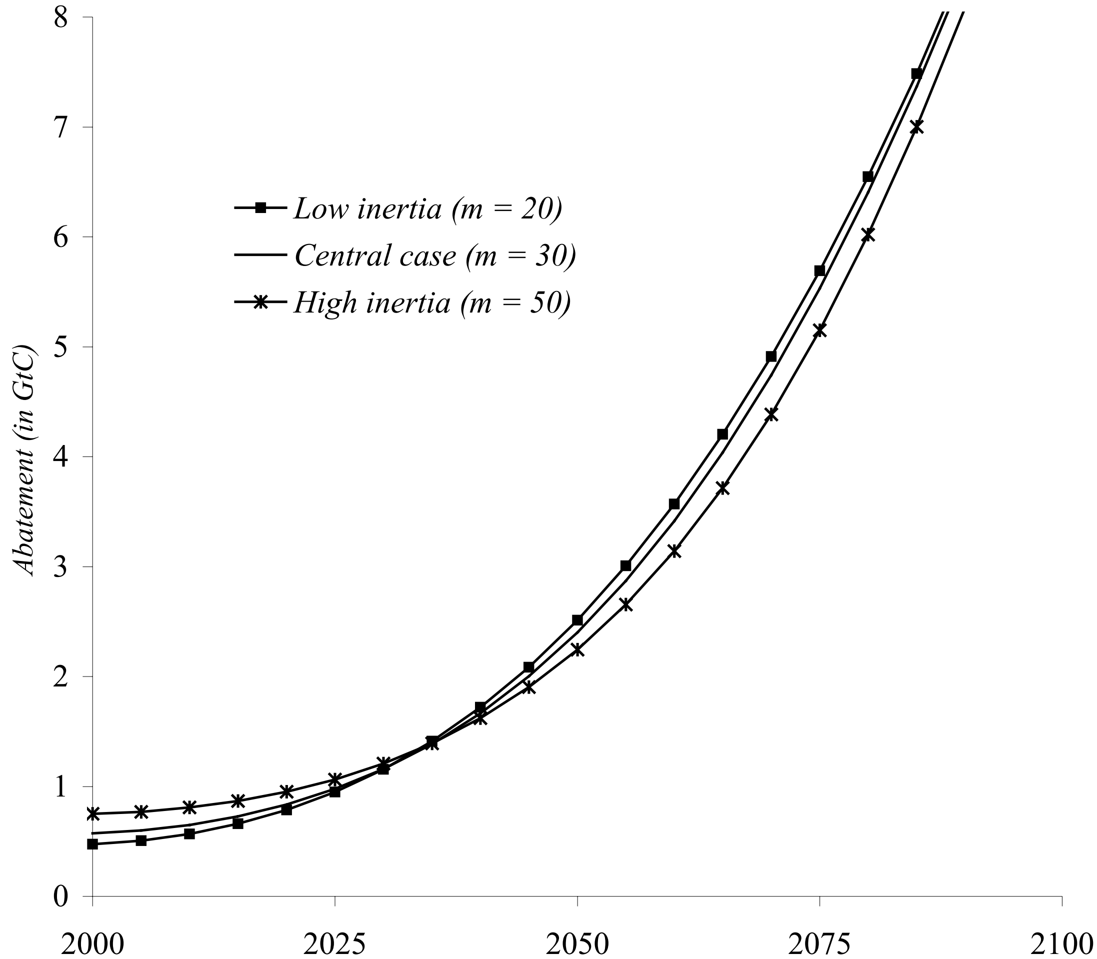


Figure 3 **Sensitivity of optimal abatement with respect to inertia**

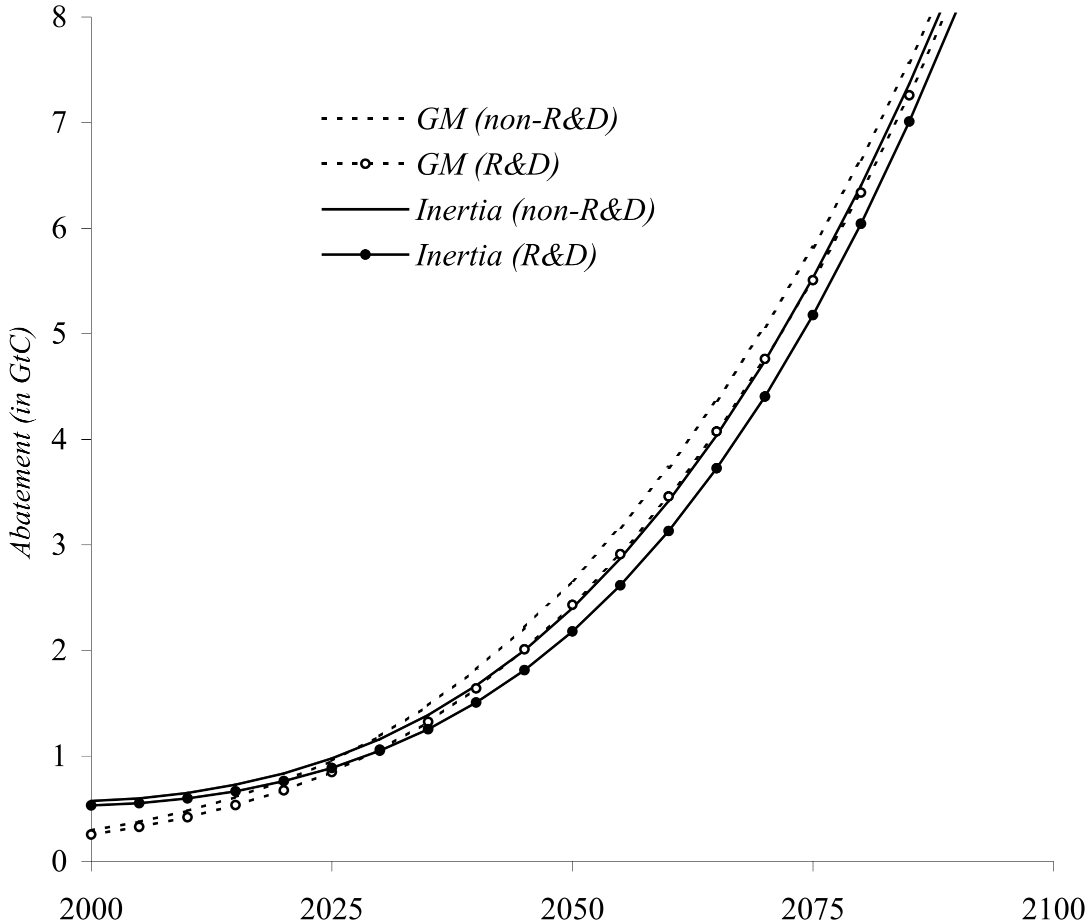


Figure 4 **Alteration of optimal abatement through R&D**

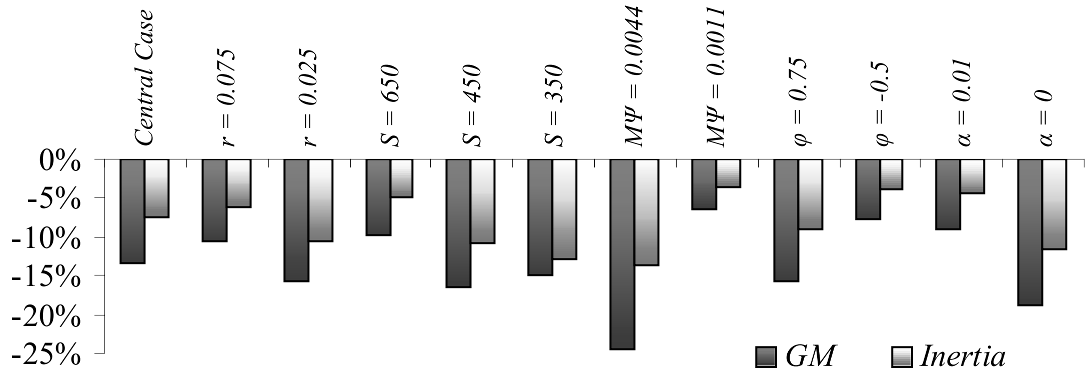


Figure 5 **Change of optimal initial abatement through R&D**
(R&D relative to non-R&D)

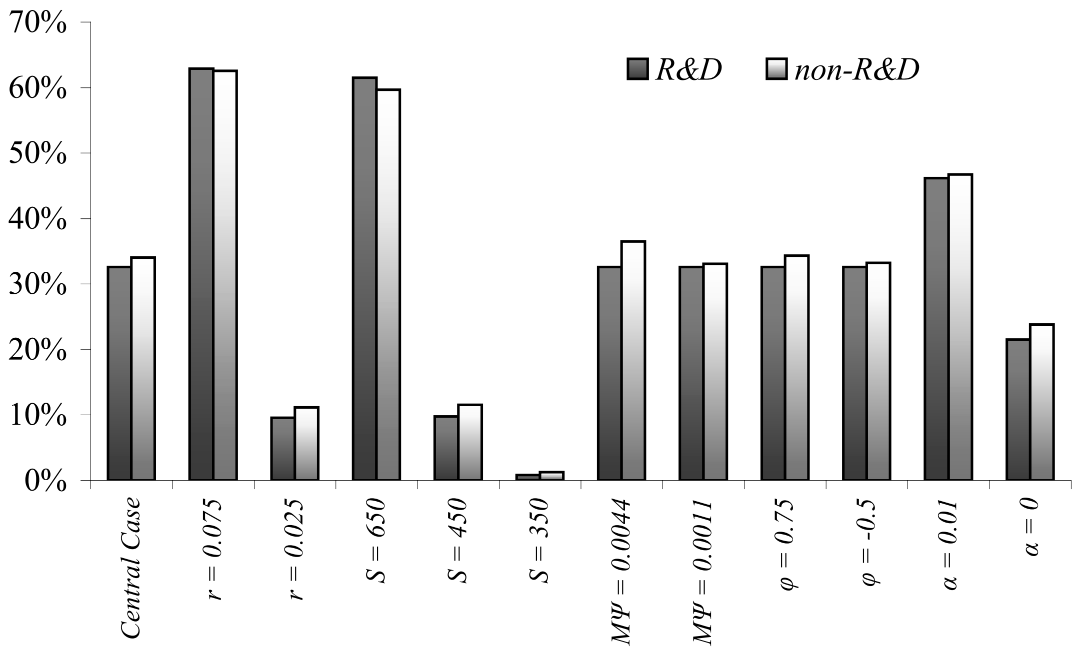


***Figure* 6 Sum of discounted costs of change during the first 100 years as percent of the sum of discounted total abatement costs**

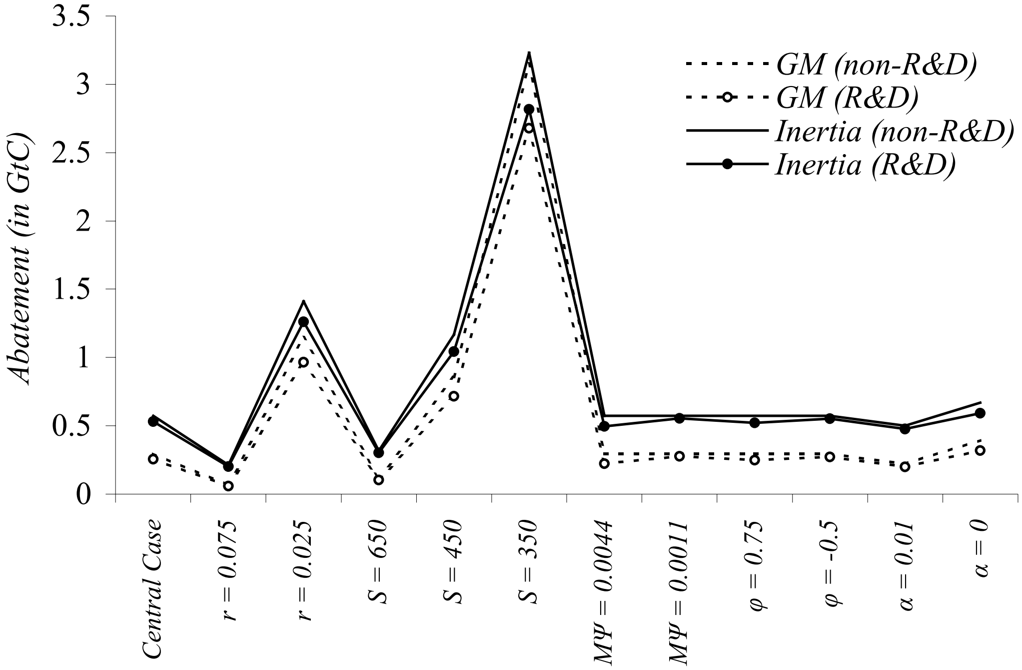


Figure 7 **Abatement in 2000**

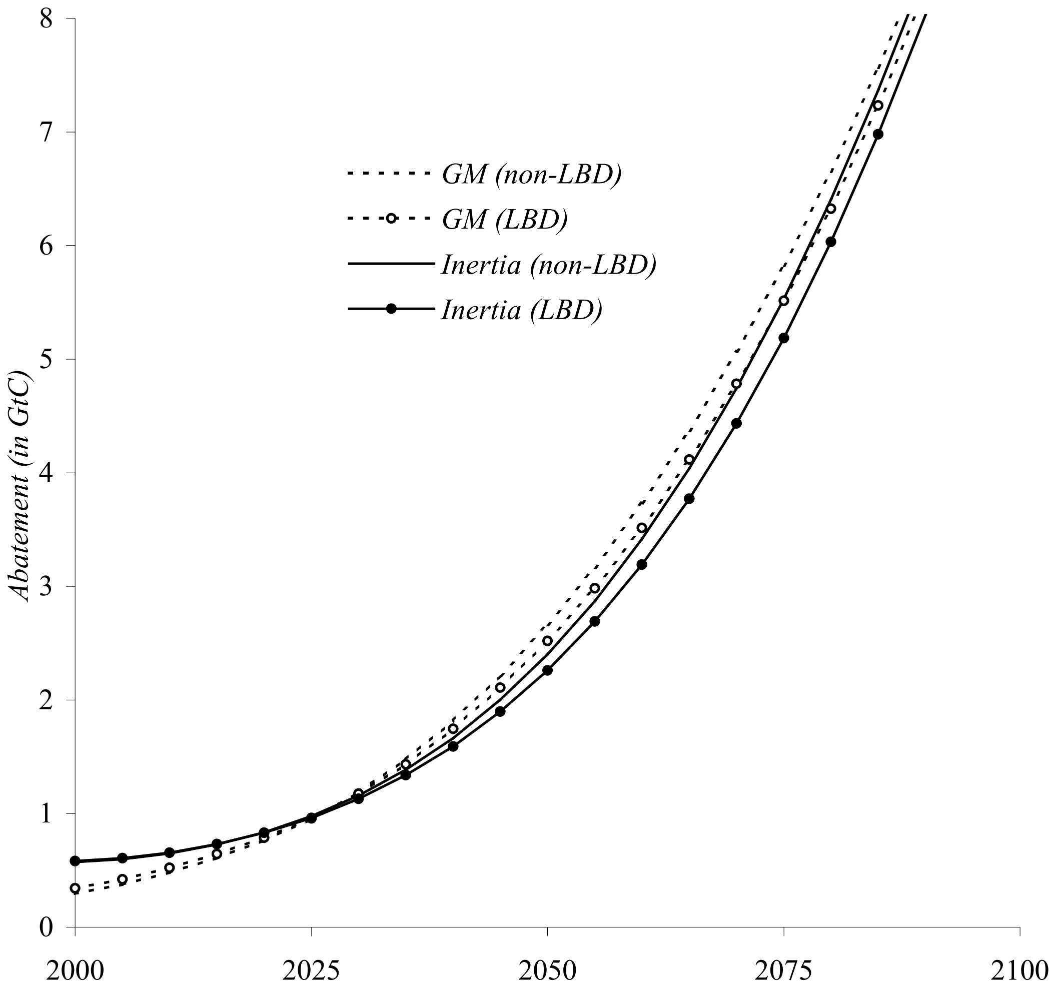


Figure 8 **Alteration of optimal abatement through LBD**

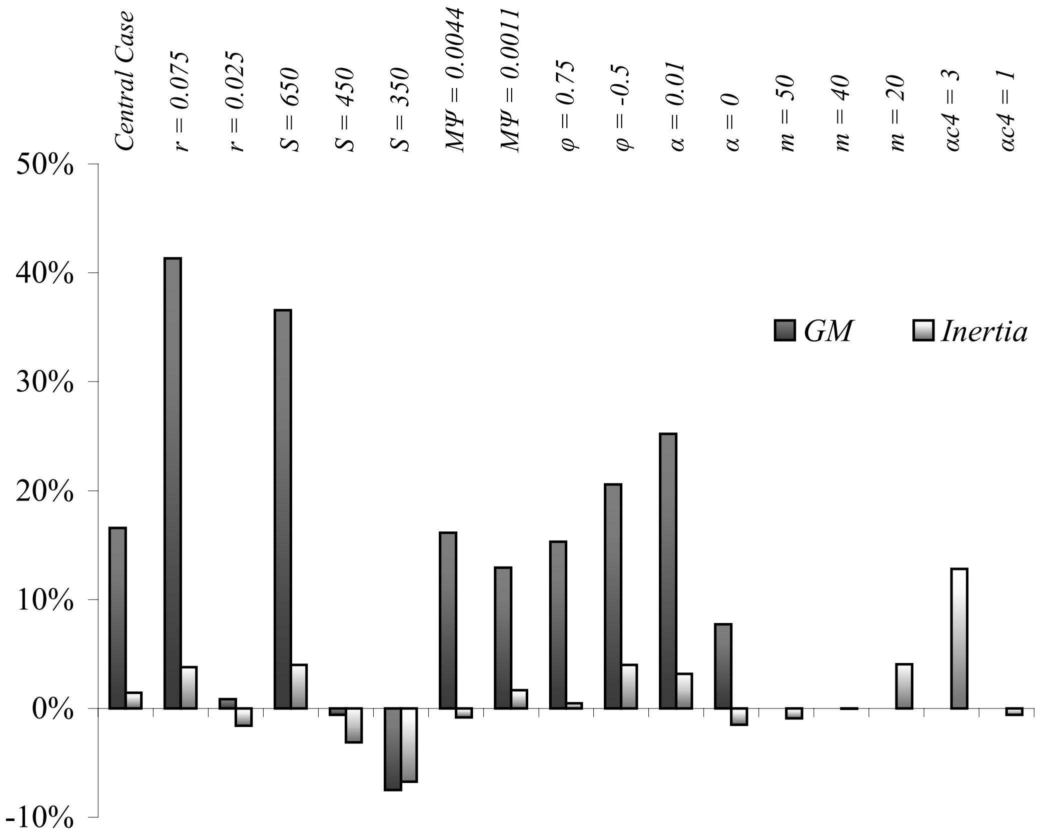


Figure 9 **Change of optimal initial abatement through LBD (LBD relative to non-LBD*)***

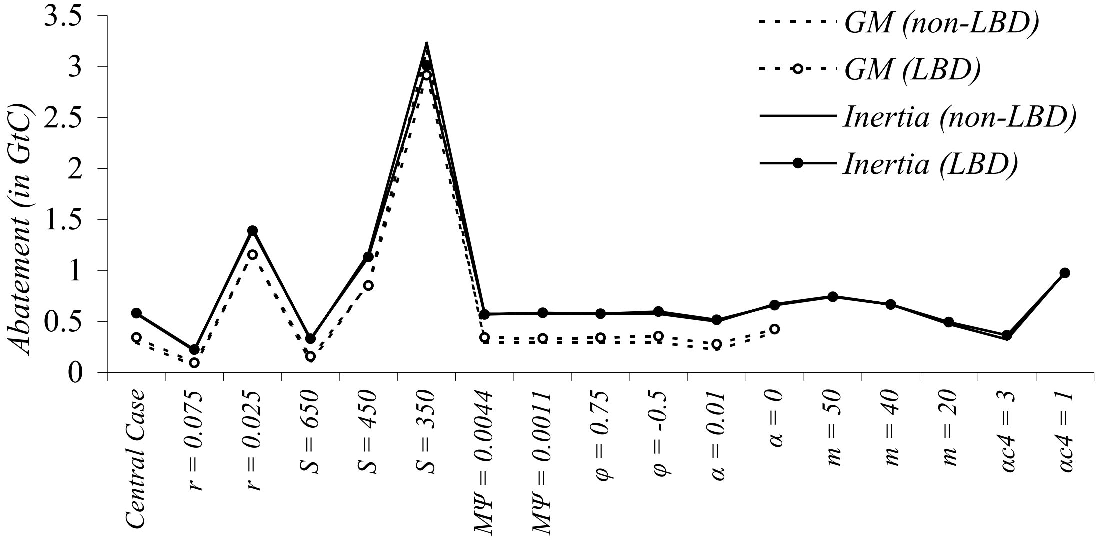


Figure 10 **Abatement in 2000**

Table 2 Reduction of stabilization costs and optimal CO_2-tax

	R&D					**LBD**			
	Discounted costs *Non- R&D: ≈ $400 billion*			**CO_2-tax (τ_{opt})** *Non-R&D: $3.8 per ton of carbon*		**Discounted costs** *Non- LBD: ≈ $400 billion*		**CO_2-tax (τ_{opt})** *Non-LBD: $3.8 per ton of carbon*	
	GM	Inertia (direct costs)	Inertia (total costs)	GM	Inertia	GM	Inertia	GM	Inertia
Central Case	-22.5%	-21.8%	-20.2%	-26.1%	-24.2%	-35.0%	-32.0%	-36.5%	-34.6%
$r = 0.075$	-17.8%	-17.0%	-15.2%	-20.3%	-18.0%	-30.7%	-25.4%	-31.9%	-27.7%
$r = 0.025$	-29.9%	-29.2%	-28.3%	-34.7%	-33.4%	-39.8%	-38.7%	-41.3%	-40.8%
$S = 650$	-16.1%	-15.3%	-13.4%	-19.1%	-16.8%	-31.6%	-26.4%	-33.6%	-29.8%
$S = 450$	-30.6%	-29.8%	-28.9%	-34.4%	-33.1%	-37.4%	-36.1%	-38.1%	-37.4%
$S = 350$	-43.5%	-42.7%	-42.5%	-47.8%	-47.0%	-37.8%	-37.6%	-37.5%	-37.5%
$M_{\Psi} = 0.0044$	-40.0%	-38.9%	-36.1%	-44.5%	-41.7%	-53.4%	-48.9%	-55.0%	-52.3%
$M_{\Psi} = 0.0011$	-10.9%	-10.5%	-9.7%	-13.0%	-12.0%	-20.7%	-18.9%	-21.7%	-20.6%
$\varphi = 0.75$	-26.4%	-25.6%	-23.8%	-30.4%	-28.3%	-39.7%	-36.3%	-41.1%	-39.1%
$\varphi = -0.5$	-13.2%	-12.7%	-11.7%	-15.6%	-14.4%	-22.8%	-20.8%	-24.2%	-22.9%
$\alpha = 0.01$	-15.2%	-14.6%	-12.8%	-18.1%	-16.2%	-28.9%	-24.8%	-30.4%	-27.9%
$\alpha = 0$	-32.2%	-31.4%	-30.1%	-36.1%	-34.4%	-41.9%	-39.8%	-43.1%	-41.8%
$M = 50$	-	-21.4%	-18.3%	-	-22.7%	-	-28.5%	-	-32.1%
$M = 40$	-	-21.6%	-19.3%	-	-23.5%	-	-30.3%	-	-33.4%
$M = 20$	-	-21.9%	-21.1%	-	-24.8%	-	-33.5%	-	-35.6%
$\alpha_{c4} = 3$	-	-21.9%	-21.6%	-	-25.2%	-	-32.8%	-	-36.1%
$\alpha_{c4} = 1$	-	-20.1%	-17.9%	-	-21.9%	-	-24.3%	-	-29.1%

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