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Optimizing Climate Change Abatement Responses: On Inertia and Induced Technology Development

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Abstract

This paper reviews evidence that technical change in the energy sector has historically responded to external pressures (rather than being an autonomous process) and presents a preliminary analysis of how optimal responses to climate change may alter if abatement efforts induce technology development. This is linked with the inertia that characterizes energy system dynamics.

An optimizing model is developed which takes these dimensions explicitly into account in a highly simplified manner. The model optimizes the emissions trajectory given abatement costs which are related explicitly to both the degree and the rate of abatement. Altering the coefficients associated with each of these two dimensions reflects different perspectives on the inertia of change, relative to the ultimate technical and behavioral flexibility of society. Low inertia and high absolute costs (no induced technology development) reproduces the kind of results found in other optimizing cost–benefit studies. But if the major costs are those associated with the rate of abatement rather than the absolute degree – i.e., high transitional costs but an optimistic perspective on the ultimate potential of technology and/or behavioral patterns to adapt to such constraints – the optimal strategy and long-run prospects are radically altered. In this case, abatement rises within a few years above the level incurred in the "conventional" case, and long-run stabilization of atmospheric concentrations may be approached after some decades, at moderate costs, as an optimal response even for moderate values for the climate damage function.

The analysis thus highlights the importance of considering these dimensions of systemic inertia and induced technical and behavioral adaptation that have been neglected in previous quantitative studies of optimal abatement responses.

1. Introduction

How much effort should we make to control climate change? How do the benefits of early moves to limit emissions compare against the costs? Is there any prospect of stabilizing global emissions – or beyond that even atmospheric concentrations, which the Climate Convention states as the ultimate goal - without incurring very high costs? How do actions taken today fit in the context of a problem which involves cumulative and irreversible changes over centuries?

Cost/benefit studies of the climate problem seek to address these questions explicitly, by attaching monetary values to benefits and costs and comparing them in terms of present values. Great uncertainty surrounds the values adopted, but this paper is not concerned directly with these uncertainties. Rather, it seeks to illustrate in a simplified way the potential impact upon abatement costs and optimal strategies of two factors which have not been explicitly included in cost–benefit studies to date.

These issues are, respectively, inertia in the systems which generate greenhouse gases, and the role of technological and behavioral adaptation to abatement efforts – "responsive" (or induced or endogenous) "technology" (or systemic) development. It is shown that these factors can be captured in a simplified cost–benefit framework, and that doing so can substantially alter conclusions concerning optimal abatement trajectories and costs. Comparing optimal emission trajectories under differing assumptions about inertia and technology development points to the importance of starting to reflect these factors in models, and of seeking to understand better how to characterize these factors. Other possible research applications of the models developed are also outlined.

2. A Brief Review of Cost/Benefit Modeling Studies

The first published attempt at a cost-benefit modeling analysis of the climate problem was that by Nordhaus (1991). This sought to treat the problem in a classical static cost–benefit framework, adapted for the climate problem by developing a series of equations to link emissions with global temperature change. Together with assumptions about the cost imposed by a given temperature change, and the cost associated with a given emission reduction, this yielded an estimate of the emission reductions which would be optimal in a "steady-state" of constant emissions and concentrations.

In later work, Nordhaus (1992) developed an alternative, numerical model ("DICE") for optimizations in which emissions and concentrations could change over time. Both studies, using Nordhaus' cost assumptions, suggested that only modest abatement efforts were justified. Kolstad (1992) developed a stochastic version of DICE to explore the impact of uncertainty upon the optimal emissions path. Peck and Teisberg (1992) coupled an energy model (a simplified version of the Global 2100 model) to an atmospheric model to examine the trade-off between abatement costs and reduced climatic impacts.

Schlesinger and Jiang (1991) adopted a different approach, focusing upon the changes implied by delaying emission responses by ten years. They concluded that the impact of such a delay would be small, so that delaying policies to await greater scientific certainty would be rational. In subsequent interchanges, they drew upon Nordhaus' analyses to defend their conclusions (Schlesinger, 1992).

Many of the criticisms made of these analytic studies focus on arguments that they greatly underestimate the damage or risks associated with changing the atmosphere's radiative properties (e.g., Cline, 1992; Ayres and Walters, 1991; Grubb, 1993). Some dispute that the cost–benefit framework can be used at all because the climatic uncertainties are too profound and the inertia too great. For example, Swart and Hootsmans (1991) argue that there may be major instabilities in the global system and that by the time we can see evidence of this it will be too late to stop, leading to proposed "safety limits" on atmospheric change.

This paper is not directly concerned with such issues. Rather, it adopts the cost–benefit framework, along with the inevitable caveats about valuing climatic damage, and focuses upon issues concerning the abatement side of the process which are not reflected in the above studies.

The optimizing cost–benefit analyses cited above have assumed that abatement costs are a direct function of the degree of abatement only, and that they are unrelated to the *rate* of abatement. This is unrealistic. Clearly, abatements costs do depend upon the rate at which emissions depart from the baseline trend – more rapid changes incur higher costs, for several independent reasons noted below. In short, the systems which emit greenhouse gases are characterized by great *inertia.* This may be expected to affect strategy particularly under conditions of high uncertainty and learning, features which certainly characterize the climate problem.

A second important issue is that technology may be expected to develop. Indeed, a technologically optimistic outlook, such as that argued in the immense study of renewable energy technologies and applications edited by Johansson *et al.* (1993), is that emissions could be reduced below current levels in the long term with *no* long-term additional costs; it is argued that technologies already visible on paper could develop to the point at which they can deliver sufficient useful energy at similar overall costs to fossil fuels. While some authors suggest that technologies for extensive low-cost abatement are abundant now, for supply substitution in particular most authors invoke the argument that costs will fall greatly if and as alternative technologies are developed and deployed on a large scale. Recently, some economists have begun to emphasize the importance of considering such technology issues, notably Anderson and Bird (1992), and Hourcade (1993).

The key issue concerning technical change in this context is whether or not it is responsive or *induced*, i.e., whether it responds to trends and pressures. This contrasts with *autonomous* technological change, which is projected to occur irrespective of other developments. The distinction is critically important. If technical change is induced, efforts to limit emissions help to stimulate technical and other developments, including economies of scale and learning, which in turn help to lower the costs of further abatement efforts. If technical change is autonomous, the costs associated with abatement are constant irrespective of policy, the history of abatement efforts, and the size of markets for lower carbon technologies.

In modeling terms, these may be termed respectively *endogenous* (i.e., embodied within the model as a function of other factors) and *exogenous* (i.e., defined external to the model) technical change. Any model can be designed and run to encompass exogenous technical change, by lowering assumptions about the future costs of lower carbon technologies, and/or by using higher values for "autonomous" efficiency improvements. But no model yet applied to the cost–benefit problem, of which the author is aware, embodies technical development as a response to the abatement or other circumstances, although Anderson and Bird (1992) come close in linking the unit costs of carbon-free technologies to the scale of deployment.

The issues of inertia and induced technical change are distinct, but related. Technology studies such as those collected in Grübler (1991), have emphasized the way in which technologies tend to generate "clusters" of interlocking systems. Hourcade (1993) points out the implication that gradual change, developing a new and self-reinforcing trajectory of interrelated technical change, may be relatively cheap and self-sustaining, with little cost difference from an alternate "business-as-usual" trajectory which leads ultimately to a wholly different pattern of emissions and technologies. Rapid change, however, may require large-scale adoption of technologies not well suited to current systems, incurring high transitional costs which decline only as the relevant supporting systems develop.

3. Inertia and Induced Technology Development in Energy Systems: The Evidence

The evidence for inertia in energy systems scarcely needs elaboration. Whatever the benefits, change is rarely costless, and the faster the change the greater the costs tend to be. At the most simple level, this reflects past investment in capital stock which may be rendered worthless; the OECD among others have pointed to the importance of including this effect with "putty semi-putty" or other capital stock modeling (Hoeller *et al.*, 1993). Rapid structural changes also generate macro-economic disequilibria costs, as capital cannot be automatically switched from one sector or kind of investment to another. In social terms, sensitivity to the rate of change may be still higher, e.g., if it forces job losses much faster than feasible under natural turnover or even voluntary redundancy schemes. Rapid action may thus be much more expensive than action at a similar absolute level, phased over a longer period.

Technology development is an altogether more complex issue. The process of innovation is not understood – given the high level of failure, it has been characterized as "the triumph of action over analysis" (Ausubel, 1991). Various technology diffusion studies emphasize the complexity of factors which determine whether or not technological ideas are developed and adopted, and it is clear that this does depend heavily upon external conditions (Freeman, 1986). The author's own study of "Emerging Energy Technologies" which seem likely to have significant market impact over the next decade or two also concluded that "most of technologies considered reflect primarily a process of 'demand pull' rather than 'supply push' " (Grubb and Walker, 1992, Chapter 14).

Three specific examples, at successively greater levels of aggregation, illustrate the extent to which developments in technologies and energy systems are not autonomous, but reflect market and other external pressures.

First, when oil companies started operating in the deeper waters of the North Sea, it was on the basis of projections of oil prices rising to levels of \$50/bbl or more. In the early 1980s, it was estimated that the cost of oil from new deep water platforms would be around \$25/bbl. Yet as the oil price declined, companies responded with strenuous attempts to cut costs, leading to radical innovations in platform design and project management. Today, deep-water fields are still being developed by companies that believe that oil prices may not rise above \$20/bbl for many years, probably with production costs on the order of \$10/bbl. Such developments required extensive efforts and commitment of investment in new techniques; it would not have occurred to anything like the same degree without the need to survive in response to declining oil prices.

A second example concerns the uptake of energy efficiency investments. In 1980, the UK Department of Energy carried out an assessment of the potential for energy efficiency improvements in UK industry. They concluded that industrial energy intensities could be reduced by 20% over the following 20 years with cost-effective investments. In 1990, a new assessment concluded that the potential identified had in fact all already been exploited; but that, despite the lower energy prices, a further 20% of cost- effective efficiency improvements could be identified. The greater interest and investment in energy efficient techniques – in the UK and elsewhere – had apparently helped to generate greater development of more efficient techniques. Indeed, it seems a curious feature of energy efficiency studies that they seem regularly to identify cost-effective potentials for improvement of around 20-30% of current demand, almost irrespective of the potential already exploited. There is a continual process of developing new options. It is hard to judge how much of this is driven by energy price changes and greater investment in energy efficient techniques, but the persistence of such results suggests that investing in greater energy efficiency helps itself to stimulate and identify previously overlooked options.

A third example concerns the macroeconomic response to the energy price shock and subsequent decline in energy prices. In real terms, energy prices in some sectors and countries are lower than they were before the 1973 oil shock. Traditional econometric models based on price elasticities suggest that response to the price rise, marking a sharp decline in the trend of energy consumption especially outside the heavy industrial sector, should be mirrored by an equivalent rise after the price fall (after allowing for autonomous trends). In fact, although energy demand has started to rise again in most countries and sectors, the change has been nothing like as great as would be expected if there were indeed a "symmetric" response. Energy economists have in the last five years begun to discuss the need for "asymmetric" elasticities to model the observed the behavior, with the decline in consumption in response to price rises being much greater than the equivalent rise in response to price falls.[1] The argument is advanced that the price rises resulted in technology development, infrastructural investments, and behavioral changes which were not "unlearned" when the prices fell.

But this is the very meaning of endogenous technology development.[2] This example also helps to illustrate that the term "technology" development is really shorthand for a much broader phenomena; it is about the overall development of technology, infrastructure, and habits of human behavior and social systems as affected by perceptions of the cost and availability of different resources.

At all three levels therefore there is overwhelming evidence that 'technology' development in the energy sector is not purely autonomous, but responds to external pressures.[3] The data of the past 20 years is itself leading energy economists increasingly to recognize a central role to the phenomena of endogenous development. The pity is that, with the partial exception of the studies by Anderson and Bird (1992) and Hourcade (1993), none of this insight is yet embodied in models of how we should respond to climate change.

This paper does not seek to develop a means of "endogenizing" technical change in a fully consistent way; that would constitute a major disciplinary research effort. Rather, it seeks merely to show that it is possible to formulate a cost–benefit analysis which can mimic the possible impact of both inertia and endogenous technical change, and explores some of the possible implications of these phenomena for optimal abatement strategies.

[1] For example, Dargay (1993, note 2) cites no less than nine studies which address the issue of irreversibility or asymmetry in energy demand – in addition to his own empirical studies which encompass France, Germany, and the UK.

[2] Dargay (1993) clarifies his study of asymmetric responses as "challenging two of the common assumptions made ... that a return to low energy prices ... would eventually restore demand to what it would have been had prices never risen ... not only does this not seem to be happening, but it also appears highly unrealistic. It is obvious that high energy prices induced the development and application of considerably more energy-efficient technologies in all sectors of the economy, many of which will remain economically optimal despite falling prices."

[3] Note that this is not the same issue as that of "embodied" technical change discussed for example in Berndt *et al.* (1993), which refers to the persistence of technological change as embodied in the unmalleable capital stock.

4. Basic Structure of the Model

The first stage is based directly upon the problem as framed by Nordhaus (1991). The analysis concentrates upon CO_2 emissions (although it can be applied to other gases), as the major long-term contributor to radiative change and the central source of concern about the impact and timing of any constraints. Equations link emissions with concentration changes in the atmosphere and hence ultimately to climate impacts. The simplest forms used in Nordhaus (1991) are adopted; more sophisticated models of the linkages can be brought to bear, but such refinement is not important in this context. The relevant equations are as follows.

The physical system. The atmospheric concentration of greenhouse gases at time t, M(t), is given by:

$$M'(t) = E(t) - sM(t) \tag{1}$$

where $M(t)$ is the concentration (mass) of the greenhouse gas in the atmosphere; $M'(t)$ is the rate of change in atmospheric concentration; $E(t)$ is the greenhouse gas emission rate at time t; s is a "sink rate" removal constant.

This equation assumes that carbon is removed from the atmosphere at a rate in direct proportion to the atmospheric concentration. This is an adequate approximation for the present purposes; for longer-term changes in particular, it may be optimistic in that it does not recognize any saturation of the natural sinks. Given the simplification in the atmospheric model noted above (i.e., carbon removal proportionate to concentration), the equation yields a direct expression for the concentration remaining at date t:

$$M(t) = e^{-st}\left(M_0 + \int_0^t E(\tau)e^{s\tau}d\tau\right) \tag{2}$$

The parameter s may be evaluated from past data. Given a conservative estimate that only a third of anthropogenic CO_2 emissions accumulated in the atmosphere during the mid-1980s, for CO_2 s is approximately 3.7%/yr.[4]

Objective. The overall objective may be considered as maximizing the global utility V, discounted over time at a rate ρ:

$$Maximize\ V = \int_0^\infty U\{C(t)\}e^{-\rho t}dt \tag{3}$$

[4] $s = 2M'/M = 2*1.5/(350\text{-}270) = 0.037$ (carbon accumulation taken for convenience in ppm).

where time t is set such that $t = 0$ represents the present, and $C(t)$ is the global consumption at time t; $U\{\}$ is the total utility associated with consumption $C(t)$; ρ is the social rate of time preference.

In pursuing his analysis, Nordhaus (1991) described a physical "steady state" analysis, in which a baseline consumption increases exponentially at rate h. This is then reduced by the cost incurred by a steady-state reduction in emissions, and the damage arising from the constant temperature increase above natural levels. By assuming this steady state, Nordhaus was able to derive the optimal degree of abatement for the assumed cost functions.

The analysis here differs in several important respects. First, the analysis does not assume a physical steady state. To avoid this very limiting constraint, Nordhaus (1992) subsequently moved to a discrete mathematical programming model with non-linear optimization. Here, it is shown that an analytic solution to the dynamic problem, in which emissions and concentrations are made an explicit function of time, is possible given certain simplifying assumptions.

Emissions control. Emissions at time $t, E(t)$, are taken to deviate from a reference path $E_r(t)$ in which there are no abatement efforts, according to a control parameter $\varepsilon(t)$:

$$E(t) = E_r(t)[1 - \varepsilon(t)] \tag{4}$$

The consumption at time $t, C(t)$, is then assumed simply to be depressed from a reference level $C_r(t)$ by the costs imposed by climate change, and by the efforts to limit emissions. Using initially generalized cost functions denoted by $g\{.\}$, the consumption path may then be written as:

$$C(t) = C_r(t)[1 - g_a\{\varepsilon(t)\} - g_I\{M(t)\}] \tag{5}$$

where $C_r(t)$ is a reference consumption path in the absence of any costs from either climate change or abatement; $g_a\{\varepsilon(t)\}$ is the cost, as a fraction of global consumption, associated with emissions abatement level; $\varepsilon(t)$ is as defined in (4); $g_I\{M(t)\}$ is the cost arising from the impacts of the concentration change $M(t)$.

Here the abatement cost $g_a\{\varepsilon(t)\}$ and the impact cost $g_I\{M(t)\}$ may be understood in a general sense, as including a monetized reflection of non-GDP losses. The functional forms are in fact very uncertain, and we have considerable freedom in choosing them. Exploring the impact of different forms is a central point of interest as discussed below.

The key general point in Equation (5) is that the concentration change $M(t)$ is ultimately a function of the emissions control parameter $\varepsilon(t)$. The question is therefore: is it possible to find explicit expressions for $\varepsilon(t)$ which maximize the total utility?

5. Analytic Principles: The Key Steps

In principle at least the answer is yes, and for some useful functional forms the results appear to be tractable. Adopting the common economic assumption that utility is an approximately logarithmic function of consumption, the objective then may be written as:

$$Maximize\ V = \int_0^\infty e^{-\rho t} \ln[C_r(t)(1 - g_a\{\varepsilon(t)\} - g_I\{M\{\varepsilon(t)\}\})]dt \qquad (6)$$

For evaluating optimal abatement responses, we are not seeking to evaluate the integral itself, but rather, the path of emissions control $\varepsilon(t)$ which will minimize it. By applying the identity $\ln(AB) = \ln(A) + \ln(B), \ln\{C(t)\}$ is separable and the optimal emissions trajectory is independent of the reference consumption path $C_r(t)$. By expanding the logarithm and taking the first-order terms (costs of abatement and impacts are considered small enough to neglect second-order terms, i.e., $g_a << 1$ and $g_I << 1$), this leaves the objective as:

$$Minimize \int_0^\infty e^{-\rho t}(g_a\{\varepsilon(t)\} + g_I\{M\{\varepsilon(t)\}\})dt \qquad (7)$$

This makes sense: it states that the optimal emissions path is one which minimizes the discounted total fractional loss of consumption.

The key step is then to apply the variational principle, which states that this function is at an extreme point (maximum or minimum) when the derivative of the integrand F with respect to the control variable $(\varepsilon(t))$ satisfies:

$$\frac{\partial F}{\partial \varepsilon_t} = \frac{d}{dt}\left(\frac{\partial F}{\partial \varepsilon_t'}\right)$$

$$F = e^{-\rho t}(g_a\{\varepsilon(t)\} + g_I\{M\{\varepsilon(t)\}\})dt \qquad (8)$$

This is an explicit if complex equation for the emissions control parameter $\varepsilon(t)$.

6. Cost Functions and Manipulation

With sufficiently powerful numerical techniques for solving integral equations, it should be possible to derive direct solutions of the optimizing condition (8), by substituting (2) and (4), for a wide range of cost functions. With some simplifying assumptions, the complexity may be greatly reduced and even an analytic solution achieved, clarifying the results and greatly simplifying the computation.

Abatement costs. The central purpose of this analysis is to examine how optimal abatement strategies may alter when inertia and endogenous behavioral and technical changes in the systems producing greenhouse gases are taken into account. We therefore let the abatement cost function take a form which depends explicitly on both the *degree* and the *rate* of abatement. In both terms, the costs are clearly likely to rise non-linearly, and can be written as a general power relationship as:

$$g_a\{\varepsilon(t)\} = \frac{2C_a}{a+1}\varepsilon(t)^{a+1} + \frac{2C_b}{b+1}\varepsilon'(t)^{b+1} \tag{9}$$

where $\varepsilon(t)$ is the first derivative (i.e., the rate of change of abatement level); a and b are power coefficients which relate the abatement cost respectively to the degree and rate of abatement, defined such that a value of 1 implies a quadratic dependence; and C_a and C_b are the corresponding proportionality coefficients. Numerical values are developed below. This simple form for the cost function is in fact the heart of the new issues captured in the model. The first term is equivalent to the abatement cost function in existing aggregated cost-benefit studies such as DICE. The second is a direct reflection of *inertia*, in which costs depend on the rate of abatement.

Endogenous technical change is captured implicitly by lowering C_a relative to C_b. A lower C_a indicates that the long-run costs of abatement are lowered by induced technological development; the system starts adapting to abatement. If C_a declines and C_b rises, abatement costs are increasingly dominated by the inertia of moving from one state to another, relative to the recurring costs of staying at any given abatement level; and optimal response is determined by the tension between the rising transitional costs of overcoming inertia and the declining absolute costs associated with technological adaptation.

The quadratic form of (9), i.e., with $a = 1$ and $b = 1$, is the most illuminating form which the authors have found analytically tractable to date, and is the form applied in this paper. The abatement cost is then simply:

$$\text{Abatement cost } = C_a\varepsilon(t)^2 + C_b\varepsilon'(t)^2$$

Some other forms of this cost function, with arbitrary integral power coefficients for one of the terms, are analytically tractable if the other term is linear. The quadratic case is, however, the most plausible, and usefully illustrates the key points.

Impact costs. The actual impacts of changing the atmospheric concentration are extremely uncertain, in form as well as degree. Most studies have assumed that impact costs are determined by the degree of temperature change, in various ways, and that this will occur smoothly as determined by the radiative forcing and oceanic heat reservoirs.[5] In practice, such idealized temperature change is itself a rough guide. Other studies appear to suggest that interference with the radiative balance may more directly affect climate costs by creating instabilities, and it is likely that there is also some dependence directly upon the *rate* of temperature change, i.e., disruption to existing patterns, e.g., of agricultural production.

The problem is greatly simplified here simply by assuming that the impact cost is proportional to the *concentration* change:

$$g_I\{M(t)\} = \frac{C_I M(t)}{m} \tag{10}$$

where M is the pre-industrial amount of the greenhouse gas in the atmosphere; and C_I is a proportionality coefficient reflecting the severity of climate impacts such that C_I is the cost associated with a doubling of atmospheric concentrations.

If temperature change is taken as determined by a single-parameter heat lag system, this relationship is equivalent to assuming the impact costs depend on both the degree and rate of that temperature change, in a particular combination.[6] It is, of course, highly uncertain whether (10) or any other

[5]Nordhaus (1991) appears implicitly to assume a linear dependence of costs upon temperature change. Cline (1992) suggests a power-law increase. Peck and Teisberg (1992) compare a linear with a cubic dependence of costs upon temperature change.

[6]The global average temperature at time t, $T(t)$ lags the changes in atmospheric concentrations by several decades because of the thermal inertia of the oceans. In the single lag model, this is approximated as:

$$T'(t) = \alpha[T\{M(t)\} - T(t)]$$

where α is a temperature lag coefficient, and $T\{M(t)\}$ is the equilibrium temperature change which would finally be reached at a constant atmospheric concentration $M(t)$.

particular form is a reasonable approximation to climatic damage, but even very different forms are unlikely to alter conclusions about the rôle of inertia and technology development in abatement derived from this model.

Emission trends in the absence of abatement efforts are uncertain, but as for population, nearly all studies project declining rates of exponential growth which can be well approximated by simple linear projections.[7] The uncertainties in the actual rate of growth far outweigh any constraints imposed by this form. We therefore let

$$E(t) = E(0)(1 + \zeta t) \tag{11}$$

where ζ is the average projected growth rate in emissions, in the absence of any abatement efforts, as a fraction of 1990 emissions.

Given these definitions, the total cost may be expressed as:

$$\begin{aligned}
&\textit{Total discounted cost} = \\
&= \int_0^\infty e^{-\rho t} \Big\{ C_a \varepsilon(t)^2 + C_b \varepsilon'(t)^2 + \\
&\frac{C_I}{m} \left[M_r - E(0) e^{-st} \int_0^t e^{s\tau}(1 + \zeta\tau)\varepsilon(\tau) d\tau \right] \Big\} \, dt
\end{aligned} \tag{12}$$

Here M_r is the path of concentration in the reference case, and the term involving M_r is the damage arising from emissions in the reference path (i.e., without any abatement action), which, as noted above, is not relevant to the optimization. Dropping this and commuting the integral (integrating by parts) leaves the cost to be minimized as:

Costs are directly proportional to concentrations if costs rise exponentially both as a function of the temperature change, and of the *rate* of temperature change, as:

$$g_I\{T(t)\} = C_I e^{T(t)} e^{T'(t)/\alpha}$$

Given that impact costs are likely to be related both to absolute temperature change and the rate of change, and arguably to the product of them, and given that many analysts expect the costs to rise rapidly with the degree of each, this is not a wholly inappropriate functional form. It is however chosen for its mathematical convenience, not because of any more pressing evidence that impact costs will be in such a form.

[7]Excluding those which (i) assume exponentially growing rates by construction (e.g., relating emissions directly to an exponentially growing GNP), or (ii) build in assumptions that emissions will be drastically curtailed in the reference case. Emission trends in the last forty years (1950–1990) are surprisingly close to a linear trend, and projections of CO_2 emissions by the World Energy Council (1992) in three different scenarios to the year 2020 all project linear increases.

$$\int_0^\infty e^{-\rho t}\left\{C_a\varepsilon(t)^2 + C_b\varepsilon'(t)^2 - C_c(1+\zeta t)\varepsilon(t)\right\}dt$$
$$\textit{where} \qquad (13)$$
$$C_c = C_I\frac{E_0}{m}\frac{1}{\rho+s}$$

Applying the variational principle (8) yields the equation to stationarize (minimize) the integral as:

$$C_a\varepsilon + \rho C_b\varepsilon' - C_b\varepsilon'' = \frac{C_c}{2}(1+\zeta t) \qquad (14)$$

This is a second-order differential equation, with solution (satisfying the limit condition $\varepsilon(0) = 0$):

$$\varepsilon(t) = \frac{C_c}{2C_a}\left[\left(1 - \frac{\rho C_b}{C_a}\zeta\right)\left(1 - e^{\frac{\rho t}{2}\left(1-\sqrt{1+\frac{4C_a}{\rho^2 C_b}}\right)}\right) + \zeta t\right] \qquad (15)$$

This equation describes the optimal degree of abatement $\varepsilon(t)$ at time t, given the assumed quadratic dependence of abatement costs upon both $\varepsilon(t)$ and $\varepsilon'(t)$, with the weight accorded to each determined by the constants C_a and C_b. The following section presents results for specific values of the various parameters and interprets their implications.

7. Results

For illustrative purposes, results are presented for the following basic values:

rate of time preference	3%/yr
carbon removal rate s	3.7%/yr
pre-industrial concentration m	550GtC
damage from doubling CO_2 concn C_I	4% of Gross World Product
initial emissions *E0*	7.5GtC/yr
emissions growth without abatement	2%/yr

The central purpose of the present paper, other than introducing the issues and the model, is to examine how the optimal trajectory varies as the costs of abatement are increasingly dominated by the tension between the inertia and induced technology development, as represented in Equation (9). An immediate issue arises as to how to make the trade-off between the declining "absolute" costs, determined by C_a, against the rising transitional costs associated with the rate of change, determined by C_b.

In this study, these costs are parameterized by assuming that the total abatement costs associated with a linear abatement schedule rising to 50% below baseline projections over a period of 30 years are constant:

$$\int_0^T \left[C_a \varepsilon(t)^2 + C_b \varepsilon'(t)^2\right] dt = Constant \tag{16}$$

where for this analysis, T is taken as 30 years and the constant is 0.2, implying abatement costs at a level roughly equivalent to a purely fixed (exogenous) abatement cost function in which the cost incurred from a 50% emissions reduction is 2% of GDP/yr.

This parameterization defines the trade-off between C_a and C_b. A high C_b in this context reflects a view which still accepts the results from the major global top-down energy models as valid over the next few decades, but interprets most of these costs as transitional, and sees abatement costs beyond this being brought down steadily by the endogenous process of systemic adaptation to emission constraints. We examine three cases:

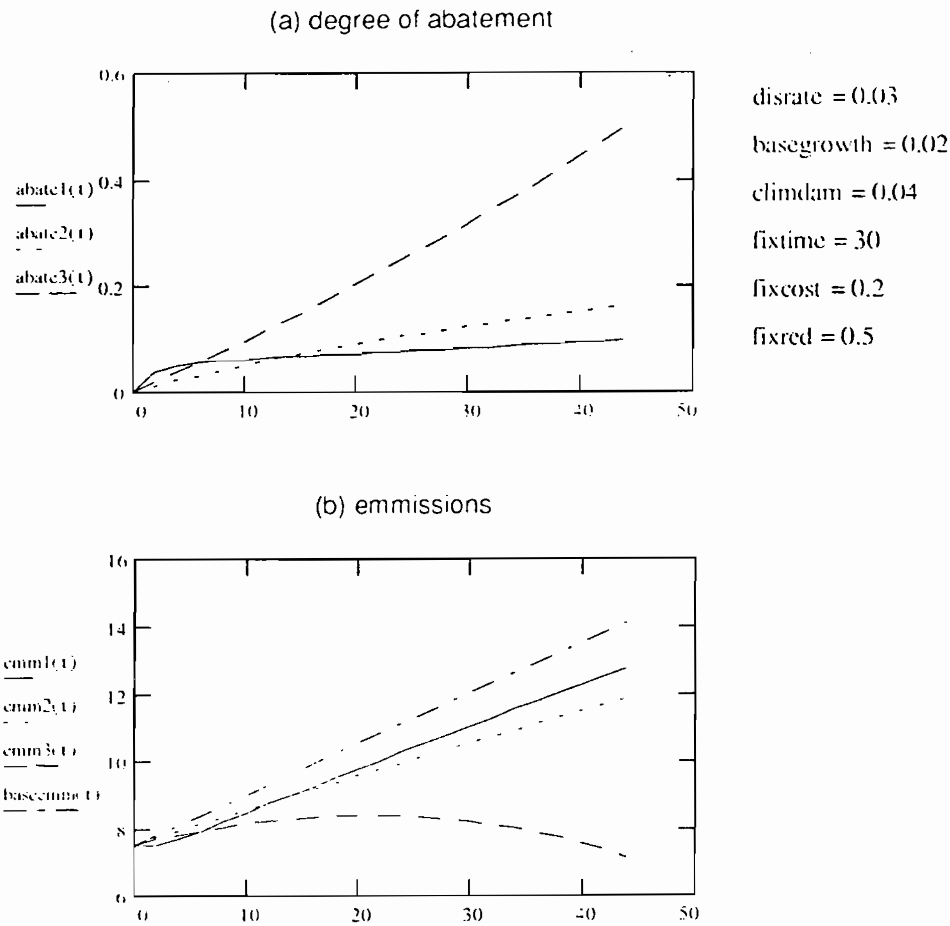
1. *Low inertia, technology exogenous* in which 99% of the costs in (16) are associated with C_a – the conventional perspective.
2. *Half and half*, in which the costs in (16) are divided equally between the two terms.
3. *High inertia, technology endogenous* in which 99% of the costs in (16) are associated with C_b.

The results are shown in Figure 1: *abate1(t)* [Figure 1(a)] and *emms1(t)* [Figure 1(b)] show respectively the optimal control and total emissions profile when 99% of the abatement cost factors can be attributed to "absolute" costs C_a (Case 1). *Abate2(t)* and *emms2(t)*, and *abate3(t)* and *emms3(t)*, show the corresponding results for cases 2 and 3.

For the classical technology exogenous/low inertia case, abatement jumps to an optimal level of about 6% emissions reduction, and then increases very slowly owing to the rising baseline emissions; this is basically the Nordhaus result, in form as well as order of magnitude.[8]

For the half-and-half case, when the abatement costs in the parameterization Equation (16) are divided equally between transitional and absolute

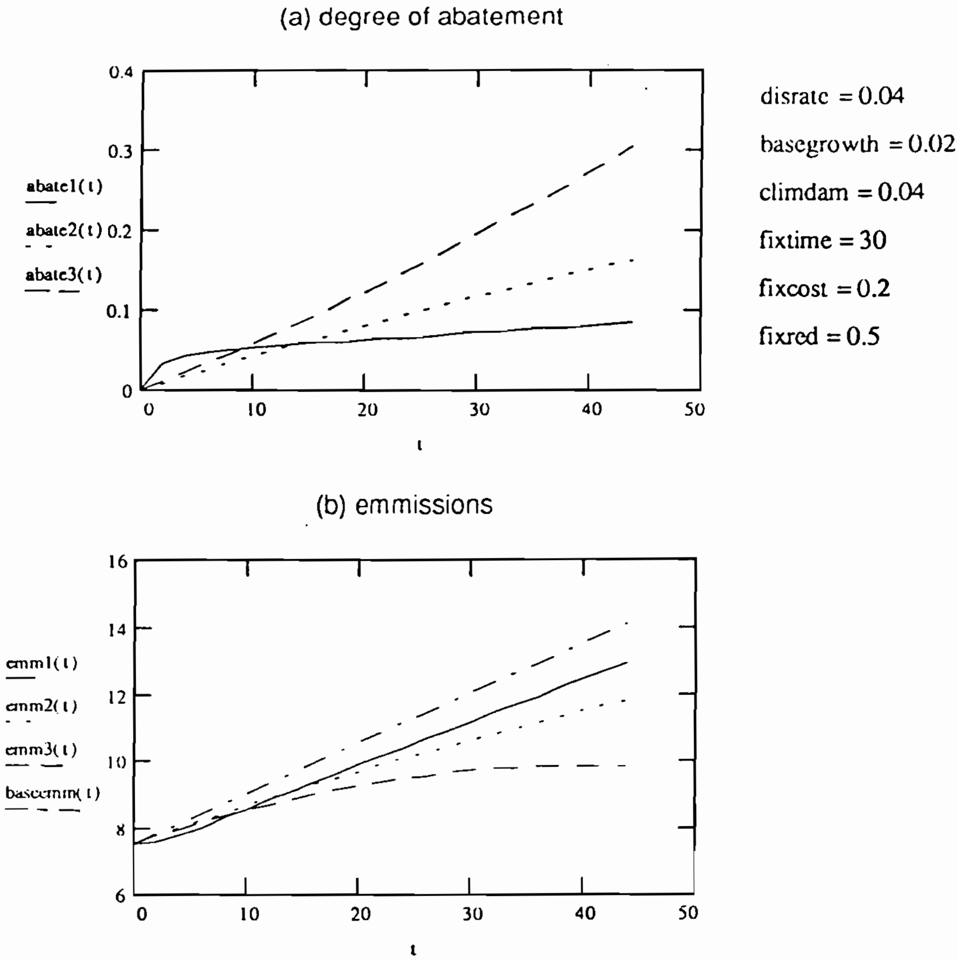
[8]In fact, Nordhaus uses a significantly lower estimate of climate damages, but a cubic cost function for abatement costs; his results reflect a trade-off at lower assumed impact and abatement costs, at such modest abatement levels, but his costs for much more extensive abatement rise very rapidly.



Case 1: Low inertia/transition costs, fixed abatement costs (exogenous technology)
Case 2: Half-and-half
Case 3: High inertia/transition costs, fully endogenous technology development

Figure 1. Optimal (a) abatement responses and (b) emission trajectories under differing assumptions about technology development processes (3%/yr rate of time preference).

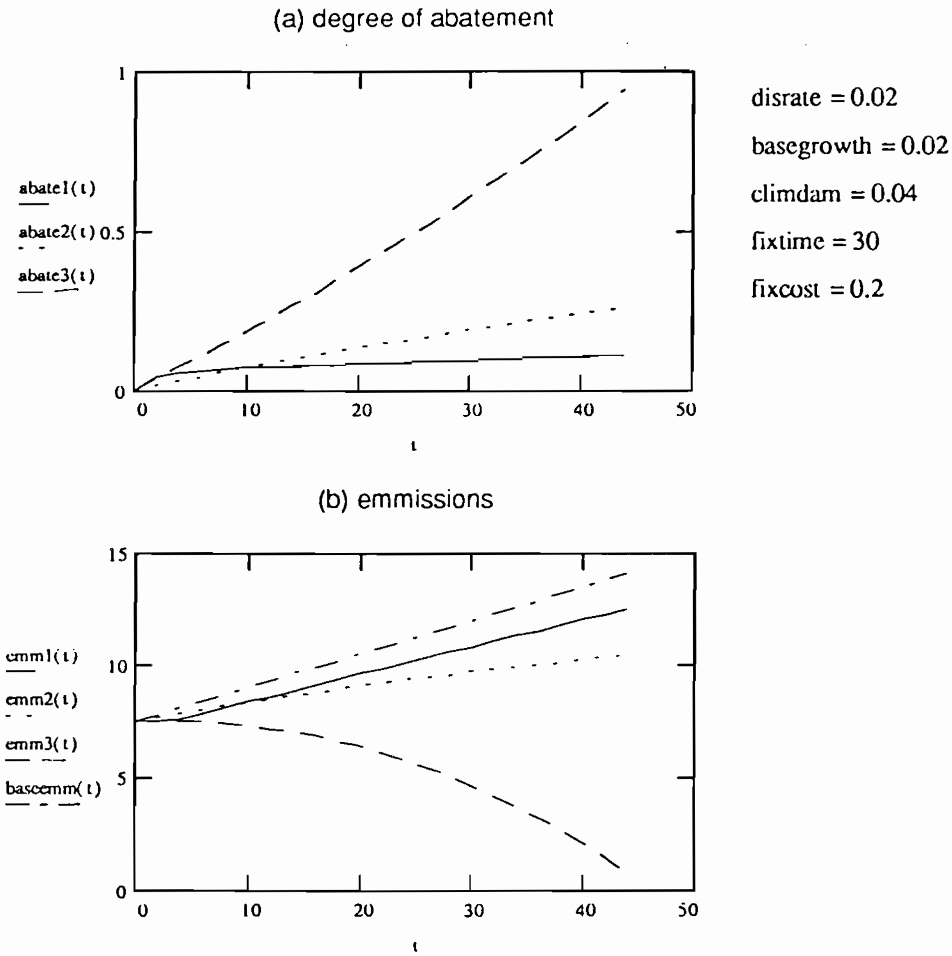
costs, abatement rises much more slowly. After about 11 years, however, it exceeds the "ceiling" level of the classical case, and carries on rising to nearly twice that level.



Case 1: Low inertia/transition costs, fixed abatement costs (exogenous technology)
Case 2: Half-and-half
Case 3: High inertia/transition costs, fully endogenous technology development

Figure 2. Optimal (a) abatement responses and (b) emission trajectories under differing assumptions about technology development processes (4%/yr rate of time preference).

In the endogenous technology/high inertia case, abatement rises to exceed the steady state level of case 1 after about 6 years, and it carries on rising at a rate which does not slacken in the period examined (in fact it accelerates fractionally owing to the rising baseline).



Case 1: Low inertia/transition costs, fixed abatement costs (exogenous technology)
Case 2: Half-and-half
Case 3: High inertia/transition costs, fully endogenous technology development

Figure 3. Optimal (a) abatement responses and (b) emission trajectories under differing assumptions about technology development processes (2%/yr rate of time preference).

The absolute impact on total emissions is shown in Figure 1(b). In the classical case, after the initial depression, global emissions carry on rising, shadowing the baseline increase. In the half-and-half case, the trajectories gradually diverge, though not enough to stabilize global emissions. For the technology endogenous case, however, emissions start to diverge rapidly; after 35 years global emissions have returned to the starting value, and are on a sharply declining trend towards stabilization of atmospheric concentrations.

It is emphasized again that this result is an optimal path for the parameter values chosen, which can hardly be considered extreme. It is not a result driven by assumptions of very high climatic damage or fixed climate thresholds, or a very low rate of time preference; nor does it reflect particularly low estimates of the cost of abatement technologies as currently perceived. It is a result driven by the consequences of endogenous technical change in which the act of limiting emissions in the first decade lowers the cost of abatement in the next, in a recurring process of technological and behavioral adaptation to the requirements of abatement.

The absolute values of course depend upon the assumptions used. Many of the key sensitivities are readily apparent from the form of the mathematical result (equation 15). Thus, the optimal degree of abatement at all points is proportional to the assumed costs of climate impacts: doubling the climate damage function doubles the optimal degree of abatement. Similarly, for a constant ratio C_a/C_b, the optimal abatement is inversely proportional to the cost of abatement.

As the rate of time preference is lowered, placing more weight upon future impacts, the optimal degree of abatement clearly rises, but the relationship is complex. Figures 2 and 3 show results corresponding to those above for rate of time preferences of 4%/yr and 2%/yr. In the former case, even with fully endogenous technology development, global emissions are barely stabilized at the end of four decades given the other values used. In the latter case – the value promoted by Cline (1992) – emissions decline so rapidly that atmospheric concentrations would probably be stabilized after three or four decades.

8. Discussion

The first conclusion of this exploratory study then is a message of relative optimism. If the process of technology development is in fact responsive to the extent modeled in case 3 above, there may be solutions to the problem of climate change, with optimal responses stabilizing the atmosphere over a period of some decades at very moderate cost. This possibility is, of course, in sharp contradiction to the conclusions of most previous cost–benefit modeling studies which have argued that the costs of stabilizing even emissions, let alone concentrations, would be high and continually increasing.

This is not a surprising conclusion when the basic hypothesis of endogenous technological change in the form modeled here is understood. Rather less intuitive is the rate of response in the first decade. It might be supposed that the rate of initial responses would be progressively depressed as the weight accorded to inertial/transitional costs increases. The results in Figure 1 illustrate that this is not the case beyond a certain point; for the high inertia, technology endogenous case (case 3), the abatement response is more rapid than in the half-and-half case.

The reason for this lies in the long-run impact on technological trajectories. Initial abatement stimulates technology and infrastructure development, and behavioral changes, which lower the cost of further abatement. As long as there is a substantial component of "absolute" abatement costs – fixed and not susceptible to endogenous cost reduction – the benefit of any endogenous cost reduction is capped after a couple of decades by the absolute component of abatement costs. If technology development is highly endogenous, however, the benefits are greater not only in terms of faster embodied cost reduction, but they also extend much further – the initial moves carry through to a pattern of more extensive abatement spanning over decades. The cost of more rapid action rises, but the benefits rise faster; and thus, it is optimal to act faster to maximize the benefits of induced technological development.

This interpretation is supported by the sensitivity studies with the discount rate. When technology development is fully endogenized, the rate of abatement rises disproportionately faster for the lower rate of time preference, reflecting the high value attached to the long-term benefits of starting early upon a "self-sustaining" abatement trajectory.

The paper has not sought to examine in depth the process of responsive or induced technology development implicit in such "endogenization"; it is a complex and poorly understood issue. The paper has, however, advanced observational evidence to suggest that technical change in the energy sector has to an important extent been of this character.

All these results point to the fact that a better understanding of the issue of endogenous technological change is essential in devising rational responses. For example, Schlesinger (1993) argued on the basis of his modeling work that:

"Rather than squabbling about near-term policies, the effects of whose differences are only minor, we should focus attention on the long-term major problem of providing energy worldwide".

This paper has demonstrated that if technology development is indeed highly responsive to market conditions (such as abatement requirements), the logic in this quotation is perverse and self-defeating: it may be the act of abatement itself which starts to generate the possibility of long-term solutions to the energy/climate problem. In this case, delaying response would not only incur marginally higher costs of climatic impact from the interim emissions; it would delay the whole schedule of feasible abatement, and increase abatement costs, over the subsequent decades.

This issue of the cost of delay under differing assumptions about technology processes is obviously one which can be examined directly with models such as the one developed here. Another and related issue is the impact of uncertainty upon optimal strategies under conditions of high inertia and/or endogenous technical change. Such work is, however, beyond the scope of this present paper, which has sought merely to introduce for scrutiny the issues and the basic modeling concept developed.

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