Influence of socioeconomic inertia and uncertainty on optimal CO2-emission abatement

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HAL Id: halshs-00002452

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The influence of inertia and uncertainty upon optimal CO_2 policies

M. Ha-Duong[1], M. J. Grubb[2], J.-C. Hourcade[1]

Following the UN Framework Convention on Climate Change [1], countries will negotiate in Kyoto this December an agreement to mitigate greenhouse gas emissions. Here we examine optimal CO_2 policies, given long-term constraints on atmospheric concentrations. Our analysis highlights the interplay of uncertainty and socioeconomic inertia. We find that the 'integrated assessment' models so far applied under-represent inertia, and we show that higher adjustment costs make it optimal to spread the effort across generations and increase the costs of deferring abatement. Balancing the costs of early action against the potentially higher costs of a more rapid forced subsequent transition, we show that early attention to the carbon content of new and replacement investments reduces the exposure of both the environmental and the economic systems to the risks of costly and unpleasant surprises. If there is a significant probability of having to stay below a doubling of atmospheric CO_2-equivalent, deferring abatement may prove costly.

The problem of climate policies is stochastic in nature: we are not likely to know soon at what concentration level « dangerous interference with the climate system » [1, art. 2] would occur. An initial abatement path consistent with reaching one selected ceiling may have to be either accelerated or relaxed in the light of new scientific information. This is why the IPCC states that: « *The choice of abatement paths involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proven unnecessary), against the corresponding risks of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital)*»[2, Ch. 8]. Incorporating uncertainty into the analysis implies that the inertia of production and consumption systems becomes critical. Without inertia, the transition costs for switching from one emission path to another would be null and uncertainty would not matter so much. But in a stochastic framework, inertia has a Janus's role: it raises both the costs of premature abatement and the costs of accelerating

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abatement if stronger action is called for after a period of delay.

Here we analyse these issues with a compact intertemporal optimisation model, DIAM, defined in Box 1. DIAM determines the least-cost CO_2 emission pathway consistent with staying below a given or stochastic concentration ceiling, given assumptions concerning abatement costs; the rate r at which exogenous technical progress reduces these costs; the societal discount rate ρ (the annual rate of decline in the present value of costs and benefits incurred in the future); and the inertia in the system D. We adopt parameters lying within the range of magnitude quoted in literature for exogenous technical progress (1% per year) and for the societal discount rate (3% and 5% per year)[2, Ch. 4 & 9], and for the model of carbon accumulation. The inertia parameter D, derived from the structure of abatement costs, is the novel aspect of the model and demands more discussion. The abatement cost at time t is expressed as a quadratic function of both the degree and the rate of abatement (Box, Eq. 6). The non-linearity of costs with respect to the degree of abatement x is well established in the literature [2, Ch. 7 & 8]. By adding a term that depends upon the *rate* of abatement A (akin to the time derivative of x), the model captures inertia explicitly. Modelling studies of capital stock turnover [3] confirm that costs depend non-linearly on the rate of abatement. In Eq. 6, additive separability between permanent costs (in $c_a(D)\,x^2$) and adjustment costs (in $c_a(D)\,D^2\,A^2$) makes it possible to explore the impact of transitional costs independently of long-run, permanent abatement costs [4]. For example, various transportation systems and urban planning patterns with very different carbon contents could have comparable operation costs; induced innovations cumulating over long periods could also reduce long-run costs to low levels. Nevertheless, starting one policy and then switching to another may entail high transition costs.

To test the sensitivity of our results with respect to the form of the cost function, we explore an alternative specification Eq. 6bis, where adjustment costs are solely determined by comparing A to the rate of capital depreciation in the energy sector. As long as A is lower than the 'natural' pace of replacement of capital $1/D$, there are no adjustment costs and the reduction cost is proportional to x^2. Above that pace, costs would be multiplied by max(1, $D\,A$).

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Dimensional analysis in both specifications shows that D is a duration, which can be be interpreted as the characteristic timescale of changes in the global energy system. If interpreted purely in terms of capital depreciation at rate δ, then $D = (\ln 2) / \delta$.

This approach allows us to capture crucial dynamic constraints without resorting either to the arbitrary upper bound on emission reduction rates, as in [5, 6, 7], or to the limitations associated with representing inertia purely in terms of uniformly depreciating capital stock, as in [8, 9]. DIAM gives approximately the same results as these latter models when we set $D = 20$ years (i.e. $\delta \approx 4\%$/yr), a reasonable average for the rate of renewal of appliances, cars, power stations, or refineries whose lifetimes range from 10 to 40 years.

But there are many other sources of inertia in the socio-economic systems that produce greenhouse gases. Time is needed to remove market and institutional barriers to the diffusion of innovations and obstacles due to imperfect information and imperfect foresight; as empirically demonstrated in [10], without specific policies, new energy sources have taken about 50 years to penetrate from 1% to only 50% of their ultimate potential. Furthermore, greenhouse gas emissions depend in part upon long-lived capital such as buildings, transport and urban infrastructures whose effects may last more than 50 years, and on the linkages between different systems, such as the complex interlinked investments in mines, ports, pipelines and power stations. Greenhouse gas emissions today are still clearly influenced, perhaps strongly, by planning and investment decisions made in the decade after the Second World War, if not before.

None of this is reflected in available 'integrated assessment' models. They do not represent explicitly energy-consuming infrastructure such as buildings or roads, or the linkages between different parts of supply systems. Nor do they capture issues of technology clustering or adaptive responses associated with induced innovation, which cumulate over decades. Other critical aspects such as the dynamics of population, economic growth and induced technology development and diffusion, within and beyond the energy sector itself, may also involve very long timescales and are not captured in the current 'integrated assessment' models.

This difference between inertia in current modelling practice (~20 years) and the larger empirical value (~40-60 years) is thus not surprising. Consequently we

explore both 20 years and 50 years for the values of D. As Table 1 and Figure 1c illustrates, with these values, adjustment costs represent from 18% to 71% of the total cost depending upon the scenario.

We initially focus upon 450ppm and 550ppm concentration ceilings. CO_2 concentrations in the range 450-500ppm - depending upon assumptions about other greenhouse gases - correspond to a total radiative forcing about double pre-industrial CO_2 concentrations, which has been the benchmark for most climate model analyses of future equilibrium climate change [11]. 550ppm represents the level given greatest attention in [12]. Under the IPCC's IS92a scenario, 450ppm is passed around 2030 and our optimal scenarios converge to this as a ceiling in 2050-60; 550ppm is passed around 2065 and converges as a ceiling in 2080-2100. Corresponding optimal pathways under different assumptions are illustrated in Figure 1(a). 650ppm is not reached until the end of the century or later.

Our main results concern the interaction of inertia and uncertainty, for trajectories in which abatement can start from 1997. The upper part of Table 1 represents optimal trajectories to a concentration ceiling known from the start, whereas the lower part represents optimal strategies when 550 ppm is the expected value of three equiprobable ultimate concentration limits of 450, 550 or 650 ppm (Figure 1b). For predetermined ceilings, the optimal trajectory is most sensitive to the ceiling. Optimal global abatement in 2020 (over and above any 'no-regret' measures) ranges from 19-24% for the 450ppm ceiling, and 3-7% for the 550ppm case. When 550ppm is the average of a stochastic target however, optimal abatement is 9-14%. Furthermore the results are now quite sensitive to the assumed inertia. With D=50yrs, optimal abatement global abatement in 2020 is 11-14%; only with low inertia and high discounting does it drop below 10%.

The explanation for this is to be found in the final columns of Table 1 and Figure 1 (c, d). Under a predetermined 450ppm ceiling, the major early expenditures arise from the transitional costs of turning the system away from the reference trajectory; for D=50 these amount up to 59% of the total discounted costs. Deferring abatement requires this effort to be squeezed into a much shorter period of time, as also demonstrated in [13]. Under the 450ppm ceiling, deferring abatement by two decades adds 70% to the total cost for $D = 50$, but only 32% for $D = 20$. As illustrated by the results for 550ppm, the costs of deferring abatement is not nearly as large when the time to stabilisation is much greater than the

characteristic time of the system. Consequently, when the ultimate target is uncertain, the costs of switching to 450 ppm pathway too late dominates costs of premature abatement in the 650 ppm case. This effect is all the more important if the resolution of uncertainties comes later (scenario U550L).

Qualitatively, our conclusions are robust to the assumed degree of inertia and discounting: even with low inertia and high discounting, corresponding to most of the models cited by [12], the abatement under uncertainty (U550B) is 9% in 2020 compared with 3% for the deterministic equivalent. But recognising higher inertia and the extent of uncertainties amplifies the economic risks associated with deferring abatement.

The results of Wigley, Richels and Edmonds [12], drawing upon various 'integrated assessment models' of climate change such as DICE [8] or MERGE2 [9], have been widely interpreted to support a policy of modest early abatement. Our results illustrate that abatement over the next few years is economically valuable if there is a significant risk of having to stay below ceilings that would otherwise be reached within the characteristic timescales of the systems producing greenhouse gases. Even if other greenhouse gases are strongly controlled, CO_2 concentration above 500 ppm would result in atmospheric changes equivalent to at least doubling of pre-industrial CO_2 levels. With continuing growth in CO_2 emissions akin to the IS92a scenario, even 500ppm is likely to be passed within about 50 years. If there is any significant risk that we need to stay below this level, the socio-economic inertia in energy systems suggests that there mey be a high cost attached to a significant delay in abatement efforts. CHECK FINAL PARA.

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Box 1: DIAM, a Model on the Dynamics of Inertia and Adaptability for integrated assessment of climate change mitigation

Indices t, u refers to time periods ; s refers to states of the world. DIAM [4] finds the optimal abatement strategy $x^*(s, t)$ by minimizing total expected discounted abatement cost J defined Eq. 1. under constraints Eq. 2, the concentration ceiling and Eq. 3, dynamic programming. Eq. 4 defines CO_2 atmospheric concentration $M(s, t)$, and Eq. 5 defines acceleration of abatement $A(s, t)$. Abatement costs $C(s, t)$ are defined by Eq. 6 . Alternatively, Eq. 6 bis is used to test sensitivity of results to the shape of the cost function.

Time profile $E^{ref}(t)$ refers to anthropogenic fossil carbon emissions in IPCC scenario IS92a . The reference CO_2 concentration path $M^{ref}(t)$ is computed from IS92a total carbon emission with the atmospheric perturbation CO_2 response function $R(u)$ using a linear carbon cycle [6, 14, model W]. $M^{ref}(1765)$, concentration before industrialization, was under 280ppmv. It was 354ppmv in 1990, increasing at 1.7 ppmv y^{-1}. [14]

Reduction costs are determined by a social risk-free discount rate ρ (3% or 5%, to account for pending controversies) ; a technical progress rate r (1%) and a characteristic time of energy systems D (20 or 50 yr). The costs scale $c_a(D)$ is normalized ($c_a(50)=1.36$, $c_a(20)=3.18$) so that total cost is comparable to DICE's one [8]. Note that when Eq.6 is reported into Eq. 1, the $c_a(D)$ can get out of under the Σ , this implying that the optimal $x^*(s, t)$ is independant of $c_a(D)$.

The stochastic concentration ceiling is defined by the number of alternatives examined N ; ceilings levels $L(s)$; subjective probabilities $p(s)$ and the date of uncertainty resolution t_{info}.

Results are shown Table 1. First we examine certainty scenarios $N=1$ for different values of D, ρ and L (sensitivity to r is mathematically the same as sensitivity to ρ). Then we explore $N=3$ with equidistribution over {450, 550, 650} ppmv, for $t_{info} = 2020$ and $t_{info} = 2035$.

(Eq. 1) $J =$ **Erreur !Erreur !**

(Eq. 2) $M(s, t) \leq L(s)$

(Eq. 3) $\forall\, t \leq t_{info}, \forall\, s, 1 \leq s \leq N, x(s, t) = x(1, t)$

(Eq. 4) $M(s, t) = M^{ref}(t) - 0.471$ **Erreur !**

(Eq. 5) $A(s, t) = x(s, t) - x(s, t-1)$

(Eq. 6) $C(s, t) = c_a(D) (1 + r)^{t_0 - t}$ **Erreur !** $[\, x(s, t)^2 + D^2 A(s, t)^2\,]$

(Eq. 6 bis) $C(s, t) = c_a(D) (1 + r)^{t_0 - t}$ **Erreur !** $[\, x(s, t)^2 \max (1, D\,A(s, t))\,]$

Table 1 : Characteristics of optimal global emissions scenarios and strategies[*]

Certainty scenarios	D yr.	ρ	L ppmv	t_{stab}	x_{2020}	x_{2020} with Eq.6bis	E_{max} GtC	$t_{E_{max}}$	Erreur !	Cost of delay
450A[acd]	50	3%	450	2060	24%	18%	8.7	2015	59%	+70%
450B[a]	20	5%	450	2050	19%	14%	9.2	2015	32%	+32%
450C	50	5%	450	2050	20%	16%	9.1	2015	74%	+72%
450D	20	3%	450	2060	23%	19%	8.8	2015	19%	+25%
550A[abd]	50	3%	550	2100	7%	4%	11.5	2050	55%	+10%
550B[a]	20	5%	550	2080	3%	2%	12.6	2050	31%	+2%
550C	50	5%	550	2090	4%	2%	12.2	2050	71%	+8%
550D	20	3%	550	2090	5%	4%	11.9	2050	18%	+3%
650A	50	5%	650	2125	3%	0%	14.1	2070	55%	+4%

Hedging strategies	D yr	ρ	N	t_{info}	x_{2020}	x_{2020} with Eq.6bis	x_{2010}	E_{2020} GtC		
U550A[b]	50	3%	3	2020	14%	15%	8%	9.6		
U550B	20	5%	3	2020	9%	6%	4%	10.1		
U550C	50	5%	3	2020	11%	12%	6%	9.9		
U550D	20	3%	3	2020	12%	9%	7%	9.8		
U550L (late)	50	3%	3	2035	21%	17%	12%	8.9		

Footnotes to Table 1 :

[*] Reduction figures refer to global average (initial reductions focused on developed countries would be proportionately greater), and to reductions additional to those not incurring significant economic costs (i.e. reductions beyond no-regret measures). Column t_{stab} shows the optimal stabilisation date, x_{2020} the industrial emissions abatement in 2020. (E_{max} , $t_{E_{max}}$) is the optimal emissions curve apex. **Erreur !** is the share of adjustement costs in total costs, see legend for Figure 1d. The **cost of delay** is the increase in discounted total cost when reduction starts in 2020 instead of 1997. E_{2020} is the optimal emissions in 2020.
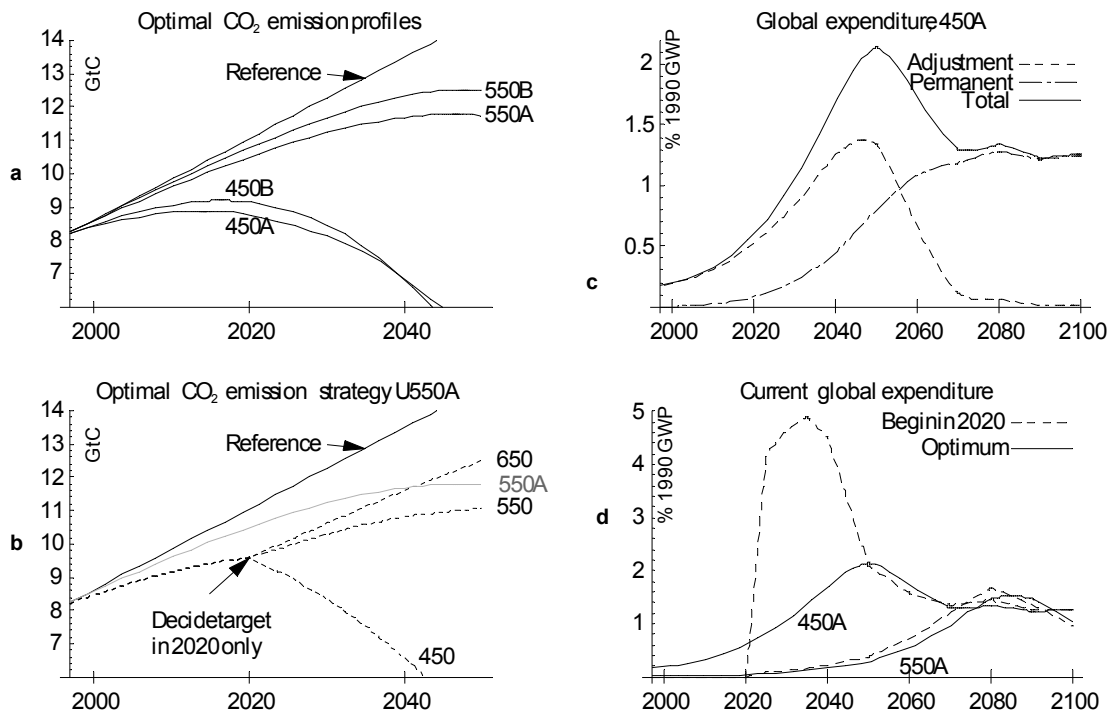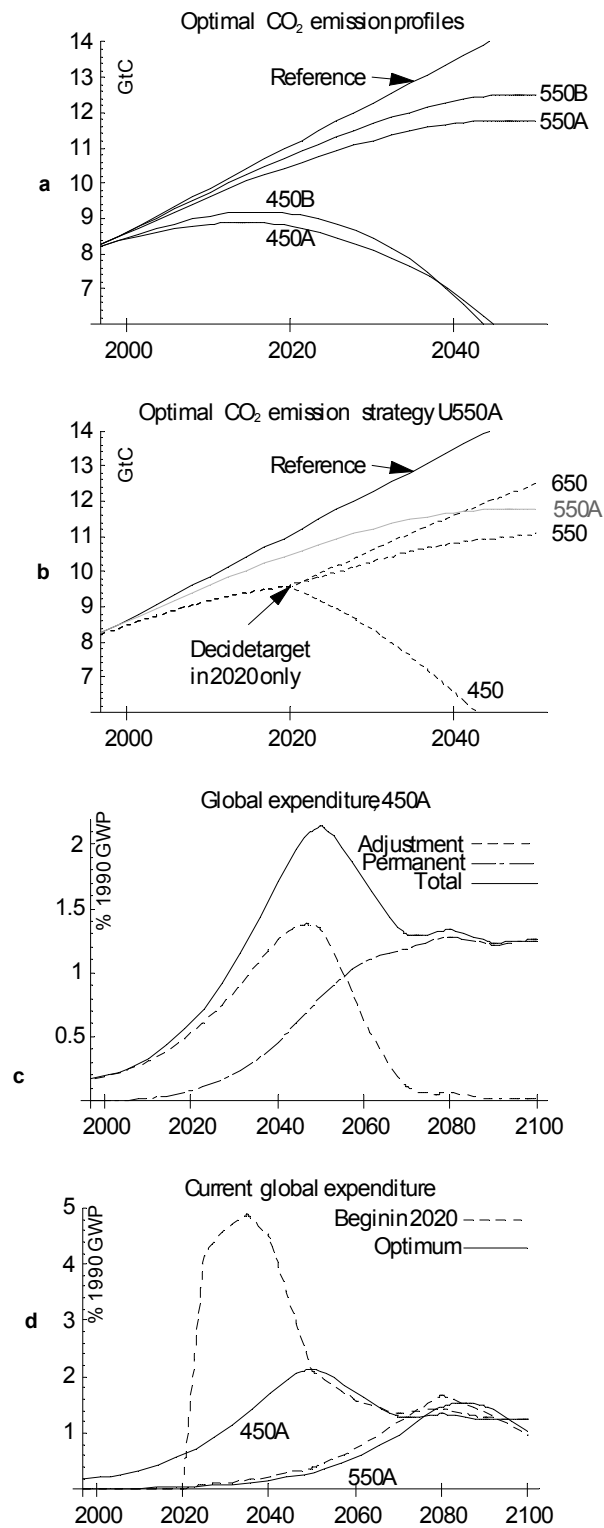
[a, b, c, d] Corresponds respectively to panel **a**, **b**, **c**, **d** in figure 1.

Figure 1. Optimal pathways

Figure 1 (alternate layout). Optimal pathways under given stabilisation constraint

Optimal CO_2 emission profiles

GtC

14
13
12
11
10
9
8
7

Reference

550B
550A

450B
450A

a

2000   2020   2040

Optimal CO_2 emission strategy U550A

GtC

14
13
12
11
10
9
8
7

Reference

650
550A
550

Decide target
in 2020 only

450

b

2000   2020   2040

Global expenditure, 450A

% 1990 GWP

2

1.5

1

0.5

Adjustment
Permanent
Total

c

2000   2020   2040   2060   2080   2100

Current global expenditure

% 1990 GWP

5
4
3
2
1

Begin in 2020
Optimum

450A

550A

d

2000   2020   2040   2060   2080   2100

Legend for Figure 1

The reference case, emissions increasing linearly by about 2%/year from 1997 level, approximates IPCC IS92a. This is assumed to be least cost without constraints, so abatement shown is global average over and above any 'no regret' reductions. One GtC equals $(12+2*16)/12 = 3.67 \ 10^{12}$ kg of CO_2 .

a: Four optimal emission pathways that minimise the total abatement costs for the given concentration ceiling, inertia and discount rate (see Table 1). The B cases have lower inertia and higher discount rate than A, both factors leading to higher near-term optimal emissions. However, optimal policy is more sensitive to the ultimate concentration ceiling, 450 or 550ppmv.

b: Optimal emission strategy U550A under stochastic constraint. The ultimate target is decided only in 2020, before that date, the strategy follows a precautionary path emitting sensibly less than the comparable case without uncertainty 550A.

Panels **c** and **d**, the vertical axis unit is % of 1990 gross world product (GWP), assuming the Nordhaus cost function [2]. Since D=50 for all curves in c and d, uncertainties in the cost scale parameter $c_a(50)$ would only affect curves homothetically.

c: Cost as the sum of adjustment cost and permanent cost, optimal path 450A. The ratio: area under the 'Adjustment' curve divided discounted by area under the 'Total' curve discounted is the share of adjustment costs, labeled **Erreur !** in Table 1.

d: Current expenditure profiles with (dashed lines) and without (solid lines) a 20 years delay, for 450 and 550 ppm stabilisation targets (case A). For 450 ppm, cost peaks abruptly and much higher with delay than without, due to higher adjustment costs in the 2020 - 2040 period. Results are not that sharp for 550 ppm, as the time available to stabilize at 550 ppm (or above) exceeds the characteristic time of the global energy system.

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your ref: G06172B PN/lcg
Montrouge, le 5 August 2004
Dr. Philip Newton
Assistant Editor, Nature
Porters South, 4-6 Crinan Street, London N1 9XW

Dear Philip,

We are pleased to submit the revised manuscript, retitled as 'The influence of inertia and uncertainty on optimal CO_2 policies'.

We have considered your points closely, and those of referees as asked, and we feel that we have indeed been able to address them in the enclosed manuscript:

We have shifted the emphasis of the paper to clarify the role of inertia, and why we believe that previous climate policy models have under-represented inertia. Although we show we can reproduce WRE results given the same assumptions (low inertie, 20 5% discount rate, 500ppm ceiling with no uncertainty), for the reasons set out we focus on different hypotheses, and consequently, when it comes to policy implications our views differ radically. Accordingly, we moved the direct reference to their paper in the last paragraph, more usually devoted to the discussion of these policy implications: although discussing the adequacy of models is important, in the end the reality rules.

We think the paper meets all your editorial guidelines, as we have shortened it considerably. We have done so by dropping much of the discussion, including that of cost-benefit analysis (except for a passing reference in one sentence). We have not removed analysis of uncertainty - which we regard as central - but we have managed to shorten the discussion by integrating it with the rest of the discussion. In the same spirit, we simplified the figure representing optimal strategies, and present it as panel b in Figure 1.

Yours sincerely,

Minh Ha-Duong   Michael Grubb   Jean-Charles Hourcade

Enclosed :

- Revised manuscript (four copies, one with the changes clearly indicated)
- Note for answering to Referee 3
- Explanation note and PC formatted HD floppy disc containing artwork.

Note for answering to Referee 3 about « delay is never efficient »:
The misunderstanding probably arises from the confusion between cost-benefit and cost-efficiency models. Diam is not cost-benefit analysis. In this framework, deferring emissions can never be optimal, because it adds a supplementary constraint to the optimisation. As Referee 1 says, « *it is qualitatively unsurprising, given any reasonable model of how the world works* ». Here is a proof :

> Proof: Let S be the set of all acceptable reduction trajectories, and let S' be the set of all acceptable reduction trajectories that track the BAU path for one or more decade. Let J be any cost function defined over S. Then because S' is a subset of S, the minimum of J over S is lower than the minimum of J over S'.

As we say in the paper, cost-benefit analysis is an important dimension of the issue that we have chosen not to develop here. The cost-benefit version of DIAM does actually find that deferring abatement decrease the reduction cost for lax targets and increase it for strict targets.With the functional specification in [Grubb et alii., 1995] , using a central discount rate of 4% and the same value of other parameters, we have :

	D	Exogenously imposed date of stabilisation	Optimal stabilisation level	Impact of waiting until 2020		
				reduction cost	climate damage	total cost
a	5	2050	488 ppmv	-5%	+6%	+2%
b	50	2050	462 ppmv	+4%	+16%	+9%
c	500	2050	459 ppmv	+11%	+19%	+15%
d	5	2150	555 ppmv	-16%	+6%	+2%
e	50	2150	516 ppmv	-25%	+9%	+4%
f	500	2150	487 ppmv	-29%	+12%	+5%

Source : Ha Duong Minh, Comment tenir compte de l'irréversibilité dans l'évaluation du changement climatique ? Thèse de Doctorat de l'Ecole des Hautes Etudes en Sciences Sociales, Paris. En préparation.

The table shows that delay increase reduction cost only for cases b and c, when the stabilisation date is close in time compared to the characteristic time of the energy system. This is what Ref. 3 termed a « strict » target. In all other cases a, d, e, f , the stabilisation date is far in time compared to D. These are « lax » targets, and delay is cost-efficient in the meaning that reduction costs are decreased. But note that even in this case, the idea that delay is never optimal still holds. This is because with delay, the savings in reduction costs are more than offset by the losses on climate damages.

However, to avoid the space required to explain this in full, we have dropped the reference from our paper.

Response to Referee 1:
We are glad to read that, more broadly, our paper is a part of a debate that is clearly important.
However, in our opinion, the assertion that WRE analysis does not address directly the question of inertia and optimal abatement in the near future is build upon rather restrictive definitions of 'directly' and 'optimal'.
WRE raise the issue of « a realistic transition away from the current heavy dependance on fossil fuels. ». Then they present pathways that are « an idealisation of the assumption that the initial departure from the BAU would be slow ». Finally they show that « Pathways involving modest reductions below a BAU scenario in the early years followed by a sharper reduction later on were found to be less expensive ».
Those three quotations illustrate why we think about our paper as directly related to WRE.
Ref. 1 points (1.) and (2.) seems to draw from the idea that we limit our paper to the remark that « deferring abatement is never optimal » and this is trivial.
First, we are unsure that the majority of Nature readership remembers that much about constrained optimisation programming. For all those, it is important to explain clearly this mathematical truth. As Ref. 3 reaction points out, the suboptimality of tracking the BAU path for a few decades is not obvious for everybody.
However, in the paper we go deeper than that. We explore <u>quantitatively</u> what a 'slow' departure from the BAU means and the cost of delay. Our approach allows to explore for what ranges of values for inertia and uncertainty WRE idealisation is more relevant than WGI.
The following loop illustrates the fundamental risk with models underestimating inertia:

```
Step 1. Define a reasonable target, neither too lax neither
        too strict. Set it according to the real intuitive
        socio economic inertia (for exemple, 500 ppmv if
        present concentration is around 360 ppmv).
Step 2. If we assume a small inertia, the target is lax.
        Therefore, it is optimal to do very little reduction in
        the next decade: « delay is cost effective ».
Step 3. Since climate is non linear and responds with many
        decades lag, no damage has happened yet. Up to now,
        everything is fine as usual. Go back to Step 1 with 10
        year more.
```

Jean de La Fontaine told a few centuries ago the story of the race between « The Hare and the Turtle ». If we are the turtle, we would better not adopt the hare's strategy, especially when we don't know how far the goal is.

Note regarding the electronic artwork provided on the disk:

The floppy disk is formatted in HD for PC, using the normal DOS file system.
Figure 1 is composed with four panels. To facilitate further publishing work, we provide two alternative layouts for them : A 2*x*2 block and a 1*x*4 column. The block was 600 points width by 371 points height, the column was 300 pts widht by 796 pts heigth.
We provide figures electronically in three formats :

- Originally, figures were generated with *Mathematica* 3.0 . The file **figure1.nb** contains the corresponding code (both layouts).

- In the paper, we used the Windows Metafile format (placeable metafile). Corresponding files are **fig1square.wmf** and **fig1column.wmf**.

- We exported to Adobe Illustrator format. Corresponding files are **fig1square.ai** and **fig1column.ai**.

Minh Ha-Duong is responsible for these figures. Please do not hesitate to contact him directly if you need supplementary information or material. Mail at haduong@msh-paris.fr, or phone at +33 146 12 18 71.