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Delayed Action and Uncertain Targets. How Much Will Climate Policy Cost?

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Summary
Despite the growing concern about actual on-going climate change, there is little consensus about the scale and timing of actions needed to stabilise the concentrations of greenhouse gases. Many countries are unwilling to implement effective mitigation strategies, at least in the short-term, and no agreement on an ambitious global stabilisation target has yet been reached. It is thus likely that some, if not all countries, will delay the adoption of effective climate policies. This delay will affect the cost of future policy measures that will be required to abate an even larger amount of emissions. What additional economic cost of mitigation measures will this delay imply? At the same time, the uncertainty surrounding the global stabilisation target to be achieved crucially affects short-term investment and policy decisions. What will this uncertainty cost? Is there a hedging strategy that decision makers can adopt to cope with delayed action and uncertain targets? This paper addresses these questions by quantifying the economic implications of delayed mitigation action, and by computing the optimal abatement strategy in the presence of uncertainty about a global stabilisation target (which will be agreed upon in future climate negotiations). Results point to short-term inaction as the key determinant for the economic costs of ambitious climate policies. They also indicate that there is an effective hedging strategy that could minimise the cost of climate policy under uncertainty, and that a short-term moderate climate policy would be a good strategy to reduce the costs of delayed action and to cope with uncertainty about the outcome of future climate negotiations. By contrast, an insufficient short-term effort significantly increases the costs of compliance in the long-term

Keywords: Uncertainty, Climate Policy, Stabilisation Costs, Delayed Action

JEL Classification: C72, H23, Q25, Q28

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1 Introduction

According to the latest IPCC report (IPCC, 2007a), there is unequivocal evidence that the climate system is warming, and this is affecting both average air and ocean temperatures, thus causing widespread snow and ice melts and average sea levels to rise. Global warming is also expected to affect both ecosystems and socio-economic systems to varying degrees, even though the impacts on natural and human environments are partly offset by autonomous adaptation actions and non-climate related drivers. The IPCC also points to widespread agreement over the fact that such changes in the climate system may be fuelled by global greenhouse gas emissions from human activities, which increased by 70% between 1970 and 2004. If emissions continue unabated, the average global surface temperature is likely to rise by an additional 1.8-4.0°C this century (IPCC, 2007a). A 2°C temperature increase is suggested to be a threshold beyond which irreversible and possibly catastrophic changes in natural ecosystems - and hence in socio-economic systems - might occur.

Parallel to this growing consensus about the scientific bases for climate change, the climate challenge has become a public policy priority, and is now ranking high in some, if not all, countries' political agenda. Even though policymakers recognise that climate change is a threat that requires widespread cooperation on an unprecedented level, they face great uncertainties, both in relation to the magnitude and severity of the impacts of climate change, and the costs of alternative mitigation strategies. Despite these uncertainties, the recognition that climate change is one of the most pressing socio-economic and environmental challenges facing our societies has led many countries to take action and implement carbon mitigation strategies. Decision making has been based on minimising the costs associated with achieving acceptable levels of emissions or concentrations. As a consequence, the analysis of economically optimal strategies that stabilise greenhouse gas (GHG) concentrations at predetermined, non-dangerous levels, has become an important research objective, as testified by the large number of studies and research efforts evaluated by the IPCC WG III (IPCC, 2007b).

Yet, even if actions to counteract climate change seem to be warranted at some level, there is little agreement over what the ultimate target should be, as the long-term stabilisation target is clearly a political decision. While the Kyoto Protocol of the UN Framework Convention on Climate Change contains important policy decisions, such as the introduction of emission trading and Clean Development Mechanisms (CDM), it falls short of a definite and effective response to climate change at a global level. Moreover, the first commitment period of the Protocol ends in 2012, and there is still great uncertainty over the details of any new global climate deal. Negotiations are

already underway to define a post-Kyoto framework, and several proposals have appeared in both academic and policy literature (see, for instance, IEA, 2002; Aldy and Stavins, 2007; Stern, 2008). However, little consensus on a given framework has emerged so far.

Policymakers therefore face an additional uncertainty: while they do expect some form of global action to be required, they do not know which countries are going to sign a climate agreement, nor do they know the ultimate climate stabilisation target that such an agreement will set. Though the UNFCCC has put forward a qualitative long-term climate stabilisation target[1], we are still far from reaching an agreement about the quantitative interpretation of this target. Two broad political positions can be identified. On the one hand, the European Union is taking the lead, demanding bold actions from its member states to meet the reduced emission targets agreed upon in the Kyoto protocol[2] and beyond 2012 (expiry of the Kyoto target). The EU and its member states are calling for concerted action to contain the global temperature increase over this century within the 2°C threshold[3]. On the other hand, less pro-active countries – notably the US – tend to focus on a less stringent stabilisation target (around 650 ppmv for all greenhouse gases, see for example, Newell and Hall, 2007), which is expected to keep temperature increase at or below 3°C by the end of the century.

Given the uncertainty about the scale and timing of future climate targets, it is also important to analyse whether the expectation of gaining better information should induce policymakers to wait before acting, or should the possibility of learning that the impacts of climate change are much worse than we now believe lead policymakers to take more stringent immediate action to avoid a necessity for abrupt and costly policy changes in the future if we are to have any hope of meeting ambitious stabilisation targets.

It is often argued that the many uncertainties surrounding climate change, its impacts and its mitigation costs warrant a delay in taking action. In particular, one of the main reasons which supporters of the learn-then-act argument put forward is that we still lack sufficient knowledge to define which level of emissions could prevent dangerous climate change and, since this uncertainty may be resolved through research and learning, we should delay expensive mitigation actions until we have a better understanding. The argument is that if we take stringent mitigation actions now, and then find out that the impacts of climate change are less significant than expected, we would have incurred unnecessary costs. On the other hand, if we learn that climate change impacts are

[1] The target is to reach atmospheric stabilisation at concentration levels that would prevent dangerous anthropogenic interference with the global climate.
[2] Emissions in 2008-2012 should be 8% below 1990 levels.
[3] EC Communication (2007) "Limiting Global Climate Change to 2 degrees Celsius: The way ahead for 2020 and beyond".

more severe, we can start undertaking stringent measures and accelerate action. But what are the consequences of deferring actions against climate change?

In a much cited paper, Wigley et al. (1996) explore the appropriate timing of CO2 abatement actions and conclude that, in general, the overall costs of reducing emissions are lower if the majority of the effort is deferred to the future. Similar results are found by Richels and Edmonds (1997) and Kosobud et al. (1994) among others. In contrast, Schneider and Goulder (1997) argue that, even though there are compelling arguments for implementing relatively mild mitigation measures in the short term, this should not justify the absence of policy action now, because it could lower abatement costs in the future.

Since the publication of these seminal papers, much effort has been devoted to identifying the optimal timing of abatement, but the majority of the existing works, however, do not explore the implications of having to deviate from the chosen emission reduction path sometime in the future. It is clear from the Fourth Assessment Report that delaying action at this point is likely to significantly constrain future opportunities to lower stabilisation levels and increase the risks of severe climatic shifts. Short term mitigation actions would avoid carbon intensity technology and development lock-ins. Yet, the IPCC Assessment Report and the studies cited do not quantify the costs implied by delaying action against climate change. We tackle this issue in the first part of the paper (Section 2), where we provide new estimates of the economic cost of climate policy assuming delayed action, i.e. slow progress towards an agreement over a climate objective.

On the other hand, advocates for immediate action invoke the precautionary principle, particularly given the risk of triggering irreversible changes in the climate system. The slow process of greenhouse gas accumulation and atmospheric decay (see Fisher, 2002) may indeed imply that, if we fail to take action to reduce emissions now and find out at a later date that climate change is more serious than expected, we may no longer be able to reverse the climatic changes that have been triggered, no matter how stringent a policy we implement. While the precautionary principle seems intuitive in the case of climate change, the results of research on decision making under uncertainty over climate policy seem to confute this intuition – indicating that the prospect of obtaining better information in the future should lead to less abatement efforts in the present. Indeed, if there is a prospect of obtaining better information in the future, this should reduce the extent to which one makes irreversible commitments in order to better exploit future information.

Several attempts at exploring the implications of uncertainty and learning on policy decisions have been proposed in the literature (see also Ingham et al., 2007 for a review) and, even though the results are not unequivocal, they seem to indicate that in general, the prospect of learning new

information would lead to a reduction in current abatement efforts. For instance, Manne and Richels (1995) use an integrated assessment model to explore the implications of uncertainty on the severity of climate change impacts. They find that if there is a prospect of resolving such uncertainty, the optimal path of emissions reduction varies considerably with respect to the optimal path without uncertainty. In particular, the earlier the uncertainty is resolved, the more it pays to wait before taking action. Similar results are found by Nordhaus and Popp (1997). Strengthening these results, Ulph and Ulph (1997) find that even when the climate system risks undergoing irreversible shifts, uncertainty does not lead to higher abatement efforts. Even by introducing learning from previous observation (though imperfect), as in Karp and Zhang (2006), abatement efforts decrease relative to the case in which no learning is possible – and the decrease is more marked when uncertainty is large, that is, when the potential scope to benefit from learning is greater.

A different approach is taken by Ha-Duong and co-authors (Ha-Duong et al., 1997), who use a stylised model to determine the optimal mitigation choices given uncertainty about the stabilisation target. They find that the existing inertia in investment decisions increases the costs of delayed actions, and that, in the presence of uncertainty about future climate targets, it is cost-effective to spread mitigation actions across generations. Similarly, Yohe et al. (2004) explore a different kind of climate uncertainty, notably uncertainty over the target that policymakers may wish – or have to – achieve in the future. Indeed, given the current agreement over the threat posed by climate change and the need to take some action, this approach seems more convincing. The authors find that imposing a carbon tax other than zero is a better strategy than doing nothing until full information becomes available.

The results of these last two papers support a policy strategy which starts at moderate levels but increases its stringency if future information on impacts of climate change confirms their relevance. In this paper, we will achieve a similar conclusion, even though the analysis is taken several steps forward. First, we apply state-of- the-art stochastic programming techniques to retrieve the optimal strategy endogenously, that is within a single optimisation. Second, we carry out the analysis using an integrated assessment model that features a realistic description of the mitigation options in the energy sector as well as induced technological change. This allows us to go beyond stylised modelling representations and to evaluate the impact of uncertainty on the optimal portfolio of abatement technologies and innovation.

This paper therefore focuses on the effects of *policy uncertainty*, thus following the recommendation of institutions such as the IPCC that, in the latest report, advocates “a risk management or ‘hedging’ approach [that] can assist policymakers to advance mitigation decisions

in the absence of a long term target and in the face of large uncertainties related to the cost of mitigation, the efficacy of adaptation and the negative impacts of climate change" (IPCC, 2007c, p.43). Similar suggestions are given in Stern (2007, Ch. 8.6, p. 202 of the online version) who writes "Early abatement paths offer the option to switch to a lower emissions path if at a later date the world decides this is desirable. […] Similarly, aiming for a lower stabilisation trajectory may be a sensible hedging strategy, as it is easier to adjust upwards to a higher trajectory than downwards to a lower one."

The objective of this paper is to provide a policy-relevant answer to the issue of delayed action timing and to suggest a globally optimal policy in the face of uncertain climate stabilisation targets. To do this, we use a computational model, WITCH (Bosetti et al., 2006), designed to analyse the interactions between socio-economic systems, climate change and mitigation policies. WITCH is a regional integrated assessment hard-link hybrid model. Its top-down component consists of an intertemporal optimal growth model in which the energy input of the aggregate production function has been expanded to integrate a bottom-up-like description of the energy sector. World countries are grouped in twelve regions, whose strategic interactions are modelled through a dynamic game. A climate module and a damage function provide the feedback on the economy of carbon dioxide emissions into the atmosphere.

The WITCH model is structured so as to provide information on the optimal responses of world economies to climate damages and to model the channels of transmission of climate policy to the economic system. The dynamic and strategic features of the model, the energy sector specification and the technical change options make WITCH an especially suited tool to analyse the climate change policy issue, marked by medium-term investment choices and long-term economic dynamics and environmental responses.

The paper is organised as follows. We begin by exploring the economic implications of delaying mitigation actions (Section 2). We are thus able to quantify how climate policy costs depend upon inaction time, providing useful information for future international climate agreements. Then , we analyse how uncertainty surrounding the stringency of future climate targets affects early abatement, technology choices and innovation strategies (Section 3). By explicitly incorporating uncertainty into decision making, we provide a risk management approach that can help policymakers in the choice of optimal hedging strategies. The paper is concluded with a summary of the main results and a discussion of their policy implications (Section 4).

2. The cost of delaying action

As discussed in the Introduction, uncertainty surrounding the willingness and ability to take global action – and the expectation that such uncertainty may be resolved in the next one or two decades – may induce policymakers to adopt a waiting strategy. What then, are the economic implications of continuing along a business-as-usual path e.g. for the next 20 years, and agreeing on some stabilisation target at a later date?

In this section, we explore the global implications of different decisions about the course of action to be followed in the coming 20 years on the Net Present Value (NPV) of policy costs for this century. In particular, we assess the sensitivity of 450/550 ppmv CO2 only (roughly 550/650 all greenhouse gases) policy costs to a 20-year delay in action, and also the cost of initiating a climate mitigation policy (either stringent or mild) and subsequently dropping it.

The analysis is performed by assuming that a global cap and trade scheme is implemented (either now or with a 20 years delay) to achieve a given stabilisation target (either 450 or 550 ppm CO2 only).[4] The optimal investment and innovation strategies (particularly in the energy sector) are then computed and the climate policy economic cost is determined (see Bosetti et al. 2007 for a description of how policy costs are computed with WITCH). Table 1 summarises our main results.

	Continue along the business as usual path	**Undertake a mild* climate control policy**	**Undertake a stringent** climate control policy**
Take action now	-	0.3% (0.2%)	3.5% (2.3%)
Wait 20 years on the business as usual path	-	0.4% (0.3%)	7.6% (5.5%)
Wait 20 years on a mild policy* path	-0.03% (0.06%)	-	4.2% (2.7%)

*550 ppmv CO2 only, roughly equivalent to 650 ppmv all gases
**450 ppmv CO2 only, roughly equivalent to 550 ppmv all gases

Table 1: The cost implications of delayed action, NPV GWP loss to 2100, discounted at 3% (and 5%).

If world policymakers jointly start taking action now to control climate change, the net present value of stabilisation costs at a 3% (5%) discount rate ranges from 0.2% (0.3%) to 3.5% (2.3%) of Gross World Product (GWP), depending on whether we undertake a mild policy (550

[4] We assume all countries to take action at the same time. An analysis of the implications of differentiated timing of action is provided in Bosetti *et al.* (2008).

ppmv CO2 only, equivalent to 650 ppmv all gases) or a stringent policy (450 ppmv CO2 only, equivalent to approximately 550 ppmv all gases). These figures represent the additional cost of stabilisation, compared to a world in which no costly abatement actions (the BAU scenario) are undertaken. Notice that our figures are somewhat higher than the IPCC's estimates, since we explicitly account for free-riding incentives and other inefficiencies deriving from environmental, R&D and market externalities (see Bosetti et al., 2007).[5]

As shown in Table 1, the cost implications of delaying actions for 20 years vary considerably. In particular, they crucially depend on whether policymakers decide to undertake mild or stringent policy action after the delay period. While the costs of delaying to undertake mild actions are relatively modest (the net present value of the cost is equivalent to 0.4% of GWP as opposed to 0.2% of GWP with an immediate start), moving from the business-as-usual to a stringent climate stabilisation target after the 20-year delay is extremely costly – up to 7.6% (5.5% at 5% discounting) of the net present value of GWP over this century. This represents either an increase of policy costs of about 130-140%, or an equivalent loss of 5.7 (2.2 at 5% discounting) trillion USD *per year of delay*. Of course, this is likely to disrupt the common understanding of the economic feasibility of any stringent action as currently perceived by policymakers.

Another important result emerges from our analysis: a policy strategy that immediately begins to undertake some emissions reductions that are consistent with a 550 ppmv CO2 only stabilisation target, and in 20 years reverts to the business-as-usual scenario, does not harm global welfare, and actually leads to a very mild increase of GWP, thanks to the internalisation of the various externalities on carbon, exhaustible resources, and innovation. The same mild mitigation policy can be tightened at lower costs than continuing along a business-as-usual path for the next 20 years: the net present value of the costs of shifting from a mild to a stringent policy reaches 4.2% (2.7%) of GWP, still well below the cost of inaction for 20 years followed by embracing a stringent climate policy in 20 year's time.

The policy implications of this exercise are quite clear, and support the arguments that call for immediate action to tackle climate change (see, e.g. Stern, 2007, 2008): if we continue doing nothing for 20 years, the costs of shifting from a business-as-usual to a stringent climate policy are extremely high. On the other hand, undertaking some form of mild stabilisation policy seems to be a hedging strategy which, at virtually no cost, would allow us to revert to business-as-usual and, at relatively modest cost, to undertake more decisive action if a more stringent stabilisation policy is decided upon.

[5] Most existing studies assume a central global planner and therefore internalise all these inefficiencies and externalities.

The cost effectiveness of starting with a mild policy, leaving open the possibility of more stringent actions in the future has also been highlighted in previous research (see e.g. Olmstead and Stavins, 2006; Olmstead, 2007), even though no quantitative assessment was provided. Yet, the political feasibility of such an approach – from an intergenerational perspective – can be questioned (Frankel, 2007; Aldy et al., 2001). In particular, such a strategy would impose a constraint on the action of future decision makers and political leaders, who may reject it. To overcome this issue of inconsistency over time, decision makers should take into account the uncertainty over the willingness to control climate change in the future whilst taking action today.

In the next section, we formalise the uncertainty that surrounds the climate objective. This enables us to devise the optimal abatement strategy and portfolio of mitigation technologies taking into account that future policymakers may choose from a large range of different climate targets.

3 Optimal stabilisation strategy under climate target uncertainty

In this section, we use a stochastic programming version of the WITCH model to investigate an optimal policy strategy given the uncertainty about the stringency of the stabilisation target that will eventually be established in an international climate agreement. This version of WITCH has been used to analyse other forms of uncertainty in climate change economics (see for example Bosetti and Tavoni, 2008, for an analysis of the uncertain effects of R&D). We frame the analysis on a scenario tree, solve for all scenarios simultaneously and account for non anticipativity constraints (action has to be the same for different scenarios before the disclosure of uncertainty, while the optimal reaction to the information revealed when uncertainty is eliminated is allowed afterwards).

This formulation enables us to devise the optimal strategy before uncertainty is disclosed, and identify potentially optimal hedging behaviour. It also enables us to determine the most suitable portfolio of mitigation technologies given the uncertainty on stabilisation targets that will be adopted in the future.[6] Let us assume that uncertainty about the climate target is resolved twenty seven years from now, in 2035. However, today, the future target is unknown and three scenarios are assumed to emerge with equal probability:

In our study, we compute the optimal non-cooperative Nash equilibrium policies instead.

[6] Such a risk-management approach is particularly important given the low capital turnover of energy investments. As a consequence investment decisions crucially depend on potential future climate policy scenarios. Inertia in the energy sector could support an argument in favour of early deployment of mitigation technologies, given that once an investment is made, it can last for decades, let alone early retirement or "retrofitting" cleaner technologies, both notoriously expensive (Stern, 2007). On the other hand, a similar argument could hold for capital irreversibility of investments in renewables, thus suggesting that "wait and see" would be the optimal choice (Kolstad, 1993; Kolstad, 1996a; Kolstad, 1996b).

- *BAU(no target):* no constraint on emissions. No agreement on a common target is achieved, and countries are free to adopt their own BAU emission levels. This is an extreme scenario in which there is a complete stall in international negotiations and consequently single regions decide not to commit to any mitigation from 2035 on. It could also be read as a scenario in which by 2035 either we discover that climate change theories are unfounded (or un-anthropogenic) or we discover a perfect geo-engineering solution that allows carbon emissions to be decoupled from climate warming.
- *550 ppm CO2 stabilization.* We assume an international climate agreement is reached, with a target of carbon concentrations in 2100 of 550 ppm (CO2 only; 650 ppm all GHGs).
- *450 ppm CO2 stabilization.* We assume an international climate agreement is reached, with a target of carbon concentrations in 2100 of 450 ppm (CO2 only; 550 ppm all GHGs).

We adopt a uniform probability distribution[7] to express an uninformative a priori that foresees equal chances of any of the three scenarios materialising.

3.1 Emissions and investments in the energy sector

Using the above assumptions, we compute the optimal investment path for all energy technologies, for physical capital and for R&D as a non-cooperative equilibrium of the game among the twelve world regions represented in WITCH. Figure 1 reports the resulting global carbon emissions trajectories over this century for the stochastic case and the deterministic cases of no target, 550 and 450, up until 2100 (left panel) and in more detail to 2030 (right panel).

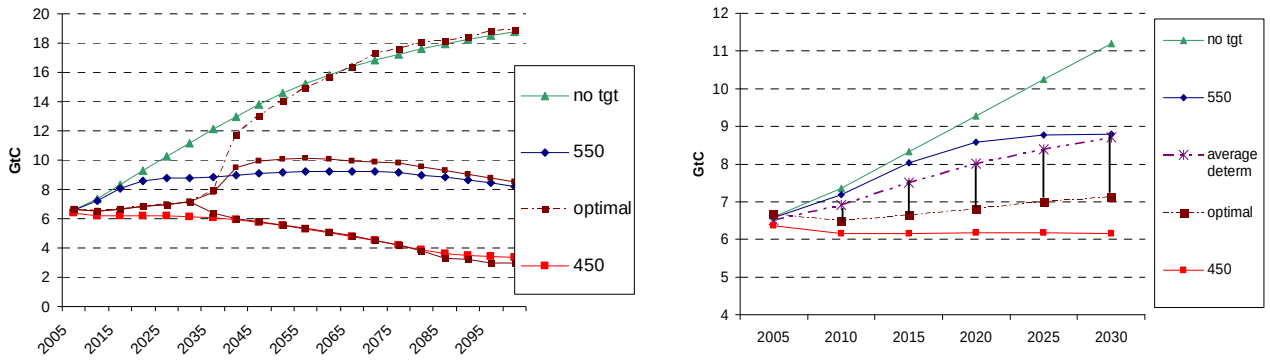


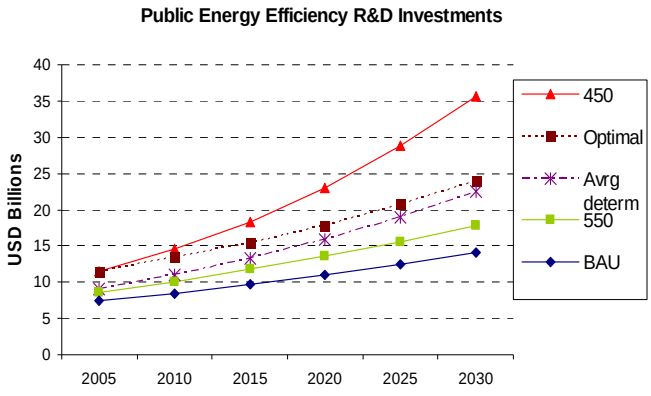
Figure 1: Fossil fuel emissions for optimal stochastic and deterministic cases, to 2100 (left) and to 2030 (right).

[7] We also experimented with different probability distributions, and found the results to be robust.

The figure shows the three different deterministic cases vis à vis the stochastic one that takes into account the fact that all three are possible. It provides clear evidence of hedging behaviour: the optimal strategy before uncertainty is resolved is to engage in significant mitigation. In 2030, emissions are 57% lower than in the BAU scenario, essentially the same as they are today. That is to say, in a world that has an equal chance of being confronted with no climate policy, a mild policy or a stringent policy in 30 year's time, the best strategy in the short-term (for the next two decades) is to minimise emission growth. Emissions in 2030 would also be 23% lower than the target prescribed by the mild policy, and only 14% higher than the more stringent one.

The low level of emissions in the stochastic scenario is driven by the possibility of a stringent climate target, albeit this has just a 33% chance of occurring. The convexity of marginal abatement costs in the mitigation levels is the reason for this risk-averse approach. As shown in the right panel of Figure 1, the optimal emission path is always below the average of the three deterministic cases, by 1.6 GtC in 2030, or 22%. This quantifies the dimension of the precautionary strategy.

From a public policy perspective, it is interesting to see how the portfolio of mitigation options is affected by explicit accounting for climate target uncertainty. Figure 2 highlights two important implications for investment strategies, aimed at improving energy and carbon efficiency respectively. Optimal public expenditure on R&D to enhance energy efficiency in the stochastic case (left panel) is close to the amount spent in the more stringent scenario especially in the first period, and always above the average of the deterministic cases. This indicates that energy-saving measures are optimal in the short term even when a weak stabilisation target is likely to be set in the future. This is in line with the common belief that energy efficiency measures are a priority and should be undertaken anyway.



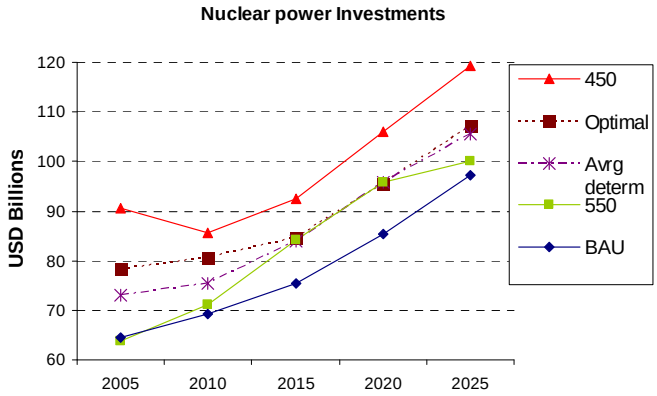


Figure 2: Investments in Energy Efficiency R&D (left) and Nuclear power capacity (right).

Nonetheless, in order to attain the emission reductions required by the optimal hedging strategy, the energy sector should also adopt substantial decarbonisation measures; the right panel of Figure 2 shows that in the stochastic case investments in carbon-free nuclear power plants are above those in the BAU scenario and in the 550 (CO_2 only) scenario. Again, these optimal investment profiles describe a hedging strategy that would decrease the carbon intensity of energy beyond the average of the three deterministic cases.

In terms of the policy prescriptions that we can derive from the optimal trajectory, investments in public energy R&D should be roughly doubled with respect to those in the BAU scenario, which would be a spending policy akin to the innovation effort of the 1980s. A similar path should be undertaken for increasing nuclear power capacity, with average global additions at about 15 GW per year up to 2035.

Figure 3 shows the aggregated picture of departures from the BAU scenario in terms of energy intensity (total primary energy supply over GWP) and carbon intensity of energy (carbon emissions over total primary energy supply). The picture shows that optimal climate policy under uncertainty requires action for both energy efficiency and decarbonisation, and that more ambitious targets require a shift along both the horizontal and vertical axes.

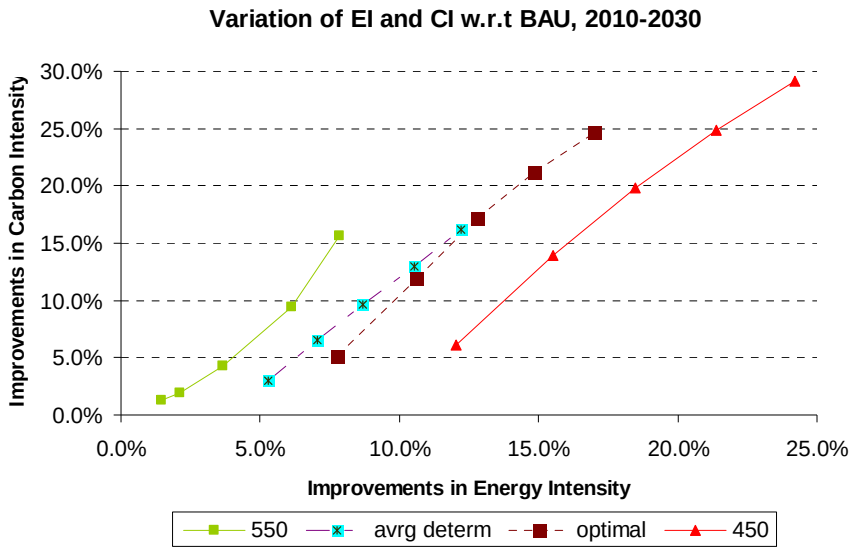


Figure 3: Improvements of energy and carbon intensities over BAU, 2010-2030

Once again, we see how the optimal strategy under uncertainty lies between the 450 and 550 scenarios. It also lies to the right of the average of deterministic cases, reinforcing the message that the hedged mitigation portfolio should give comparable priority to energy savings and carbon-free technology development.

3.2 **The economic cost of sub-optimal strategies.**

Another interesting exercise is to quantify the economic loss resulting from non-compliance with the hedging strategy detailed in the previous section, and the pursuit of the optimal investment strategies for the deterministic cases. In order to do this, we run the stochastic version of the model, but fix all the choice variables to those of the three deterministic cases until 2035 (the time frame to uncertainty resolution); from that point on, the model is free to optimise for each of the three states of the world, given the sub-optimal choices undertaken during the first periods. This enables us to quantify the economic losses that would result from sticking to either a BAU Scenario, a 550 ppm stabilisation policy or a 450 ppm stabilisation scenario (thus not adhering to the optimal strategy) in the periods before the final outcome of the ICA is known.

The first important result is that following the BAU scenario from now to 2035 does not allow a feasible solution to the optimisation problem if the target after 2035 is the ambitious one (450 CO2 (550e)). In other words, a BAU strategy for the next three decades precludes the attainment of the more stringent stabilisation target. This result extends the one seen in the first part of the paper, which showed that policy costs increase sharply with the period of inaction. It should be noted that accounting for technologies that can achieve negative carbon emissions might allow a solution even in this case; however, such a scenario is highly questionable and has thus not been included in this analysis.

Sub-optimal strategies aiming at 550 and 450 result in more and less emissions (respectively) than the optimal strategy does before 2035 - and vice versa thereafter - as noted in the previous section. We thus expect that following a mild 550 policy would lead to improved outputs in the first decades, followed by deterioration, and that the opposite would be true if we followed an emission mitigation policy that was more stringent than the optimal one, such as aiming for the 450 target. This is what is shown in Figure 4, where the gap between the expected value of Global World Product for the sub-optimal cases and the optimal one is shown.

One can see that committing to more mitigation results initially in economic loss, but leads to a higher output after the resolution of uncertainty, due to the fact that burden of meeting the stringent target in the future has been alleviated. On the other hand, a sub-optimal 450 strategy inflicts costs that are somewhat higher than the benefits of a milder choice (-0.8% GWP losses in

2035 for 450, as opposed to +0.45% gains for 550) in the short term. The picture reverses after 2035, when the costs of under-abatement before shifting to a stringent policy are higher than the benefit of a more virtuous early strategy.

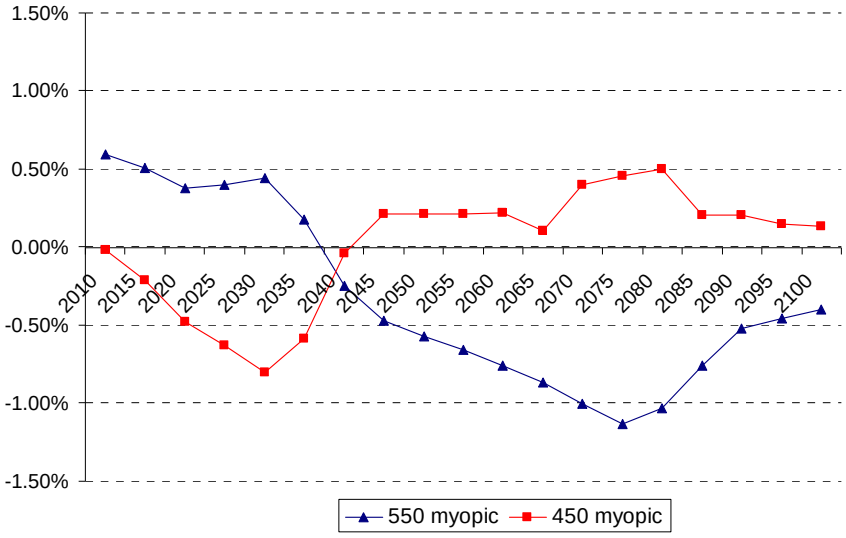


Figure 4: GWP differences of sub-optimal strategies w.r.t the optimal hedging one.

Eventually, the way we discount variations of GWP over time determines the merit order of either sub-optimal strategies, see Table 2. Using a low actualisation rate (3%), we find that the sub-optimal 550 ppm strategy entails an economic penalty of around 17% (from the 1.4% GWP loss for the stochastic case to 1.7% GWP loss in this case), whereas in the 450 ppm case, the loss is much smaller (1.7%, from 1.4% to 1.5%). The opposite holds when we discount at a higher rate (5%), which essentially implies more emphasis on the costs and benefits attained in the first half of the century: here, a milder climate change strategy has almost no negative economic impact on policy costs, as it allows for greater initial economic growth, whereas a more ambitious one leads to a penalty of about 16%.

Discount factor for NPV calculation	***3%***	***5%***
Sub-optimal 550	17.2%	0.01%
Sub-optimal 450	1.7%	16.2%

Table 2: Economic penalty (extra NPV GWP loss) of sub-optimal strategies at 450 and 550 (w.r.t to the optimal one under uncertainty).

Summing up, the optimal strategy before 2035 in the presence of uncertainty about future stabilisation targets is a mitigation policy that results in an emissions trajectory that lies between the 450 and 550 trajectories. Choosing either of those two policies results in economic inefficiency ranging from about zero to 16-17% of GWP, depending on the discount rate. Pursuing less mitigation than the 550 ppm policy significantly increases these extra costs (to unbearable levels if no action is undertaken).

4 Conclusions

Despite the emergence of a scientific consensus over the necessity of stringent climate targets, no effective international agreement to reduce carbon emissions has yet been achieved. As a consequence, the definition of a global stabilisation objective for the next decades is at present, and for the foreseeable future, very uncertain. The economic analysis of climate change policies should take this uncertainty into account to avoid misleading policy recommendations.

This paper constitutes an attempt to provide better information to policymakers by identifying the short-term implications of uncertainty about future climate targets and by computing the cost of delaying the introduction of effective mitigation strategies.

Despite general warnings on the risks of inaction, most estimates of the cost of mitigation policies have tended to underestimate the cost of delaying action. In the first part of the paper, we show that this cost is far from negligible, even in a model in which technology is flexible and endogenous, and R&D investments are optimally chosen. We quantify the cost of a 20-year delay in action as an increase of GWP losses of about 140%, or in the range (depending on discounting) of 2.2-5.7 trillion USD per year of delay. We also show how committing to a mild abatement effort in the short-term might substantially reduces the cost of delaying action.

In the second part, we analyse the short-term policy implications of the uncertainty surrounding future climate targets. Results point clearly to precautionary behaviour in which emissions are considerably reduced below the expected value of the deterministic cases. We show that the optimal portfolio of technologies in the presence of climate target uncertainty includes investments in energy efficiency improvements, but also in technologies that enhance decarbonisation.

Finally, we quantify the economic inefficiencies of sub-optimal policy strategies – i.e. those that do not account for future policy uncertainty – in different cases (ranging from inaction to strong emission reduction). We show that the adoption of a "wrong" policy strategy in the short-term may considerably increase the economic costs of GHG stabilisation.

The results presented in this paper support the adoption of a precautionary approach to climate policymaking. The optimal mitigation strategy in the presence of uncertainty is a highly

ambitious one (e.g. the one that achieves a 450 ppm target) rather than a moderate one. At the same time, the cost of adopting a moderate climate strategy in the first decades, and then shifting to the ambitious one if necessary, is relatively small. This result is consistent with the conclusion that delaying action is not too costly if a moderate climate policy is adopted in the short-term (but it may become very costly if no action is taken at all).

The model used in this paper is limited in relation to the exogenous probability distribution of future climate targets. Further research will focus on endogenising the uncertainty over the probabilities of more or less stringent future climate policies. These probabilities are indeed a function of the mitigation efforts undertaken over time, and of the resulting technological progress that would be induced.

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