INTERNATIONAL ENERGY AGENCY
AGENCE INTERNATIONALE DE L'ENERGIE

PRICE CAPS AND PRICE FLOORS IN CLIMATE POLICY

A Quantitative Assessment

IEA INFORMATION PAPER
including a French version of the Executive Summary

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INTERNATIONAL ENERGY AGENCY

INTERNATIONAL ENERGY AGENCY

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ABSTRACT

This study assesses the long-term economic and environmental effects of introducing price caps and price floors in hypothetical climate change mitigation architecture, which aims to reduce global energy-related CO_2 emissions by 50% by 2050. Based on abatement costs in IPCC and IEA reports, this quantitative analysis confirms what qualitative analyses have already suggested: introducing price caps could significantly reduce economic uncertainty. This uncertainty stems primarily from unpredictable economic growth and energy prices, and ultimately unabated emission trends. In addition, the development of abatement technologies is uncertain.

With price caps, the expected costs could be reduced by about 50% and the uncertainty on economic costs could be one order of magnitude lower. Reducing economic uncertainties may spur the adoption of more ambitious policies by helping to alleviate policy makers' concerns of economic risks. Meanwhile, price floors would reduce the level of emissions beyond the objective if the abatement costs ended up lower than forecasted.

If caps and floors are commensurate with the ambition of the policy pursued and combined with slightly tightened emission objectives, climatic results could be on average similar to those achieved with "straight" objectives (*i.e.* with no cost-containment mechanism).

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GLOSSARY

Best guess	Most likely value of a parameter; by extension, the result of a calculation in which each uncertain parameter is given its most likely value
CO_2-eq	carbon dioxide equivalent
Equilibrium temperature change	the temperature change that results from climate forcing when all interactions and feedbacks have taken place
ETP	*Energy Technology Perspectives*
Expected costs	The average of all possible cost outcomes weighted by their probability of occurrence
GHG	Greenhouse gases
Gt	Gigatonne (billion tonnes)
IPCC AR4	Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change
MAC	marginal abatement cost
Min – Av – Max	Minimum – Average – Maximum
Monte Carlo simulations	computation method relying on repeated random sampling of inputs
NPV	Net Present Value
ppm	parts per million (in volume)
price caps	Maximum price for CO_2 allowances. Above this price, additional allowances would be sold by the regulator.
price floors	Minimum price for CO_2 allowances. No allowance below this price would be sold by the regulator.
safety valve	price cap
straight targets	targets with no price cap or floor
TAC	total abatement costs
WEO	*World Energy Outlook*
WGP	World Gross Product

EXECUTIVE SUMMARY

Introduction

The climate change issue is plagued with many uncertainties. Future unabated greenhouse gas emissions trends depend on uncertain future economic growth, energy intensity, and the carbon intensity of the energy mix, which in turn depends on fuel availability and prices. The Earth's climate sensitivity itself is largely uncertain, with predictions that doubling the atmospheric CO_2 concentration would increase the temperature by two to five degrees Celsius and perhaps more in the very long term, depending on still poorly understood, slow feedback.

While these uncertainties should not delay action to mitigate emissions, they do make the task of setting policy objectives challenging. Benefit cost analysis is beyond reach, but abatement costs do matter, as do the environmental benefits.

At their meeting in Toyako, Japan in July, 2008, the G8 leaders proposed the objective of at least reducing global greenhouse gas emissions (GHG) by half by 2050. In order the reach this goal, drastic changes in the ways we produce and use energy will be necessary. However, even if the environmental benefits may far outweigh the costs of acting, the many uncertainties relative to the cost of such a big shift in our energy system make actual implementation problematic for many governments. Policies that have ill-defined costs may be unpopular and there will be resistance to adopting them.

Price caps or "safety valves", and possibly price floors, have been offered as possible complements to quantitative emission limits and emissions trading to set up a more flexible response to the threat of climate change in the context of uncertain costs. Price caps could take the form of a potentially unlimited amount of "carbon allowances" (or "compliance payments") sold by the regulator at the end of compliance periods. The price cap level is set and made public at the outset to discourage speculation. Price floors could be reserve prices (*i.e*. minimum prices) in periodic auctioning of carbon allowances, requiring no government subsidies.

Economic theory suggests that when abatement costs are uncertain, price caps reduce expected costs and reduce cost uncertainty. Moreover, price caps could facilitate setting more ambitious policies for similar expected costs. However, the uncertainty would be shifted from the cost side to the benefit side, e.g. the emission reductions. As this study confirms, some uncertainty about near-term emission levels matters less than the necessary ambition of the mitigation policy, given the cumulative nature of climate change and the other uncertainties in climate sciences.

This study quantitatively assesses price caps and price floors in the future global climate mitigation architecture, using a simple model of greenhouse gas mitigation costs building on the entire IEA expertise and flagship publications such as the *World Energy Outlook* and the *Energy Technology Perspectives 2008* – the ACTC Model (for Abatement Costs Temperature Changes). The ACTC Model also draws on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change to calculate the warming committed in the climate system by 2050. The execution of the model entails performing thousands of "Monte Carlo simulations", where uncertain parameters take random values.

Results

The modelling work first reveals that uncertainties combine to increase average abatement costs over "best guess" (*i.e.* most likely) values for each parameter. For example, on the optimal way to halve global emissions by 2050 from 2005 levels, total abatement costs during the 2011-2020 period will be USD 350 billion, according to best guess values. But the weighted average of abatement costs when uncertainties are taken in account (*i.e.* "expected costs") would be USD 929 billion.

The study then shows that price caps could reduce expected costs to a considerable extent – and the breadth of the economic uncertainty even more. However, introducing price caps alone, while leaving the quantity target unchanged, would lead to higher temperature change by 2050 – and especially if the price cap is set too low. Price caps should be commensurate to forecasted marginal abatement costs attached to target levels, if these are to be achieved — if not precisely, at least on average. Tightening the targets and/or introducing price floors may keep expected results the same or slightly better in terms of temperature change.

With straight targets the concentration level achieved is known in advance, and the uncertainty about temperature changes only comes from uncertainties on the Earth's climate sensitivity. While price caps and price floors reduce the economic uncertainty of the policy, they do introduce some uncertainty about the concentration level achieved, inasmuch as actual emissions in this case may depend on price cap and price floor levels, which must thus be carefully chosen. Nevertheless, the study reinforces and extends conclusions reached in previous work that the flexibility introduced with price caps and price floors, if set at appropriate levels, has little discernible influence on the climate, if any. The uncertainties on the Earth's climate sensitivity add to the cumulative nature of the climate change to explain this result. Indeed, price caps could allow for defining strategies to achieve either:

- the same environmental results as halving 2050 global energy-related CO_2 emissions from 2005 levels, for about half the expected costs (case 1), or
- better environmental results than halving 2050 global energy-related CO_2 emissions from 1990 levels, for similar expected costs as halving emissions from 2005 levels (case 2).

These strategies would necessitate price caps and floors at the approximate levels indicated in Table 1:

Table 1: Price Caps and price Floor Levels

Price Caps*		Price Floors*		by year
Case 1	Case 2	Case 1	Case 2	
110	150	35	50	2011-2020
150	240	50	80	2021-2030
240	360	80	120	2031-2040
360	600	120	200	2041-2050

* in US dollars

These numbers are indicative only, and depend on the assumptions of the ACTC model. Price caps and floors set at significantly lower levels, such as USD 80 for cap and USD 40 for floor by 2011-2020, may give very close climate change results, as can be seen in Table2. Further, taking other greenhouses gases, sources and sinks into account would not likely change the conclusions of this study, but may allow for price caps and price floors set at lower levels to achieve similar performances.

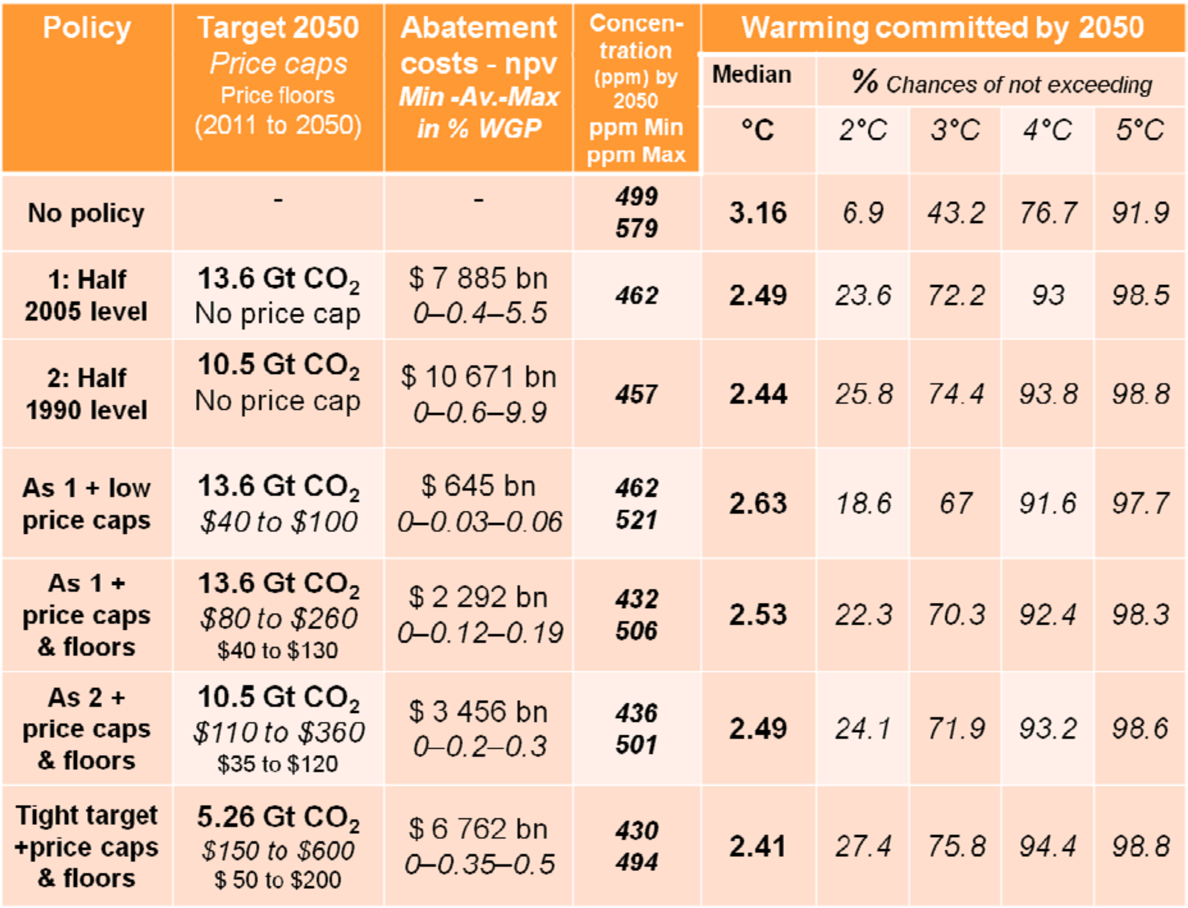
In any case, decisions relative to price caps and floors beyond 2030 need not be taken today, and will likely be taken when the residual uncertainty is lower. It is also possible that at that time, climate science and knowledge about mitigation and adaptation possibilities will lead to different decisions than those we can envision today. Smaller uncertainty ranges may make price caps and price floors beyond 2030 at lower levels than those considered in this study still very helpful.

For similar emission targets, introducing price floors slightly increases expected costs but betters the environmental results. For similar climate results, price floors allow for further reducing expected costs.

In this study, the economic gains do not only result from increased “when” flexibility – the flexibility to reduce emissions more when costs are low and less when they are high. Gains result more broadly from the “where to” flexibility – the adjustment of emission outcomes to actual costs. Thus, hybrid instruments prove more economically efficient than straight targets (*i.e.* targets with no price cap).

Future work could aim at defining concrete implementation of price caps and price floors in the international climate change mitigation architecture, as well as in domestic emissions trading schemes. It could also explore the relationship of price caps and price floors with technology innovation, development and dissemination, and with the dynamics of the negotiations.

Table 2: Summary Results



Policy	Target 2050 *Price caps* Price floors (2011 to 2050)	Abatement costs - npv *Min -Av.-Max in % WGP*	Concen-tration (ppm) by 2050 ppm Min ppm Max	Warming committed by 2050				
				Median	% Chances of not exceeding			
				°C	2°C	3°C	4°C	5°C
No policy	-	-	499 579	**3.16**	6.9	43.2	76.7	91.9
1: Half 2005 level	**13.6 Gt CO_2** No price cap	$ 7 885 bn *0–0.4–5.5*	462	**2.49**	23.6	72.2	93	98.5
2: Half 1990 level	**10.5 Gt CO_2** No price cap	$ 10 671 bn *0–0.6–9.9*	457	**2.44**	25.8	74.4	93.8	98.8
As 1 + low price caps	**13.6 Gt CO_2** *$40 to $100*	$ 645 bn *0–0.03–0.06*	462 521	**2.63**	18.6	67	91.6	97.7
As 1 + price caps & floors	**13.6 Gt CO_2** *$80 to $260* $40 to $130	$ 2 292 bn *0–0.12–0.19*	432 506	**2.53**	22.3	70.3	92.4	98.3
As 2 + price caps & floors	**10.5 Gt CO_2** *$110 to $360* $35 to $120	$ 3 456 bn *0–0.2–0.3*	436 501	**2.49**	24.1	71.9	93.2	98.6
Tight target +price caps & floors	**5.26 Gt CO_2** *$150 to $600* $ 50 to $200	$ 6 762 bn *0–0.35–0.5*	430 494	**2.41**	27.4	75.8	94.4	98.8

RÉSUMÉ

Introduction

De nombreuses incertitudes compliquent le problème du changement climatique. Les tendances futures d'émissions de gaz à effet de serre en l'absence de toute action pour les réduire dépendent d'une croissance économique incertaine et de l'intensité en émissions carbonées de l'énergie, laquelle dépend elle-même de la disponibilité et des prix des sources d'énergie. La sensibilité climatique de la planète est elle aussi largement incertaine, avec la prévision que le doublement de la teneur atmosphérique en CO_2 augmenterait la température de deux à cinq degrés Celsius et peut-être davantage dans le très long terme, en fonction de rétroactions positives lentes et encore mal comprises.

Si ces incertitudes ne doivent pas retarder l'action de réduction des émissions de gaz à effet de serre, elles rendent la tâche de fixer des objectifs très délicate. L'analyse des coûts et des bénéfices est hors de portée, et pourtant les coûts de réduction des émissions comptent, comme comptent les bénéfices environnementaux.

Lors de leur réunion de Toyako au Japon en juillet 2008, les leaders du G8 ont proposé l'objectif de réduire au moins de moitié les émissions mondiales de gaz à effet de serre (GES). Pour atteindre ce but, des changements drastiques dans la façon dont nous produisons et utilisons l'énergie seront nécessaires. Cependant, même si les bénéfices pour l'environnement peuvent l'emporter largement sur les coûts de l'action, les nombreuses incertitudes relatives au coût d'un tel changement de notre système énergétique en compliquent la mise en œuvre pour de nombreux gouvernements. Les politiques qui impliquent des coûts mal définis peuvent être impopulaires et leur mise en œuvre suscitera des résistances.

Des prix plafonds, ou « soupapes de sûreté », et éventuellement des prix planchers, ont été proposés pour compléter des objectifs quantifiés d'émission et des échanges de permis d'émissions, afin de bâtir une réponse à la menace du changement climatique plus flexible dans ce contexte d'incertitudes économiques. Les prix plafonds pourraient prendre la forme d'une quantité potentiellement illimitée de permis d'émission supplémentaires (ou « paiements de conformité ») vendus par le régulateur, à la fin de chaque période. Leur niveau est fixé et annoncé au début de la période d'engagement, de façon à décourager toute spéculation. Les prix planchers pourraient être des prix de réserve (prix minimum) lors des mises aux enchères périodiques des permis carbone, sans qu'il soit besoin de subventions gouvernementales.

La théorie économique suggère que quand les coûts de réduction des émissions sont incertains, les prix plafonds réduisent les « espérances de coûts » et l'incertitude sur les coûts. De plus, les prix plafonds peuvent faciliter la fixation d'objectifs plus ambitieux pour des espérances de coûts similaires. Cependant, l'incertitude serait basculée du côté des coûts vers celui des bénéfices, c'est-à-dire des réductions d'émissions. Comme cette étude le confirme, cette incertitude au sujet des niveaux d'émissions à court terme est moins importante que la nécessaire ambition de la politique climatique, étant donné la nature cumulative du changement climatique et les autres incertitudes dans la science du climat.

Cette étude évalue quantitativement les prix plafonds et prix planchers dans l'architecture future de réduction des émissions mondiales, utilisant un modèle simple des coûts de réduction des émissions bâti sur toute l'expertise de l'Agence internationale de l'énergie et ses publications majeures telles que le *World Energy Outlook* et les *Energy Technology Perspectives 2008.* Ce modèle intitulé « *Abatement Costs Temperature Changes* » (ACTC) utilise aussi le Quatrième Rapport d'Evaluation du Groupe Intergouvernemental d'Experts sur l'Evolution du Climat pour calculer le réchauffement irréversiblement engagé en 2050. L'utilisation du modèle repose sur la réalisation de milliers de simulations dites « Monte Carlo », au cours desquelles les paramètres incertains prennent des valeurs aléatoires.

Résultats

Le travail de modélisation révèle tout d'abord que les incertitudes se combinent pour augmenter les espérances de coûts par comparaison avec les meilleures estimations (c.-à-d.les valeurs les plus probables) concernant chaque paramètre. Par exemple, sur la trajectoire optimale de division par deux des émissions mondiales en 2050 à partir des niveaux de 2005, les coûts totaux de réduction des émissions durant la période 2011-2020 seraient de 350 milliards de dollars des Etats-Unis, selon les meilleures estimations. Mais la moyenne pondérée des coûts de réduction quand les incertitudes sont prises en compte (c.-à-d. les espérances de coûts) serait 929 milliards de dollars.

L'étude montre ensuite que les prix plafonds réduisent considérablement les espérances decoûts en incertitude - et davantage encore l'ampleur de l'incertitude économique. Cependant, introduire seulement des prix plafonds, en laissant inchangés les objectifs d'émissions, conduirait à des changements de température plus importants en 2050 – surtout si les prix plafonds sont trop bas. Les prix plafonds devraient être proportionnés aux coûts marginaux de réduction des émissions relatifs aux objectifs quantifiés, afin que ceux-ci soient atteints – sinon très précisément, du moins en moyenne. Sévériser les objectifs et/ou introduire des prix planchers permet d'obtenir des résultats moyens en termes de changement de température identiques ou légèrement améliorés.

Avec des objectifs « certains » la concentration atmosphérique de GES est connue á l'avance, et l'incertitude sur les changements de température est entièrement due à l'incertitude sur la sensibilité climatique de la planète. Alors que prix plafonds et prix planchers réduisent l'incertitude économiques, ils introduisent de l'incertitude sur le niveau de concentration atteint, dans la mesure où les émissions dans ce cas peuvent dépendre des niveaux des prix plafonds et prix planchers, lesquels doivent donc être soigneusement choisis. Néanmoins, l'étude renforce et prolonge les conclusions atteintes au cours de travaux précédents selon lesquelles la flexibilité introduite par des prix plafonds fixés à un niveau approprié a peu d'influence discernable sur le climat, voire pas du tout. Les incertitudes sur la sensibilité climatique de la planète se combinent à la nature cumulative du changement climatique pour expliquer ce résultat. En fait, les prix plafonds et les prix planchers peuvent permettre de définir des stratégies pour obtenir :

- Ou bien les mêmes résultats environnementaux qu'une division par deux en 2050, par rapport à 2005, des émissions mondiales de CO_2 liées à l'énergie, pour des espérances de coûts réduites de moitié environ (cas 1);
- Ou bien de meilleurs résultats environnementaux qu'une division par deux en 2050 par rapport à 1990, des émissions mondiales de CO_2 liées à l'énergie, pour des espérances de coûts comparables à celles liées à la division par deux des émissions par rapport à 2005 (cas 2).

Ces stratégies nécessiteraient des prix plafonds et planchers aux niveaux approximatifs indiqués sur le Tableau 1:

Tableau 1 : niveaux des prix plafonds et planchers

Prix plafonds*		Prix planchers*		années
Cas 1	Cas 2	Cas 1	Cas 2	
110	150	35	50	2011-2020
150	240	50	80	2021-2030
240	360	80	120	2031-2040
360	600	120	200	2041-2050

* en dollars des Etats-Unis

Ces chiffres sont seulement indicatifs, et reposent sur les hypothèses introduites dans le modèle ACTC. Des prix plafonds et planchers fixés à des niveaux significativement plus bas, tels que 80 dollars pour le plafond, et 40 dollars pour le plancher pour les années 2011-2020, pourraient donner des résultats climatiques très proches, comme on le voit sur le Tableau 2. De plus, la prise en compte des autres gaz à effet de serre, autres sources et puits, ne changerait probablement pas les conclusions de cette étude mais pourrait permettre à des prix plafonds et planchers fixés à des niveaux plus bas d'accomplir des performances similaires.

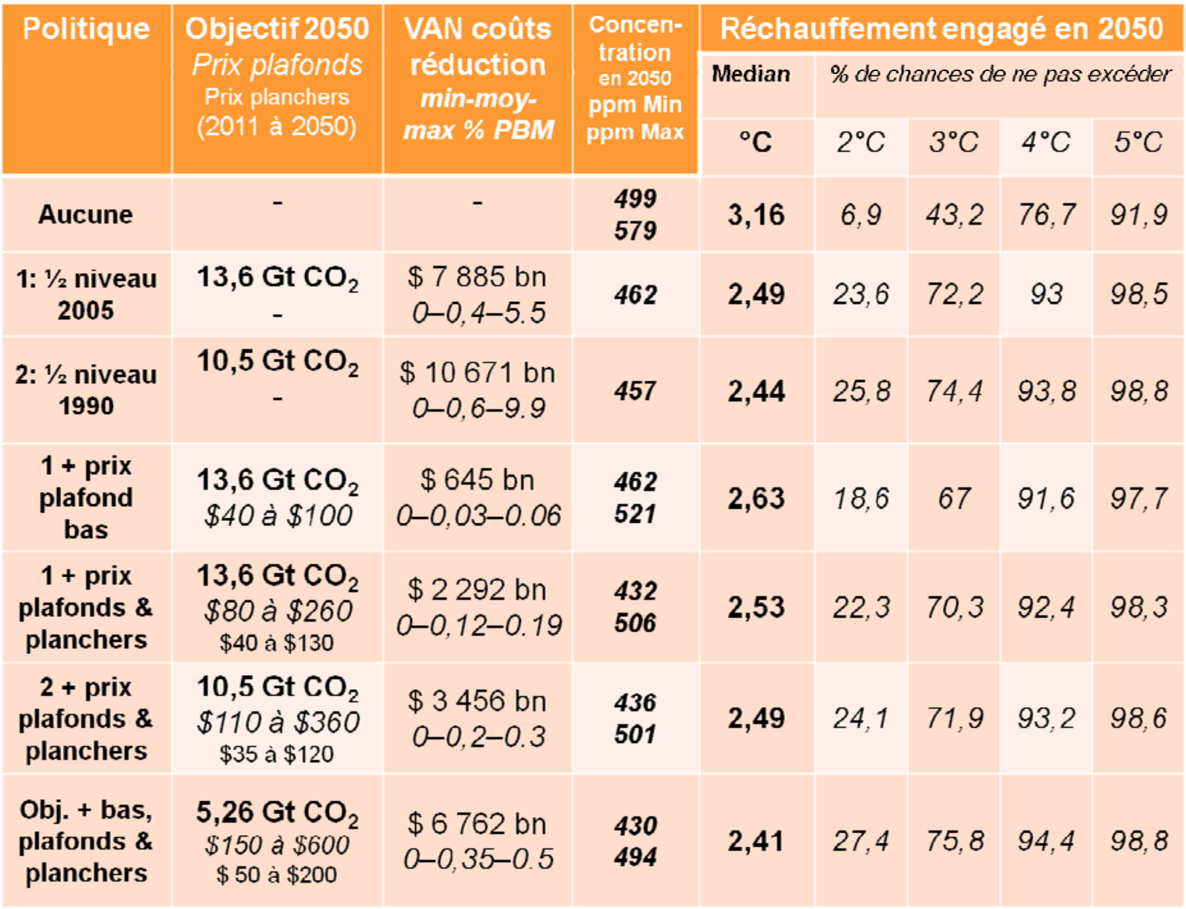
Dans tous les cas, les décisions relatives aux prix plafonds et planchers au-delà de 2030 ne doivent pas être prises dès maintenant, et seront probablement prises quand l'incertitude résiduelle sera plus faible. Il est aussi possible qu'à ce moment-là, la science climatique et la connaissance des possibilités de réduction des émissions et d'adaptation conduisent à des décisions différentes de celles que nous pouvons imaginer aujourd'hui. Des fourchettes d'incertitudes plus étroites peuvent faire que des prix plafonds et des prix planchers au-delà de 2030 de niveaux plus faibles que ceux envisagés dans cette étude seraient quand même très utiles.

Pour des objectifs quantitatifs similaires, introduire des prix planchers augmente légèrement les espérances de coûts mais améliore les résultats environnementaux. Pour des résultats similaires, les prix planchers permettent de réduire davantage les espérances de coût.

Dans cette étude, les gains économiques ne résultent pas seulement d'une plus grande flexibilité temporelle – la flexibilité de réduire les émissions davantage quand les coûts sont faibles et moins quand ils sont élevés. Les gains proviennent plus généralement d'une flexibilité sur les résultats – l'ajustement du niveau effectif d'émissions en fonction des coûts réels. Ainsi, les instruments hybrides s'avèrent économiquement plus efficients que les objectifs fixes (c.-à-d. sans prix plafonds).

Un travail ultérieur pourrait viser à définir la mise en œuvre pratique des prix plafonds et prix planchers dans l'architecture internationale de lutte contre les changements climatiques, aussi bien que dans les schémas domestiques d'échanges de permis d'émissions. Il pourrait aussi explorer les relations des prix plafonds et prix planchers avec l'innovation technologique, le développement et la diffusion des technologies, ainsi qu'avec la dynamique des négociations.

Tableau 2: Résultats



Politique	Objectif 2050 *Prix plafonds* Prix planchers (2011 à 2050)	VAN coûts réduction *min-moy-max % PBM*	Concen-tration en 2050 ppm Min ppm Max	Réchauffement engagé en 2050				
				Median	*% de chances de ne pas excéder*			
				°C	*2°C*	*3°C*	*4°C*	*5°C*
Aucune	-	-	***499*** ***579***	**3,16**	*6,9*	*43,2*	*76,7*	*91,9*
1: ½ niveau 2005	**13,6 Gt CO$_2$** -	$ 7 885 bn *0–0,4–5.5*	***462***	**2,49**	*23,6*	*72,2*	*93*	*98,5*
2: ½ niveau 1990	**10,5 Gt CO$_2$** -	$ 10 671 bn *0–0,6–9.9*	***457***	**2,44**	*25,8*	*74,4*	*93,8*	*98,8*
1 + prix plafond bas	**13,6 Gt CO$_2$** *$40 à $100*	$ 645 bn *0–0,03–0.06*	***462*** ***521***	**2,63**	*18,6*	*67*	*91,6*	*97,7*
1 + prix plafonds & planchers	**13,6 Gt CO$_2$** *$80 à $260* $40 à $130	$ 2 292 bn *0–0,12–0.19*	***432*** ***506***	**2,53**	*22,3*	*70,3*	*92,4*	*98,3*
2 + prix plafonds & planchers	**10,5 Gt CO$_2$** *$110 à $360* $35 à $120	$ 3 456 bn *0–0,2–0.3*	***436*** ***501***	**2,49**	*24,1*	*71,9*	*93,2*	*98,6*
Obj. + bas, plafonds & planchers	**5,26 Gt CO$_2$** *$150 à $600* $ 50 à $200	$ 6 762 bn *0–0,35–0.5*	***430*** ***494***	**2,41**	*27,4*	*75,8*	*94,4*	*98,8*

1. INTRODUCTION

The purpose of the study is to assess the consequences of introducing price caps and price floors in global climate mitigation architecture. According to economic theory, when abatement costs are uncertain, introducing price caps would reduce expected costs.[1] Philibert and Pershing thus argued that price caps make it possible to set more ambitious policies for the same total expected costs (IEA, 2002).

This paper presents the results of our research to determine the extent to which targets could be tightened as a result of price caps and price floors – and the optimal levels to which price caps and price floors could be set to maximise their advantage.

For this research we developed a model of costs of climate mitigation policies, the ACTC Model (for "Abatement Costs Temperature Changes"). The ACTC Model is a highly aggregated model of the global economy, with no distinction of countries or sectors. It projects the growth rate of the global economy and future global energy-related CO_2 emissions. It includes abatement cost curves built on IEA expertise, as published in the IEA's *World Energy Outlook 2007*, and *Energy Technology Perspectives 2008* publications. Uncertainty ranges are further specified according to the *Fourth Assessment Report* (AR4) of the Intergovernmental Panel on Climate Change (IPCC). Probability functions have been defined that give greater weight to the IEA's forecasts.

The ACTC Model affords an opportunity to study the costs[2] of quantitative emissions objectives at a global level, objectives which can be either "certain" ("straight"), or "loose" (if there are price caps). It includes an assessment of CO_2 concentration levels and resulting temperature changes, but no attempt to monetise policy benefits. The Appendix provides a fuller description of the ACTC Model.

To take full account of uncertainties, we have performed thousands of Monte Carlo simulations, thereby testing as many possible combinations of the uncertain values that the most important parameters may take. This method is especially necessary, as the introduction of price caps truncates cost and benefit curves in a way that can hardly be evaluated algebraically. One must thus use the pure force of computers to find out what the effects might be.

1.1 Halving global energy-related emissions by 2050

The G8 leaders, at their meeting in Heiligendam, Germany in July 2007, agreed that … "In setting a global goal for emissions reductions […] involving all major emitters, [they] will consider seriously the decisions made by the European Union, Canada and Japan which include at least a halving of global emissions by 2050." A year later, at their meeting at Toyako, Japan, in July 2008, they further declared that they "seek to share with all Parties to the

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[1] The expected benefits would also be reduced, but by much less than costs, in the case of climate change, it has been argued, due to its cumulative nature – GHG concentrations, not emissions, do change the climate. For a review of the literature, see Philibert (2006a).

[2] This paper distinguishes expected costs *i.e.* the weighted average of all possible costs outcomes taking full account of uncertainty, from best guess costs resulting from a calculation where each uncertain parameter takes its best guest, *i.e.* most likely value. Under uncertainty, rational decision-making should rest upon expected values and not best guesses.

UNFCCC the vision of, and together with them to consider and adopt in the UNFCCC negotiations, the goal of achieving at least 50% reduction of global emissions by 2050."

Responding to these goals, we thus focussed our analysis on at least halving global emissions by 2050. The various proposals mentioned in the G8 communiqué of 2007 had different reference years, some referring to 2005 levels, others to 1990 levels. Such differences have significant implications. With respect to energy-related CO_2 alone, halving global emissions from 1990 levels allows emitting 10.5 Gt CO_2, while taking 2005 emissions as a reference level permits emitting 13.6 Gt CO_2, or 29% more.

In this study we took half of the global 2005 emissions as a maximum by 2050, and sought whether some smaller emission levels could be achieved for similar expected costs when price caps and, if needed, price floors are introduced in the global architecture.

For the sake of simplicity, we considered ten-year periods, rather than individual years, in the ACTC model. There has been a 15-year time lag between the adoption of the Kyoto Protocol and the end of its first 5-year commitment period. The length of future commitment periods may be made longer than in the case of the first period in the Kyoto Protocol (Buchner, 2007). Hence, considering decadal periods may be an acceptable simplification.

The ACTC Model does not include a representation of policy benefits, *i.e.*, avoided climate change. The main criterion to assess policies is the "warming committed by 2050" – *i.e.* the long-term equilibrium warming that would result from a stabilisation of CO_2 concentrations at the level reached by 2050. In other words, this takes no account of ulterior emissions – or CO_2 captures – that would modify the concentration. This committed warming must also be distinguished from the realised warming at that date, always lower due to the inertia of the climate system and, in particular, the Ocean.

Section 2 presents the Model outputs in the absence of climate policy, thus setting the scene. Section 3 considers straight targets with certain results, defining intermediate targets on the basis of best guess values, and then assessing the implications of uncertainties on marginal and total abatement costs. Section 4 assesses the effects of price caps and price floors and the possible tightening of targets they might facilitate. Section 5 concludes with a discussion of the results, pointing out some caveats and considering future work.

1.2 Differences with earlier studies

Earlier work attempted to assess the introduction of price caps – most often, without price floors – in global mitigation architectures or domestic emissions trading schemes. In particular, Pizer (2002), building on Weitzman (1974), showed that expected welfare gains would be five times greater with carbon taxes than with tradable permits, and that emissions caps associated with price caps would offer approximately the same advantages. Pizer (2003) further explored under which conditions pure quantitative targets may still be preferred. He showed that severe catastrophic climate damages triggered by known GHG concentration thresholds may indeed call for pure quantitative targets. Newell and Pizer (2003) generalised the analysis of "stock" (*i.e.* cumulative) pollution problems.

The main differences between this study and Pizer's are the following:

Pizer (2002) considered the difficulty of choosing a discount rate as a major source of uncertainty, which he introduced in his model simulations. Uncertainty over discount rates considerably increases the overall uncertainty and explains about half of the increase in expected net benefits of climate policy due to price caps. This study does not consider the discount rate as a real source of uncertainty, and gives the discount rate a firm value of 5% (see page 46 in the Appendix for justification), thereby focusing on other "real" sources of uncertainty.

Pizer offered views on the optimal level of abatement and looked for the optimal setting of targets and price caps, or taxes. This study considers that halving emissions by 2050 is approximately optimal, and only questions if such an objective must be reached with a great level of precision and certainty despite uncertain abatement costs, or not. Thus, it does not attempt to define optimal abatement pathways where marginal cost would always equal marginal benefit. Instead, it takes for granted the total expected costs that the international community may accept to spend to mitigate climate change risks, and seeks for the best use of that money in setting various target levels, with and without price caps and floors.

There are, indeed, two possible rationales for setting more ambitious targets after price caps are introduced. If the objective is to maintain optimality in setting targets, one should introduce price floors if one introduces price caps; only the symmetry of these instruments allows keeping marginal benefits at the same levels. If price floors are deemed too complex or politically or financially difficult to introduce, their absence must be compensated by some tightening of the original target (Cournède and Gastaldo, 2002). If price floors are actually introduced, no tightening of the original target is necessary or recommended, as it could lead to some sub-optimal result.

If, however, the uncertainty on marginal benefit is too “deep” and there is no real best guess (Schneider, 2003), then the reasoning might be different. The idea is to maximise the expected environmental benefits for given expected costs. Therefore, even if price floors are actually introduced, tightening the original targets still makes sense. One first step is to seek the target that provides the same expected benefits, after price caps (and price floors) are introduced. In theory, this is still compatible with a great reduction of expected costs. A second step is to seek the target that entails the same expected costs, but with much greater expected benefits (Philibert, 2006a).

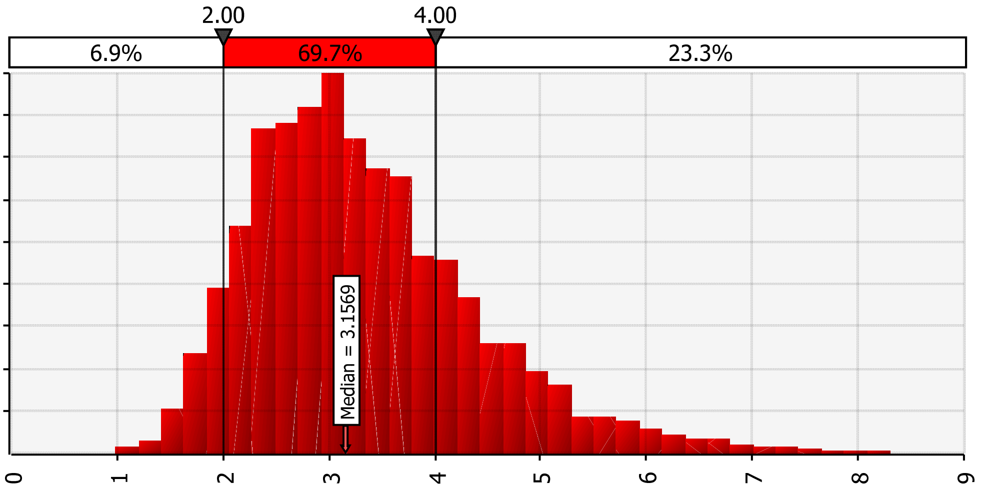
2. NO POLICY CASE

The ACTC Model, reflecting IEA forecasts, indicates that in the absence of policy, global energy-related CO_2 emissions would continue to grow, reaching 42 Gt CO_2 by 2030 and 60 Gt CO_2 by 2050 (under best guess). This would lead to CO_2 concentrations of 534 parts per million (ppm) by 2050, under best guess values.

To move from best guess estimates to plausible ranges of future concentrations taking uncertainties into account, we performed 3 000 Monte Carlo simulations with our model. GDP growth rate per decade and carbon intensity take random values in the specified range. This number of simulations is high enough to ensure an excellent convergence level — more simulations would not significantly change the results. Moreover, we used a sampling technique called Latin Hypercube Sampling, which ensures that events with low probabilities but important consequences are duly taken into account, even with a relatively small number of random simulations.

By 2050, CO_2 concentrations range from 499 to 579 ppm. Figure 2.1 represents the probability distribution of the temperature change committed by 2050 in the no policy case (temperature changes in Celsius degrees are in abscissa, the taller the bar the greater the probability). There is only a 6.9% chance that the warming would not exceed 2°C. There is a 50% risk that the warming would exceed 3.16°C (median value). There is a 23.3% risk that the warming would exceed 4°C. Emissions beyond 2050 would presumably increase temperature much more.

Figure 2.1: Warming committed by 2050 in the no policy case



KEY FINDINGS

❖ *In the absence of climate policy, the warming committed by 2050 has only a 6.9% chance of not exceeding 2°C, a 50% risk of exceeding 3.16°C and a 23.3% risk of exceeding 4°C.*

3. STRAIGHT TARGETS

In this section we first selected intermediate targets only on the basis of abatement cost optimisation over time and best guess values for all model parameters. We then ran the ACTC model with thousands of Monte Carlo simulations to find out the expected abatement costs when uncertainty is taken in account.

3.1 Setting intermediate targets

First, range of targets to be considered was selected. On the basis of the G8 final communiqué in Heiligendam, we considered a reduction of 50% of global emissions by 2050 — with the following two possible reference levels: 1) the 2005 energy-related CO_2 levels as suggested by Canada and Japan, and 2) the 1990 energy-related CO_2 levels as suggested by the European Union.

Thus, we factored in two alternative targets for 2041-2050. The first is 135.68 Gt CO_2, ten times half of 2005 levels, the second is 105.12 Gt CO_2, ten times half of 1990 levels.[3] The IPCC (2007) considers emission reductions by 50 — 85% below 2000 levels to be compatible with stabilised CO_2 concentrations of 350 to 400 parts per million (ppm), or all GHG concentrations in CO_2-equivalent of 445 to 490 ppm, and global mean temperature increase above pre-industrial at equilibrium using “best estimate” climate sensitivity from 2°C to 2.4°C.

Note that the simplicity of the model leads us to slightly more demanding targets — halving global emissions on average on the period 2041-2050 may require either halving annual emissions already from 2041, or may require emissions by 2050 below the target if emissions in some of the earlier years in the decade remain higher than that level.

From this target of 2050 we proceeded backward to establish a full set of decadal targets. That is, the ACTC Model was run to find the intermediate target values (2011-2020, 2021-2030 and 2031-2040 periods) that minimise the net present value of overall abatement costs up to 2050. We first ignored the uncertainty, that is, we used only best guess values, to keep the computation loads manageable (in any case, the remainder of this study shows that best guess and expected marginal abatement cost curves follow similar patterns over time, though at different levels; hence a different procedure would unlikely lead to significant differences in results). Possible variations in benefits were not included in this optimisation process, as benefits are not given monetary values in the Model.

Tables 3.1 and 3.2 below indicate the allowed emissions, percentage of reference levels, marginal abatement costs (MAC) and total abatement costs (TAC) for the optimal pathways towards 2050 levels for the two mid-term targets studied – respectively 50% of 2005 levels and 50% of 1990 levels. The MAC curve has been set so that MAC by 2050 fits the best-guess values implicit in the IEA’s *Energy Technology Perspectives 2008;* this is further explained in the Appendix describing the ACTC Model in full.

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[3] The targets are for 10-year commitment periods.

Table 3.1: Intermediate objectives for halving emissions by 2050 from 2005 levels

	2011-2020	2021-2030	2031-2040	2041-2050	Total (npv)
Reference 2005	94 %	83.5%	74.5%	50%	
Cap (Gt CO_2)	257.835	234.156	206.237	135.680	833.9
MAC (\$/t CO_2)	67	101	158	252	
TAC (bn \$)	350	1 119	3 002	6 575	2 754

Several remarks can be drawn from these results. First, the growing values of marginal abatement costs over time result from the optimisation process, notably from discounting. Running the model with a zero discount rate would equalise the marginal abatement costs of all periods and would narrow the gap between abatement volumes in all periods, as this gap would only result from the differences in the marginal cost curves.

Table 3.2: Intermediate objectives for halving emissions by 2050 from 1990 levels

	2011-2020	2021-2030	2031-2040	2041-2050	Total (npv)
Reference 1990	120.5%	106.1%	88.7%	50%	
Cap (Gt CO_2)	253.255	223.109	186.446	105.120	798.491
MAC (\$/t CO_2)	88	135	212	341	
TAC (bn \$)	658	1 826	4 558	9 696	4 283

Comparing the two charts above, the 2011-2020 objectives are not very different in each case, and represent a small reduction from 2005 levels (-6% or -6.66 %). According to such pathways, global emissions would optimally peak at some point between 2011 and 2020. This is in line with IPCC (2007). The net present values of total abatement costs from 2011 to 2050 differ significantly, though, with USD 2.75 trillion in the first case (halving from 2005 levels) and 4 283 trillion in the second (halving from 1990 levels).

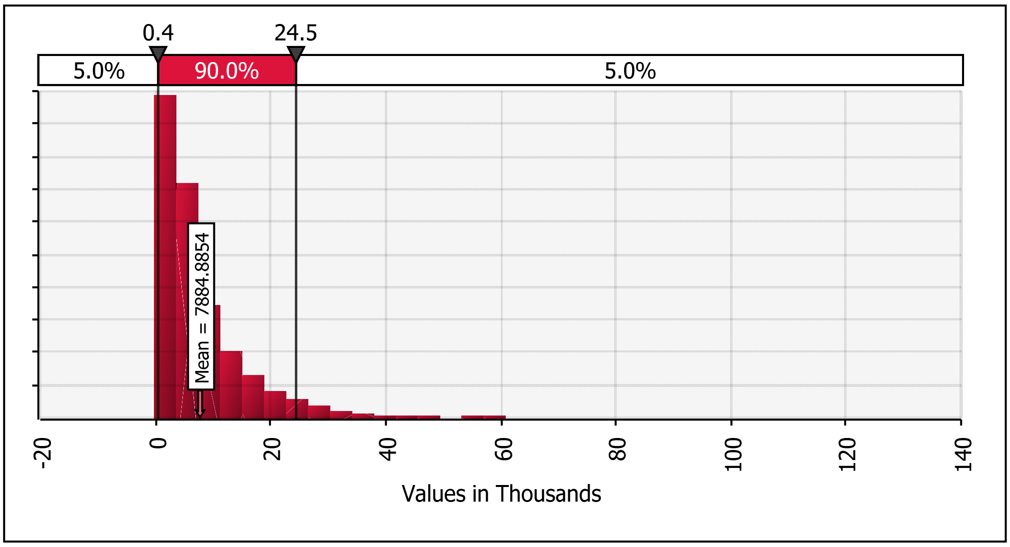
Next, we ran 3 000 Monte Carlo simulations using ACTC model to take uncertainties into account. GDP growth rate per decade and carbon intensity, but also coefficients driving the MAC curve, were assigned random values. No price cap was factored in. We looked at the cost outcomes – MAC, TAC during the first period 2021 to 2020, net present value of total abatement costs to 2050 in absolute terms and in percentage of World Gross Product (WGP) – when halving global emissions by 2050 from both 2005 levels and 1990 levels.

The following sections present our findings for the two baseline levels of 1990 and 2005.

3.2 Halving global emissions from 2005 levels, straight targets

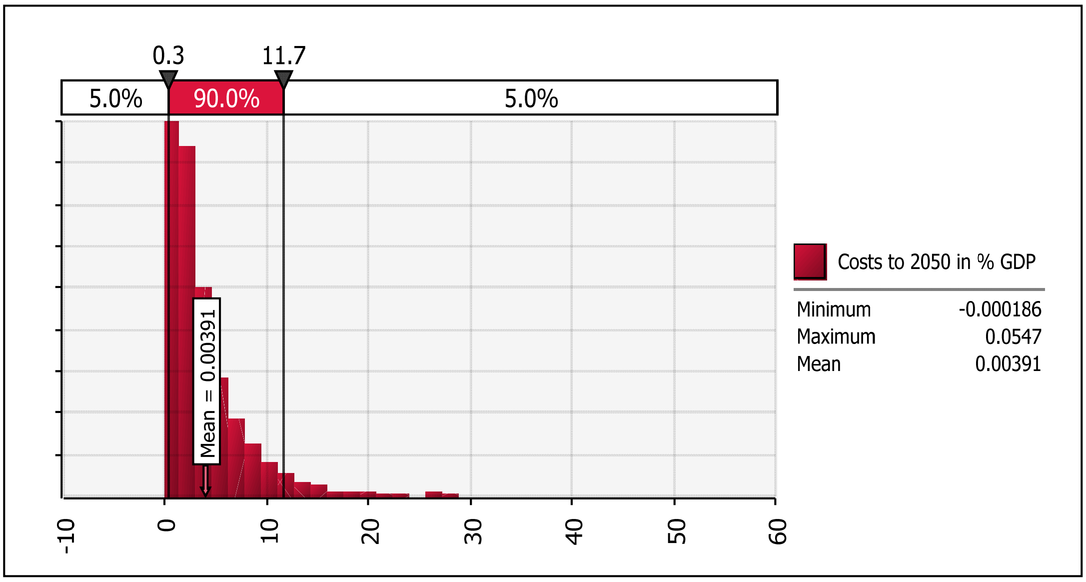
Figure 3.1 shows the net present value of total abatement costs till 2050. It has a mean value of USD 7 885 billion, against a best guess value of 2 754 billion. To compute best guess values, each parameter (growth rate, marginal abatement cost, etc.) is given its value considered most likely, as if it were not uncertain at all. In contrast, expected costs take the uncertainty in account in computing an average of all possible outcomes weighted by their probabilities of occurrence. Sound decision-making in uncertainty rests on expected values, not best guesses. Here, the expected value when uncertainty is taken in account is thus much higher than the best-guess value, when uncertainty is not considered. This important finding results from the slopes of the marginal abatement cost curves.

Figure 3.1: Net present value of abatement costs to 2050 (no price cap)



It is also interesting to consider total abatement costs as a percentage of the World Gross Product. This is shown on Figure 3.2 (the value "10" in abscissa corresponds to 1%). The mean value is 0.39%, and the considerable dispersion extends from minus 0.019% to 5.47%.

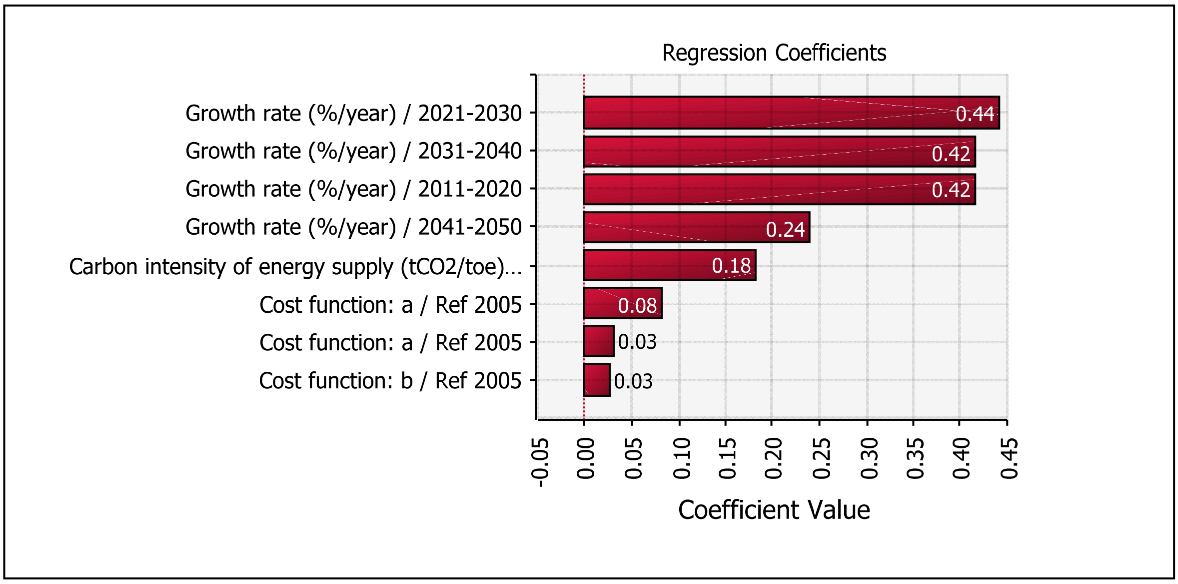
Figure 3.2: Total abatement costs to 2050 as a percentage of world gross product



Indeed, uncertainty about GDP growth rates is the main driver of the variation in abatement costs, as shown in Figure 3.3. The intrinsic uncertainty about marginal abatement costs per se results in much smaller effects. Thus, more abatement is required as more emissions are driven by a faster economy, and the marginal and total costs increase rapidly.

Looking closer at the first period, 2011-2020, marginal abatement costs (MAC) in the period 2011 to 2020 are shown in Figure 3.4. The mean or average value is at USD 92, roughly 40% higher than the best guess value of USD 67. This stems from the steepness of the MAC function: higher-than-expected unabated emissions increase MAC much more than lower-than-expected unabated emissions reduce MAC.

Figure 3.3: Regression coefficients of the net present value of total abatement costs 2011-2020



Uncertainties have more dramatic effects when total abatement costs for the same 2011-2020 period are computed, as is apparent on Figure 3.5. The mean value is USD 929 billion. (It was only USD 350 billion under best guess values for all parameters.) Total costs are computed as an integral of the marginal cost function, and thus grow faster than marginal costs when the required abatement augments.

Figure 3.4: Marginal abatement costs in the period 2011-2020

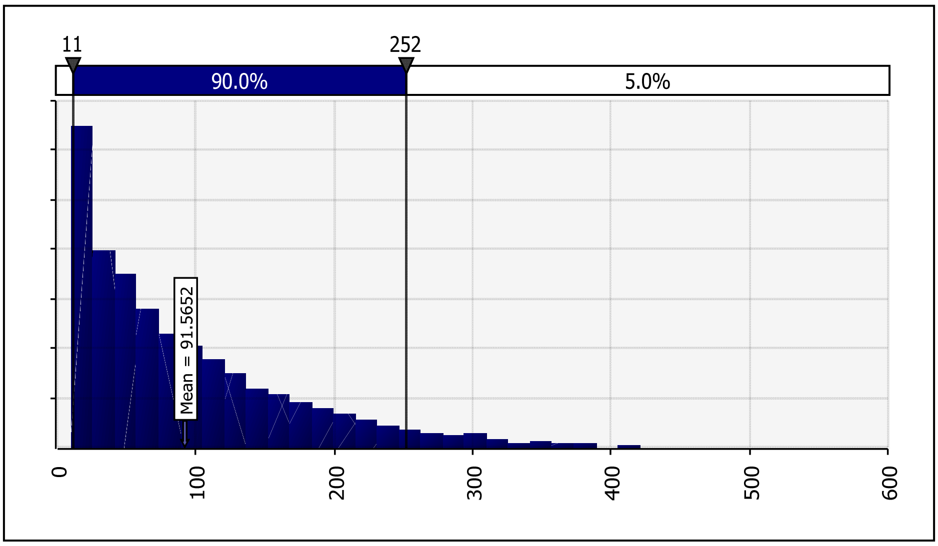


Figure 3.5: Total abatement costs in the period 2011-2020 (no price cap)

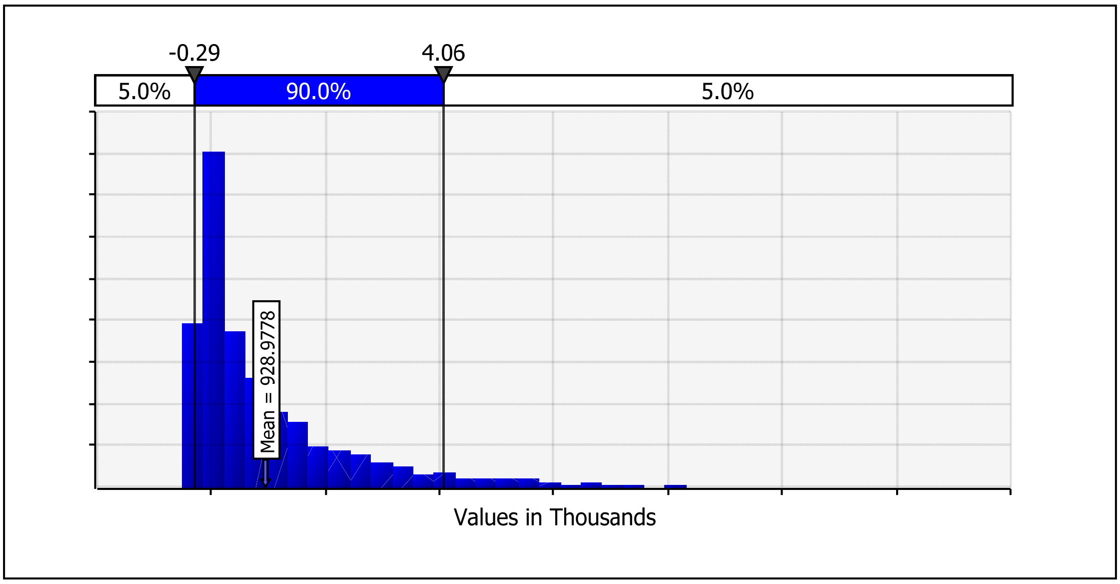


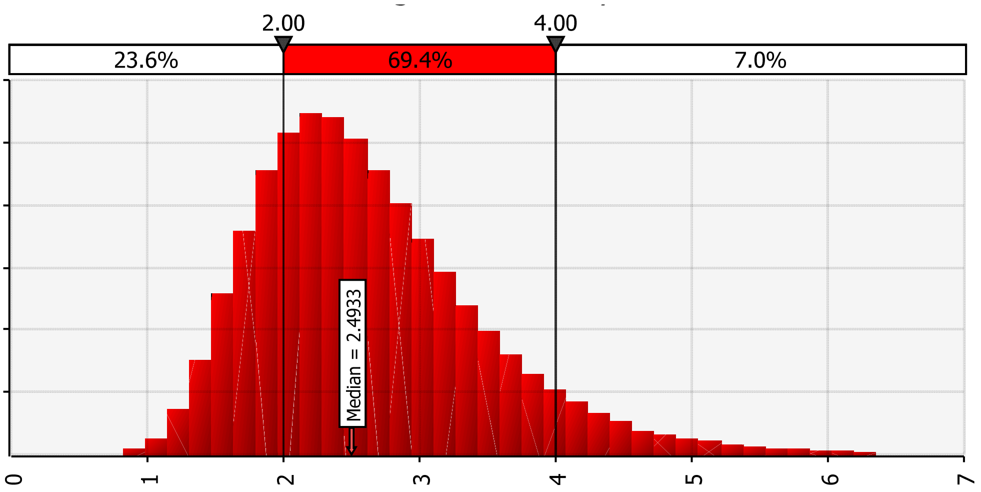
Table 3.3 summarises the expected MAC, TAC and TAC in proportion to the WGP during the following periods to 2050, by comparison with the best guess values, while halving global emissions from 2005 levels. It is worth noting that, although mean values are several times higher than best guess values, the percentage of total expected costs does not exceed 1% of expected GDP in any period – a result that is consistent with the Stern Report.

Table 3.3: Marginal and total abatement costs to 2050, halving CO_2 from 2005 levels

		2011-2020	2021-2030	2031-2040	2041-2050	Total (NPV)
MAC ($/t)	Best guess	67	101	158	252	
	Mean	92	181	288	504	
TAC (bn$)	Best guess	350	1 119	3 002	6 575	2 754
	Mean	929	3 729	8 307	18 179	7 885
TAC in % WGP	Best guess	0.04%	0.10%	0.20%	0.33%	
	Mean	0.11%	0.30%	0.50%	0.80%	0.39%

Let us now consider the environmental results of this policy – to 2050. The CO_2 concentration reached by 2050 is 462 ppm and is perfectly known, as emissions over the years to 2050 are known with certainty (assuming full compliance). The results in temperature change, however, reflect the uncertainty that affects the equilibrium temperature change in the IPCC AR4 (Figure 3.6). By comparison with the no policy case, the results are important. The median value of warming committed by 2050 is down from 3.16°C to 2.49°C. The chances of not exceeding 2°C are up from 6.9% to 23.6%, and the risks of exceeding 4°C are down from 23.3% to 7%.

Figure 3.6: Warming committed by 2050, straight targets half 2005 levels



3.3 Halving global emissions from 1990 levels, straight targets

Our next operation involved running the model with 3 000 simulations to halve global emissions by 2050 from 1990 levels. The results show that the net present value of total expected abatement costs to 2050 increase from a best guess value of USD 4 283 billion to a mean value of USD 10 671 billion, or 0.53% of the discounted value of total expected World Gross Product over the same period.

The marginal abatement cost for the period 2011-2020 has a mean value of USD 116 (against a best guess value of only USD 88), again due to the steepness of the marginal abatement cost curve. The total abatement costs for the same period reach USD 1 363 billion (against a best guess value of USD 658 billion).

Table 3.4 provides the marginal and total abatement costs and the latter in proportion of the WGP during the following periods to 2050 when reducing global emissions from 1990 levels.

Table 3.5 summarises the best guess and expected values (mean) of MAC and TAC during the first period, and indicates the NVP of overall abatement costs to 2050 of halving global emissions from both 2005 and 1990 reference levels.

Table 3.4: Marginal & total abatement costs to 2050, halving CO_2 from 1990 levels

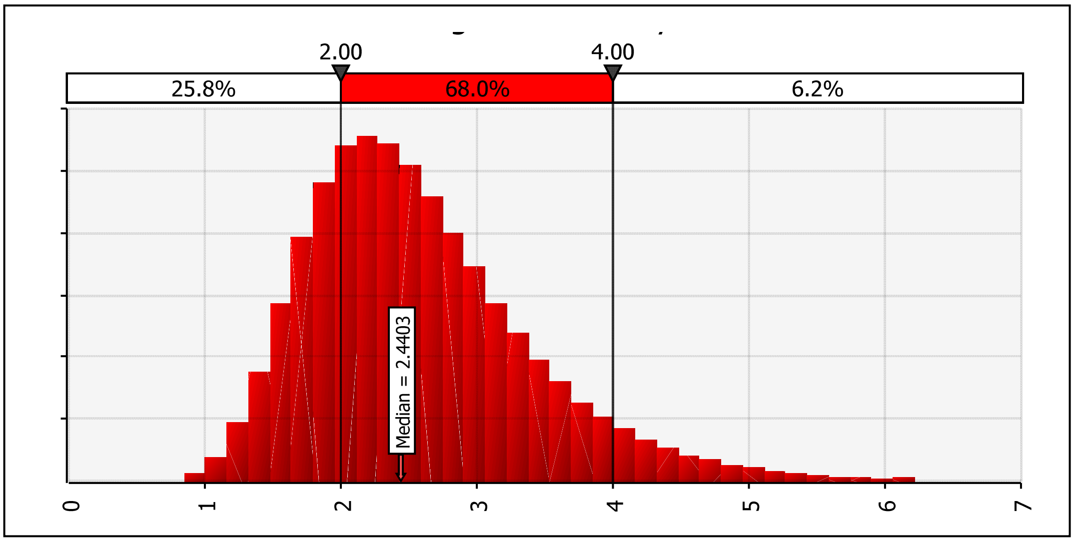
		2011-2020	2021-2030	2031-2040	2041-2050	Total (NPV)
MAC ($/t)	Best guess	88	135	212	341	
	Mean	116	228	357	657	
TAC (bn$)	Best guess	658	1826	4 558	9 696	4.283
	Mean	1 363	5 090	10 701	24 888	10 671
TAC (% WGP)	Best guess	0.08%	0.16%	0.30%	0.48%	
	Mean	0.16%	0.42%	0.65%	1.11 %	0.53%

Table 3.5: Costs of halving global emissions by 2050

		MAC 2011-2020 ($)	TAC 2011-2020 (bn $)	NPV costs to 2050 (bn $)
From 2005 levels	Best guess	67	350	2 754
	Mean	92	929	7 885
From 1990 levels	Best guess	88	658	4 283
	Mean	115	1 363	10 671

Let us consider the environmental results of this policy. The CO_2 concentration reached by 2050 is 457 ppm — 5 ppm lower than in the previous case. The median value of warming committed by 2050 is 2.45°C — a twentieth degree lower than when emissions are halved from 2005 levels. The chances of not exceeding 2°C are further increased to 25.8%, and the risks of exceeding 4°C are further reduced, though by less than 1% (Figure 3.7).

Figure 3.7: Warming committed by 2050 — straight targets half 1990 levels



KEY FINDINGS

- *Halving global energy-related CO_2 emissions by 2050 slows the global warming significantly, augmenting the chances of not exceeding 2°C and reducing the risks of exceeding 4°C.*
- *Total expected abatement costs when uncertainties are taken in account, notably on economic growth, are two to three times higher than best guess estimates when all uncertain parameters take their most likely value.*

4. ASSESSING PRICE CAPS AND PRICE FLOORS

In this section we assess the efficacy of employing price caps for the four periods to 2050. We show the results of our testing various levels to find out the likely effects on both abatement costs and actual emissions. We tightened the targets and introduced price floors with the same purpose. Next, we researched the combination of targets, price caps and floors that would lead to similar environmental results – starting with the same average concentration levels. Then we looked for the combination that would entail the same expected costs, presumably with better environmental results.

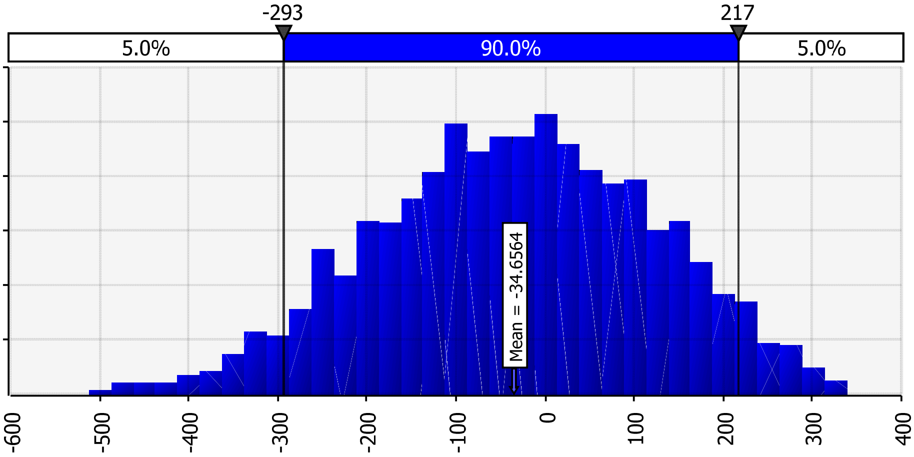
Price caps could be simple compliance payments to governments (for domestic sources) and/or to some international entity (for governments) at the end of commitment periods – at prices set up and known by all at their outset. Contrary to compliance "penalties", they would waive the obligation to surrender allowances to cover emissions, on a tonne-per-tonne basis. Price floors could be reserve prices (minimum prices) in periodic auctioning, thus creating no liability for government (no subsidy needs).

4.1 Half of the 2005 levels and low price caps

We tested three different price cap schedules. The first, "low price caps", was set deliberately about one-third below MAC in each period. The second, "middle-high", was set slightly higher than the MAC in each period. The third, "high", was set about fifty percent higher than the MAC in each period.

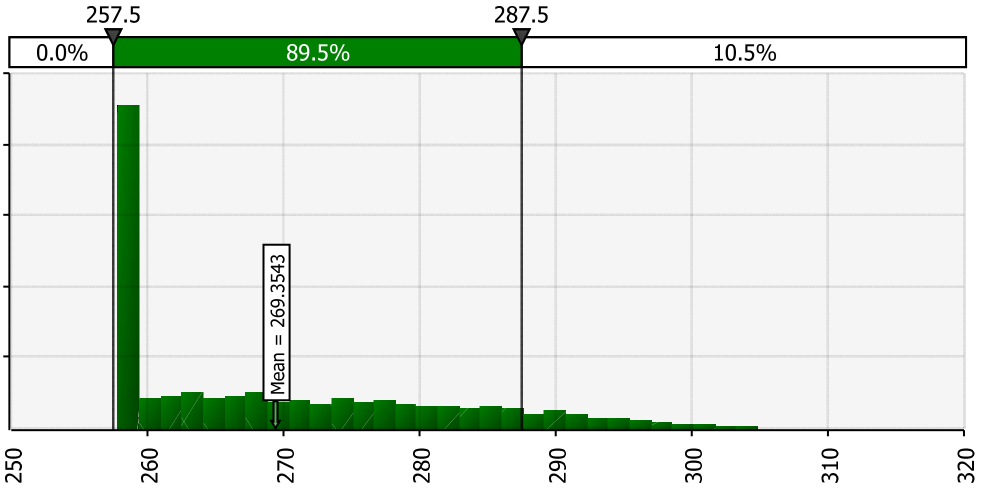
We defined "low price caps" at USD 40, 60, 80 and 100 in the four respective periods and ran the ACTC Model 3 000 times. Total expected abatement costs during the first period are considerably reduced – indeed, they become negative, at minus USD 34 billion, as energy savings (negative to no cost options) are more important than positive costs of other emission reductions (Figure 4.1).

Figure 4.1: Total abatement costs 2011-2020 with USD 40 price cap



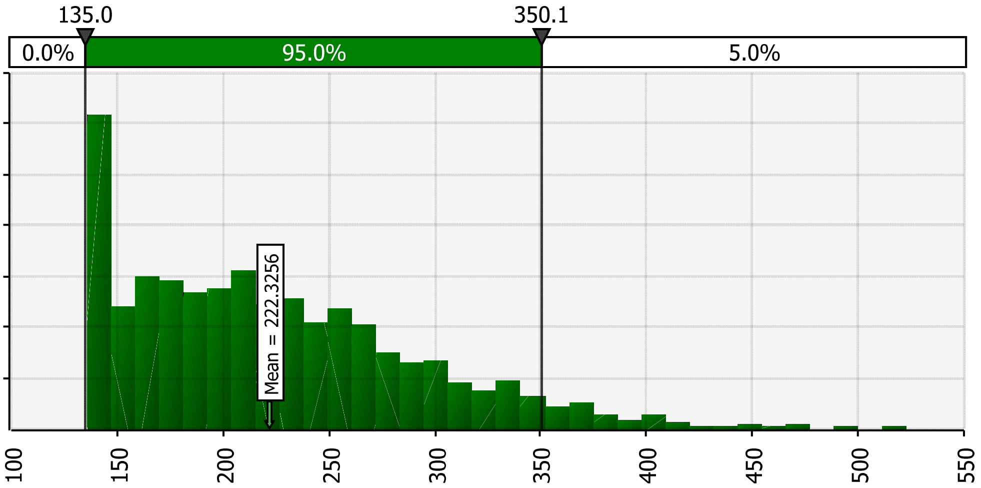
However, emissions during the first period 2011-2020 are on average about 12 Gt CO_2 higher than the 257.835 Gt CO_2 target, and in about 10% of the cases, 30 Gt CO_2 above the target, as shown in Figure 4.2 (the highest bar shows the probability of achieving the target, while the lower bars to the right show the frequency of outcomes when the price caps kick in).

Figure 4.2: Actual emissions 2011-2020 with USD 40 price cap



The deviation from the desired emission trajectory increases over time and in the last period, 2041-2050, emissions are way above the target (136 Gt CO_2 in 10 years) at 222 Gt CO_2 on average (a 63% increase!) – twice as high in about 20% of the cases (Figure 4.3).

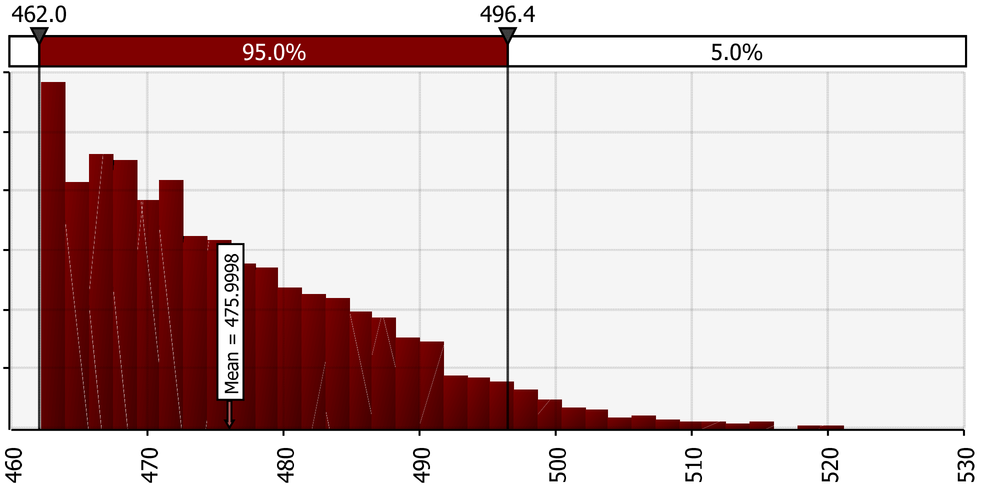
Figure 4.3: Actual emissions 2041-2050 with low price caps



Over the entire 2011-2050 period, the net present value of total expected abatement costs is down to USD 645 billion, a sharp reduction from the case with straight targets. Furthermore, the uncertainty range is much narrower, and the maximum value does not exceed 0.063%, two orders of magnitude below the maximum costs entailed by straight targets.

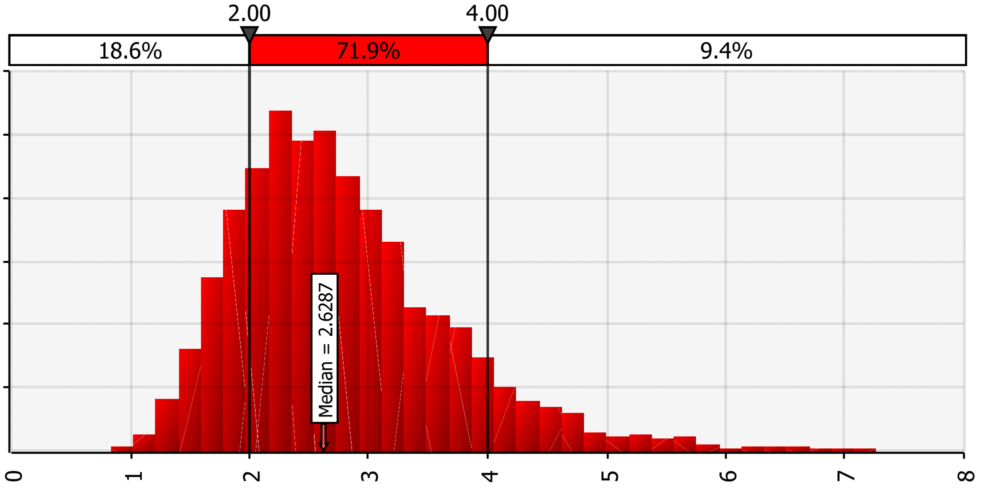
CO_2 concentrations range from 462 to 521 ppm by 2050. If the most likely outcome is 462 ppm, the mean value is 476 ppm (Figure 4.4). This illustrates the cumulative nature of the climate change issue: deviations of 63% in emissions (2041-2050) end up with a 3% increase in concentrations. The warming committed by 2050 has a median value of 2.63°C (Figure 4.4). There is an 18.6% chance of not exceeding 2°C, and a 9.4% risk of exceeding 4°C.

Figure 4.4: CO_2 concentration by 2050 with low price caps



These results are clearly more favourable to the environment than the “no policy case”. However, they reveal some degradation of environmental outcomes when compared with straight targets. Low level price caps do reduce expected costs and the cost uncertainty of climate policy, but weaken its environmental results, though perhaps less than expected.

Figure 4.5: Warming committed by 2050 with low price caps



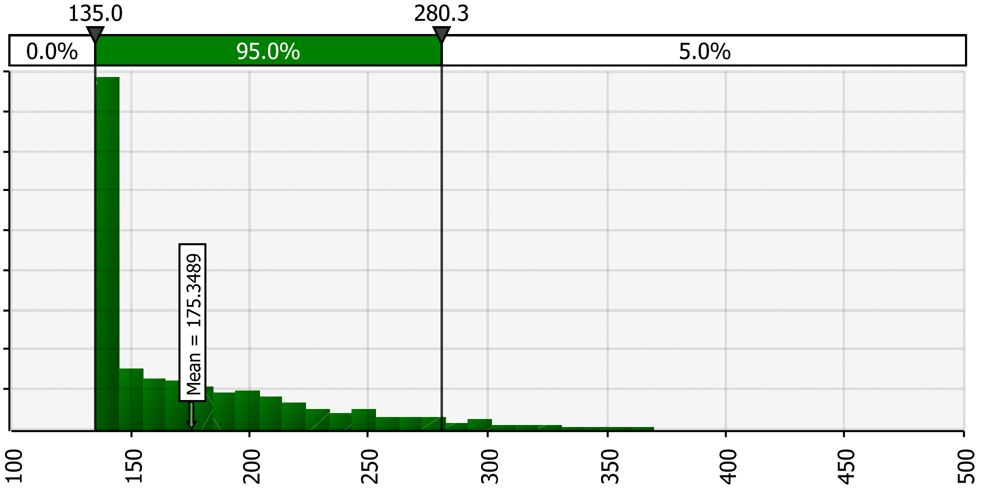
4.2 Half of the 2005 level and middle-high price caps

Let us now consider middle-high price caps. We set them at USD 80, 120, 180 and 260 in the four respective periods. Expected costs during the first period are USD 246 billion on average, close to the best guess value and almost four times less than the mean value with no price cap. The deviation of average emissions is much smaller, at 5.6 Gt CO_2 (Figure 4.6).

Figure 4.6: Actual emissions 2011-2020 with middle price cap

By our calculations, emissions by 2041-2050 would remain significantly higher than the target, though, with a mean value of 174 Gt CO_2 (Figure 4.7).

Figure 4.7: Actual emissions 2041-2050 with middle-high price caps

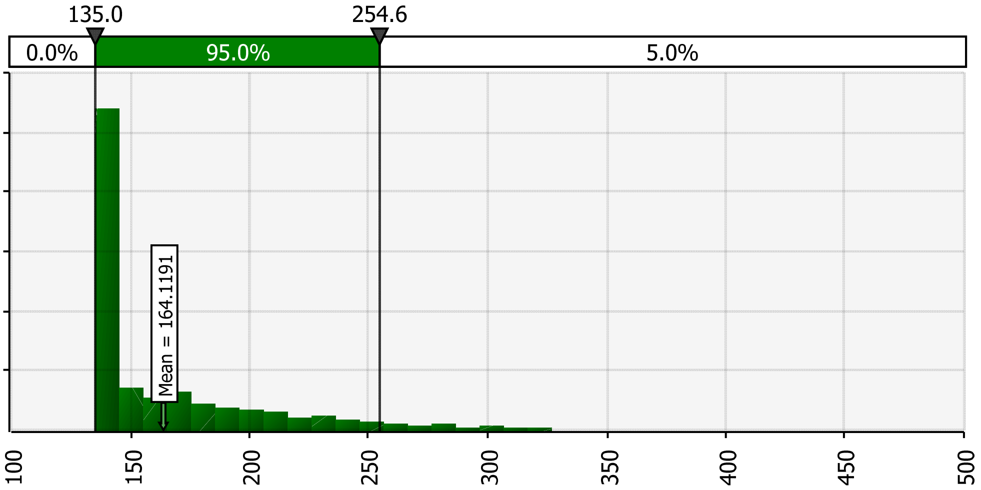


Over the entire 2011-2050 period, total expected abatement costs (NPV) would amount to USD 2 202 billion – about a third of the initial value with no price cap. CO_2 concentrations end up in the range 462-509 ppm, with a mean value 469 ppm, against 462 ppm with straight targets.

4.3 Half of the 2005 levels and high price caps

For this projection, prices caps were set higher, at USD 110, 150, 230, 350 for each respective period. Expected costs during the first period reached USD 428 billion, which is about half their initial level. Emissions during that period remained higher than the target at 261 Gt CO_2. Emissions during the 2041-2050 period have a mean value of 164 Gt CO_2, about 20% above the target (Figure 4.8). Even relatively high price caps create significant deviation from desired objectives.

Figure 4.8: Actual emissions 2041-2050 with high price caps



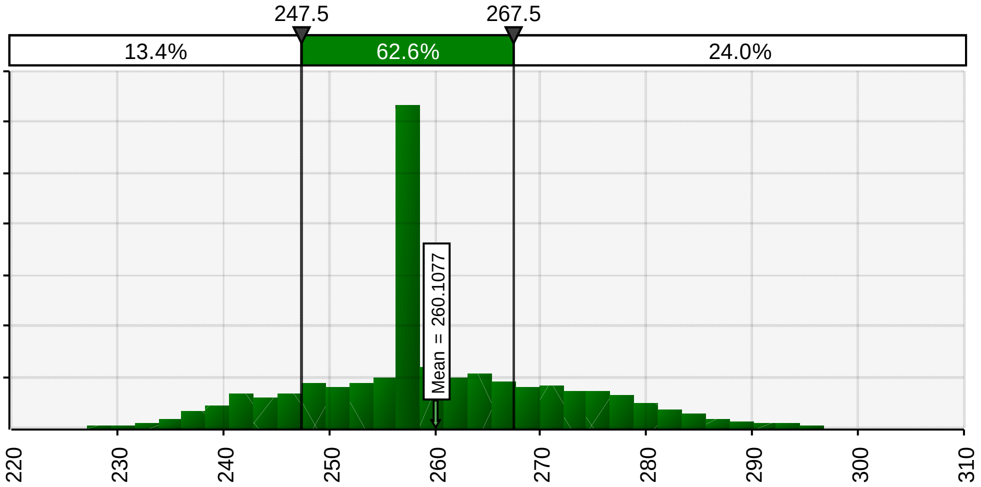
Over the entire period 2011 to 2050, total expected costs would have a net present value of USD 2 925 billion. CO_2 concentrations would be in the range 462 to 506 ppm, with a mean value 467 ppm. Both the high level of the price caps (hence the low probability of high concentration values) and the lack of price floors combine to make this mean value relatively close to the lower end of the uncertainty range in concentrations.

4.4 Price caps and price floors

Next, we combined middle-high price caps and price floors. We set price caps at USD 80, 120, 180 and 260 for the periods 2011-2020, 2021-2030, 2031-2040 and 2041-2050, respectively, and price floors at half these levels, *i.e.* USD 40, 60, 90 and 130.

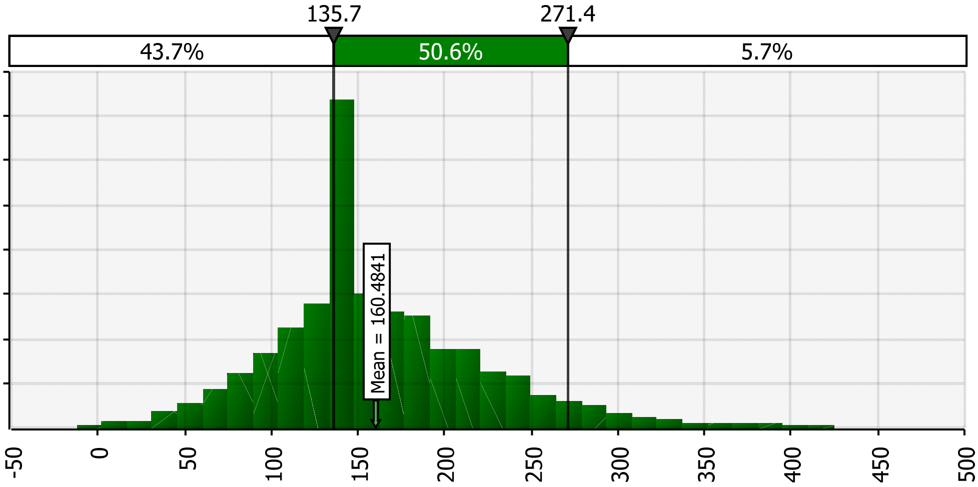
Emissions during the first period have a mean value of 260.1 Gt CO_2, only 1% above the 257.835 Gt CO_2 target. The deviation is much smaller with price floors than without them. In about 24% of the cases, the target would be exceeded by 1 Gt CO_2 per year or more, while in about 13.4% of the cases, emissions would be 1 Gt CO_2 per year below the target (Figure 4.9). Abatement costs would decrease to USD 297 billion, which is a third of their initial value.

Figure 4.9: Actual emissions 2011-2020 with USD 80 price cap and USD 40 price floor



Emissions during the last decade have a mean value 160.5 Gt CO_2, still higher than the 135.680 Gt CO_2 target, which is reached or beaten in 43.7% of the cases. However, there would be a 5.7% risk that emissions would be twice as much or more than the target (Figure 4.10).

Figure 4.10: Actual 2041-2050 emissions with price caps and price floors

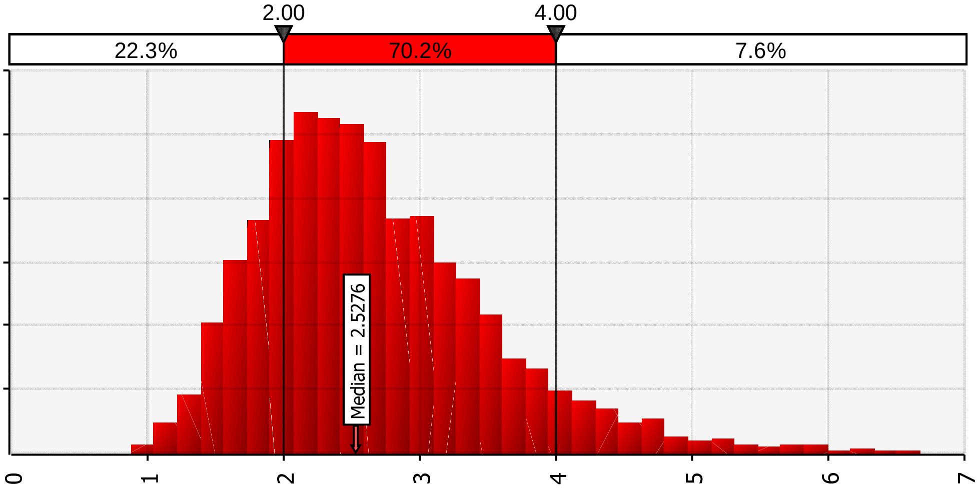


Over the entire period to 2050, the net present value of total expected abatement costs would be USD 2 292 billion. This is an interesting result, as it suggests that price floors are really useful. In comparison with middle-high price caps, the increase in costs due to price floors is rather small, probably because they help maintain emissions closer to an optimal path. In comparison with high price caps, total costs are reduced by 21.6% (USD 2 292 billion vs. USD 2 925 billion)

Despite this additional cost reduction, concentration results are slightly better than with price caps only; CO_2 concentrations by 2050 are in the range 432 to 506 ppm with a mean value of 466 ppm.

Results expressed in temperature changes are worth considering, as they are rather close to those obtained with straight targets, though not exactly similar (Figure 4.11).

Figure 4.11: Warming committed by 2050 with price caps and price floors

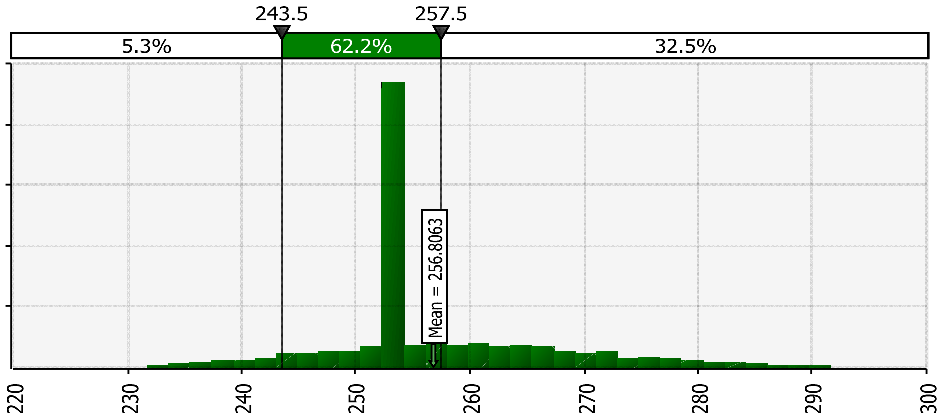


4.5 Half the 1990 levels with price caps and price floors

With the objective to achieve the same environmental results as with straight targets, we optimised intermediate targets towards half of the 1990 levels by 2050, and factored in price caps at levels slightly higher than marginal abatement costs at USD 110, 150, 240 and 360 in the four periods, and price floors at a third of these levels, at USD 35, 50, 80 and 120.

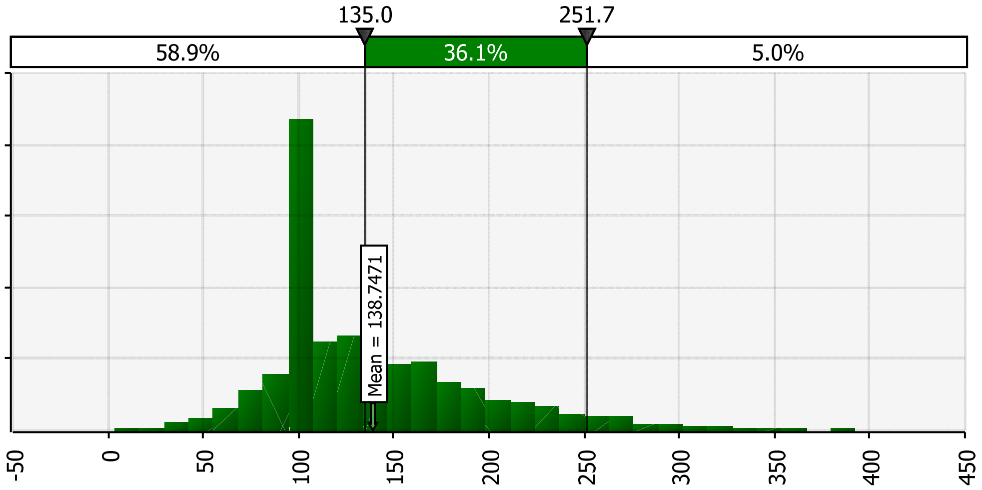
For the period 2011-2020, mean emissions would most likely have a value at the tighter 253 Gt CO_2 target, and a mean value of 256.8 Gt CO_2, which is slightly below the original target; however, this original target might be exceeded in about 30% of cases, as shown in Figure 4.12. Expected costs for that period would be USD 560 billion. In the following period, 2021-2030, emission results at 234.2 Gt CO_2 would be at the original target as well.

Figure 4.12: Actual emissions 2011-2020 with USD 110 cap and USD 35 floor



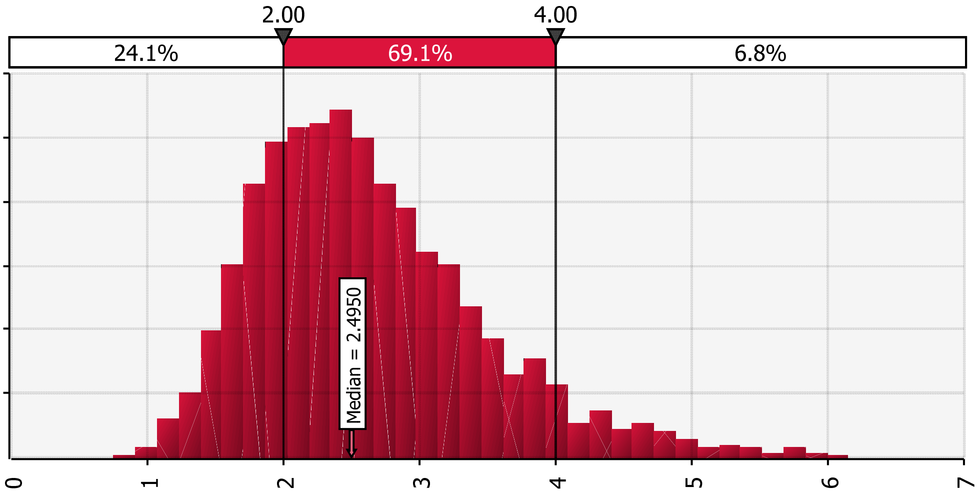
In the period 2041-2050, emissions have a mean value of 138.75 Gt CO_2 instead of 136 Gt CO_2 (Figure 4.13). This small deviation does not prevent CO_2 concentration by 2050 to have on average the same value as with straight targets, *i.e.* 462 ppm, though the range extends from 435 to 501 ppm. Total expected costs (NPV) over the entire period are USD 3 456 billion.

Figure 4.13: Actual emissions 2041-2051 with price caps and price floors



In terms of temperature changes, the results (as shown in Figure 22) are similar to those obtained with straight targets leading to the same concentration levels (as shown in Figure 4.14). Achieving a given concentration level (such as 462 ppm) exactly or on average does not make any real difference to the environmental outcome. The uncertainty introduced by price caps in concentration levels is entirely masked behind the uncertainty on climate sensitivity. Only the expected costs are different — less than half the expected costs of straight targets (USD 7 885 billion). The spread of the cost uncertainty expressed in percentage of WGP is almost reduced 20 times.

Figure 4.14: Warming committed by 2050 with target of half of 1990 levels, price caps and floors



These results confirm earlier qualitative analyses. Uncertain emission outcomes in a decade due to price caps create smaller uncertainty on concentration levels, while greenhouse gases slowly accumulate in the atmosphere. Further, this uncertainty on concentration levels is essentially unnoticeable in the final analysis in terms of temperature changes, whether one considers median values or risks of exceeding specific values. Uncertainty on equilibrium temperature change by far dominates uncertainty about concentration levels.

4.6 Tighter targets, price caps and price floors

We then looked for a combination of targets that would entail the same expected costs as straight targets and deliver presumably better environmental results.

One combination that goes a long way in that direction consists in setting the 2050 target at a quarter of the 1990 levels, or 52.6 Gt CO_2 in ten years. Optimal intermediate targets are computed to minimise the net present value of abatement costs to 2050, using best guess values, as shown on Table 4.1.

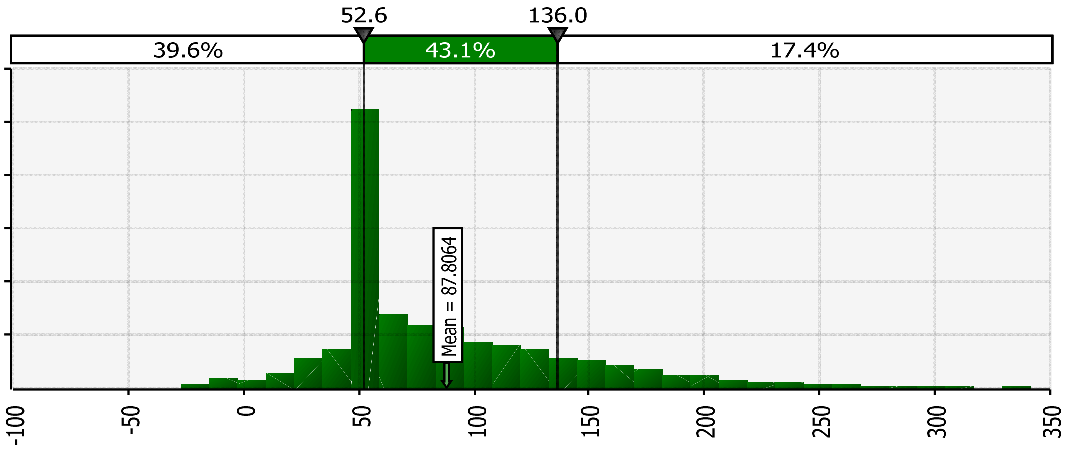
Table 4.1: Intermediate targets for reducing 2050 emissions by 75% from 1990 levels

	2011-2020	2021-2030	2031-2040	2041-2050	Total (npv)
Reference 1990	116.5%	97%	72 %	25%	
Cap (Gt CO_2)	245.034	203.562	152.125	52.560	653.321
MAC (\$/t CO_2)	135	212	338	546	
TAC (bn \$)	1 482	3 675	8 479	17 565	8 207

Price caps were set at USD 150, 240, 360 and 600, price floors were set at USD 50, 80, 120 and 200 for the periods 2011-2020, 2021-2030, 2031-2040 and 2041-2050, respectively.

The results show that emissions reach 88 Gt CO_2 on average in the period 2041-2050, or 43% of 1990 levels (30% of 2005 levels), as shown in Figure 24. This ambitious target is reached in about 40% of the cases. However, there is a 17% chance that the original, straight target representing half of 2005 levels would be exceeded (Figure 4.15).

Figure 4.15: Actual emissions 2041-2050 with target 25% 1990 levels, price caps and floors



The net present value of expected abatement costs to 2050 is USD 6 762 billion, which is still lower than halving emissions from 2005 levels with certainty. Concentrations end up by 2050 in the range 430 to 494 ppm, with mean value 454 ppm. Resulting temperature change committed by 2050 shows a median value of 2.41°C; with chances of not exceeding 2°C at 27.2% and risks of exceeding 4°C at 5.7% (Figure 4.16). These results are better than those obtained in halving 2050 emissions from 1990 with straight targets, which would entail overall expected abatement costs (NPV) of USD 10 671 billion.

Figure 4.16: Warming committed by 2050 with target 25% of 1990 levels, price caps and floors

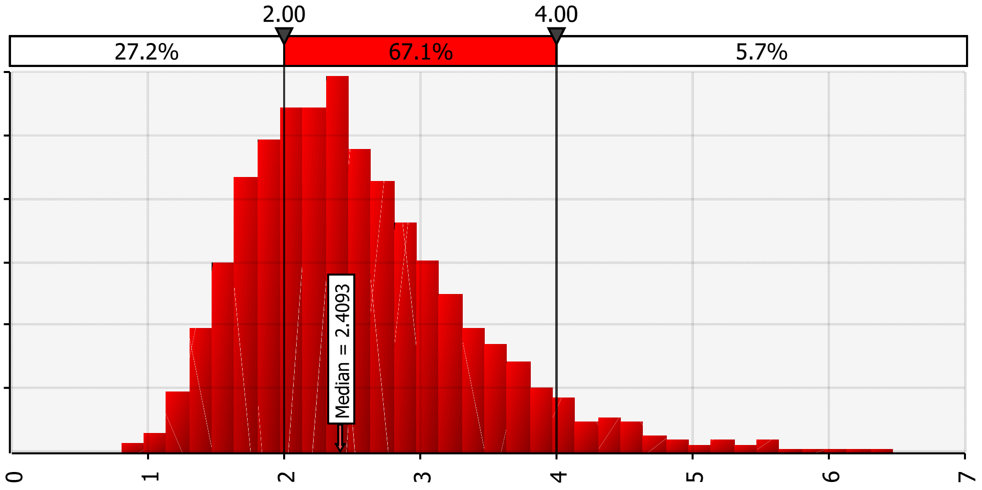
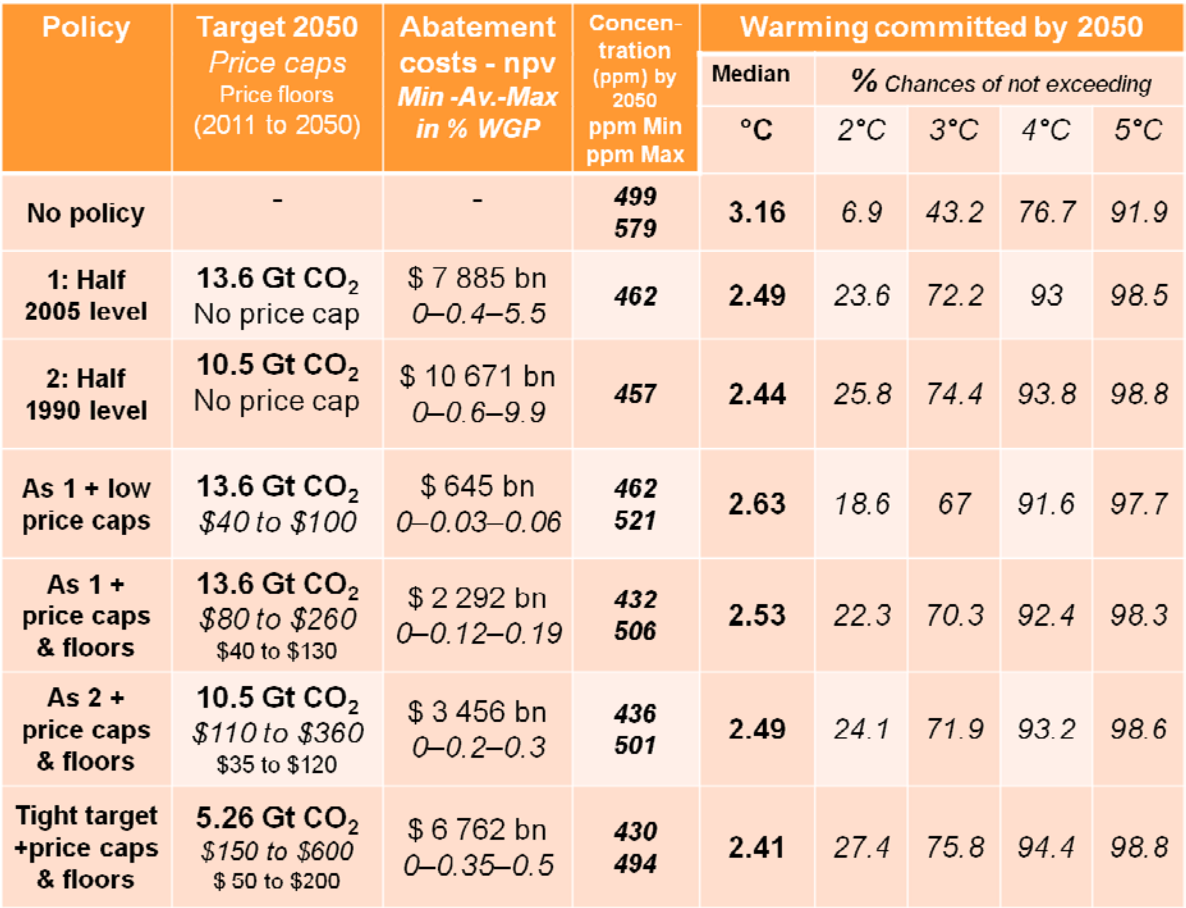


Table 4.2 summarises the most important numerical results. The policy conclusions are the following:

- In the absence of policy, there will be warming of more than 3°C in more than half the cases.
- Most policies considered reduce the median value of committed warming by 2050 to 2.5°C or less. The only exception is that of halving 2050 emissions from 2005 levels with "low" price caps (USD 40 in 2011-2020), in which case the median value of committed warming is 2.63°C.
- Halving emissions from 1990 levels by 2050 with price caps and floors offers similar environmental results as halving emissions from 2005 levels with straight targets – but for about half the expected costs.
- Setting much tighter targets (-75% from 1990 levels to 2050) with price caps and floors commensurate with those targets would provide slightly better environmental results than halving emissions from 1990 levels

with straight targets. Expected costs would be lower than the cost of halving emissions from 2005 levels with straight targets, and about 60% the costs of halving emissions from 1990 levels with straight targets.

Table 4.2: Summary results



Policy	Target 2050 *Price caps* Price floors (2011 to 2050)	Abatement costs - npv *Min -Av.-Max in % WGP*	Concentration (ppm) by 2050 ppm Min ppm Max	Warming committed by 2050				
				Median	*% Chances of not exceeding*			
				°C	*2°C*	*3°C*	*4°C*	*5°C*
No policy	-	-	***499*** ***579***	**3.16**	*6.9*	*43.2*	*76.7*	*91.9*
1: Half 2005 level	**13.6 Gt CO_2** No price cap	$ 7 885 bn *0–0.4–5.5*	***462***	**2.49**	*23.6*	*72.2*	*93*	*98.5*
2: Half 1990 level	**10.5 Gt CO_2** No price cap	$ 10 671 bn *0–0.6–9.9*	***457***	**2.44**	*25.8*	*74.4*	*93.8*	*98.8*
As 1 + low price caps	**13.6 Gt CO_2** *$40 to $100*	$ 645 bn *0–0.03–0.06*	***462*** **521**	**2.63**	*18.6*	*67*	*91.6*	*97.7*
As 1 + price caps & floors	**13.6 Gt CO_2** *$80 to $260* $40 to $130	$ 2 292 bn *0–0.12–0.19*	***432*** **506**	**2.53**	*22.3*	*70.3*	*92.4*	*98.3*
As 2 + price caps & floors	**10.5 Gt CO_2** *$110 to $360* $35 to $120	$ 3 456 bn *0–0.2–0.3*	***436*** **501**	**2.49**	*24.1*	*71.9*	*93.2*	*98.6*
Tight target +price caps & floors	**5.26 Gt CO_2** *$150 to $600* $ 50 to $200	$ 6 762 bn *0–0.35–0.5*	***430*** ***494***	**2.41**	*27.4*	*75.8*	*94.4*	*98.8*

KEY FINDINGS

- *Price caps would considerably reduce uncertainty on total abatement costs and expected abatement costs, but would shift that uncertainty onto the short-term emission outcomes.*

- *However, uncertainty on concentration level is much smaller than uncertainty on short-term emission levels, due to the slow building up of atmospheric concentrations. Further, uncertainty on the Earth's climate sensitivity far outweighs the uncertainty on concentrations induced by price caps with respect to temperature changes.*

- *A climate policy with price caps set below best guess marginal abatement costs will not achieve its stated objectives, but may remain largely preferable to the absence of any policy. Price caps should be set higher than expected marginal costs. Price floors would further reduce the expected costs of achieving a given environmental result.*

- *Price caps alone could have some negative effect on the environmental outcome if not balanced with price floors and some tightening of the emission objectives.*

- *Under the assumptions of this study, a proper combination of target with price cap and price floor can be designed to offer comparable probabilities of meeting a given temperature outcome at lower expected costs, and with much narrower uncertainty on total discounted abatement costs, than or straight target.*

- *Abatement cost savings due to price caps and, if possible, price floors, allow for setting more ambitious objectives. For example, price caps could allow for halving global 2050 energy-related emissions from 1990 levels on average, with expected costs half the expected costs of halving emissions from 2005 levels with certainty, and much lower cost uncertainty.*

- *An even tighter target with price caps and floors to 2050 would provide environmental results slightly better than halving emissions from 1990 levels, at expected costs lower than those of halving emissions from 2005 levels with certainty, and much lower cost uncertainty.*

5. CONCLUSIONS, CAVEATS AND FUTURE WORK

This study assesses the long term economic and environmental effects of introducing price caps and price floors in some hypothetical global climate change mitigation architecture. This quantitative analysis confirms what qualitative analyses have already suggested. In a context of uncertain unabated emission trends and uncertain abatement costs, expected abatement costs may be significantly higher than best guess values. However, introducing price caps could significantly reduce expected costs.

Price caps would considerably reduce uncertainties about total abatement costs, but increase uncertainty on emission outcomes. Still, they may help adopt more ambitious policies at lower expected costs. As such, they may also help strike a balance between concerns for the global economy and concerns for the global environment, and help shape an agreement between people, interest groups or countries that may give different weights to these various concerns.

Price floors would augment the costs of climate change mitigation for a given target, everything else being constant (e.g. price cap level). However, for a given expected environmental outcome, a combination of targets, price caps and price floors would entail lower expected costs than having only targets and price caps – for in that case, the targets would need to be even tighter.

Introducing price caps and price floors and tightening the quantitative emission limits at the outset makes it possible to reduce by half the expected costs of halving global energy-related CO_2 emissions by 2050, while narrowing considerably the uncertainty about total discounted abatement costs. Because climate change is cumulative and because the climate sensitivity is itself uncertain, price caps and floors could make relatively little difference for concentration levels (either above or below the concentration reached with straight targets), and little discernible difference for temperature changes, if any.

Price caps, and to a lesser extent price floors, should be commensurate with the best-guess abatement costs resulting from desired quantitative emission limits, if these are to be achieved, if not precisely, at least on average. The extent of the spread between price caps and floors will influence the size and liquidity of emissions trading — but this point warrants further study.

One limitation of this study is that it is based on energy-related CO_2 only. However, fundamental insights about price caps and floors would likely remain unchanged if other greenhouse gases (GHGs) and sources were included. As Hansen *et al*. (2008, p. 12) put it,

> “GHGs other than CO_2 cause climate forcing comparable to that of CO_2, but growth of non-CO_2 GHGs is falling below IPCC scenarios and the GHG climate forcing change is determined mainly by CO_2. Net human-made forcing is comparable to the CO_2 forcing, as non-CO_2 GHGs tend to offset negative aerosol forcing.”

Still, the inclusion of other sources and sinks of CO_2, other GHGs and other man-made climate forcings could change the marginal abatement cost schedule in achieving the target levels considered here. This, in turn, could modify the levels of price caps and price floors required to maintain or improve the desired climate results of mitigation policies.

In the ACTC Model, uncertainties about economic growth increase exponentially over time. The level of price caps required to maintain the environmental performance beyond 2030, which may today seem rather high, is somewhat speculative. When policy makers will need to set these levels, whether internationally or at domestic levels, this uncertainty, of primary importance with respect to the uncertainty on total abatement costs, will be much less than today. Price cap levels at that time may appear much lower than today, whether being effectively lower, or because perceptions may change after decades of rapid economic growth.

Another caveat is that the ACTC Model has marginal abatement cost functions of biquadratic polynomial form. This unusual assumption was necessary in order to fit with data from *Energy Technology Perspectives 2008* (IEA, 2008). More usual quadratic functions would have increased considerably the costs of smaller abatement potentials, *i.e.* the marginal and total costs in the early periods of the analysis. However, beyond 160 Gt CO_2 abatement per decade, marginal abatement costs increase rapidly, with a possibility that both cost uncertainty and total expected costs are somewhat exaggerated, thus biasing the results in favour of price caps. However, there is little available information to specify the abatement cost schedule beyond that potential, and it would have been arbitrary to modify that curve or, for example, specify some unknown “back-stop” technology available by definition in unlimited quantity with no emissions at a given price.

The ACTC Model takes into account a large potential for negative to no-cost options – as an uncertain possibility. While setting carbon prices through quantitative targets may help realise this potential, its mere existence demonstrates other market imperfections, which governments should aim at overcoming using a wide range of policies (IEA, 2008a).

Technological progress seems to be exogenous in the ACTC Model, as it does not depend on the exact achievement of intermediate emission targets. In other words, the ACTC Model does not directly link realised abatement in one period with technology development and does not adjust abatement costs in subsequent periods accordingly. However, in *Energy Technology Perspectives 2008,* technological progress largely depends on the policy pursued, and these assumptions are taken up in the Model’s abatement cost curves (see Appendix). Therefore, technological progress is not independent from the ambition of the climate policy pursued. It may depend more on this ambition than on the exact achievement of the emission limits. However, actual abatement may also have an influence on technological progress. While this influence is not explicitly modelled in the ACTC Model through changes in the cost curves, it is reflected by its global construction in which early reductions are supposed to last forever, *i.e.* they permanently reduce the emission trends. If the price cap kicks in during period *n*, less abatement is achieved in period *n* and also in period *n+1* as a result of past efforts. Thus the volume of the reductions necessary to comply in the *n+1* period is greater. This pushes the marginal abatement cost higher, hence increasing the probability that the price cap also kicks in during period *n+1* (conversely, the price floor kicking in during period *n* would ease compliance in period *n+1*).

Questions have been raised about the influence of introducing price caps and price floors, in particular, in emissions trading schemes on the incentive to invest in research, development and dissemination of climate-friendly technologies. Some see the reduction in expected costs as impeding technology developments; others link price caps and floors to reduced price volatility, which would put investors’ minds at rest. In any case, this area deserves further investigation.

It might be important to note that the ACTC model does not reveal the possible value of time flexibility. The reduction in expected abatement costs in this study results more broadly from the flexibility given to not achieve precisely the quantitative emissions targets, and not only from the flexibility to achieve a precise target with different time profiles. However, if price caps were to be set in some decades to 2050 and not others, the net present value of total costs could increase. Savings in one period could be more than compensated for by greater expenses in the following period. In other words, departing from an optimal emissions path might be costly. This does not mean that time flexibility has no value *per se,* only that this model, by construction, does neither identify nor quantify it.

It would be tempting to extend this study to stabilisation levels or, say, to the end of the century. However, this would be highly speculative, as little information is available today on distant technological developments, business-as-usual emissions, fuel mixes and abatement costs. Furthermore, it is yet unclear if stabilisation of CO_2 concentrations will be compatible with some level of emissions, or if climate change “slow feedbacks” will, to the contrary, require zero or even negative emissions to achieve stabilisation. This may also depend on the level of stabilised greenhouse gas concentrations ultimately deemed “non dangerous”.

It is perhaps more important to consider how price caps and price floors could be implemented in practice, in ways that would not create incentives for “gaming” and speculating. This study rests on the assumption of a global regime with full trading, and while this is likely to remain a long-term objective for some time, it might be helpful in the context of the on-going climate negotiations to see how the international regime and individual countries can set up price caps and floors, and what interplay between them would be possible or not. Other issues in this context might be, for example, how fluctuations in currency regimes across the world could interfere with running a global architecture with price caps and floors. One may also want to consider how price caps and floors of an international architecture could be reflected in policy mixes encompassing economic and other instruments that do not reveal the costs of emission reductions.

6. APPENDIX: THE ACTC MODEL

6.1. Abatement Costs

This appendix describes the model of abatement costs and temperature changes (ACTC) that is being used in this paper to assess price caps and price floors in global climate change mitigation architectures, starting with a brief description of the model structure, then considering how the model addresses business-as-usual emissions and abatement costs, with best guess values, uncertainty ranges, and probability distributions.

The model is implemented on a spreadsheet. A commercial add-in allows specifying uncertainty distributions for any variable, running Monte Carlo simulations, and facilitates the collection and presentation of the results.

6.2. Model structure

Our model is a highly aggregated model of the global economy. It does not distinguish countries or sectors, as if all energy-related CO_2 emission sources, in all countries, were similarly capped with perfect emissions trading.

The business-as-usual emission pathways and abatement cost functions are consistent with the literature, and in particular, the IEA publications – *World Energy Outlook 2006* and *World Energy Outlook 2007*, *Energy Technology Perspectives 2008*– which gather and express the whole energy expertise of the IEA, as well as the literature assessed by the IPCC Fourth Assessment Report.

6.3 Business-as-usual emissions assumptions

Baseline energy-related CO_2 emissions (in billion tonnes, or Gigatonnes, or Gt) are calculated by multiplying the World Gross Product (WGP), expressed in USD billion (using purchase power parities by the energy intensity of the economy and the carbon intensity of the energy mix. The energy intensity of the economy is expressed in tonnes oil equivalent per thousand dollars (toe/1000 USD), and the carbon intensity of the energy supply is expressed in tonnes CO_2 per tonne oil equivalent (tCO_2/toe).

The initial World Gross Product, world energy production and world energy-related CO_2 emissions are set at USD 54 618 billion, 11 468 million tonnes oil equivalent (toe) and 25 billion tonnes of carbon dioxide (Gt CO_2) by 2005, respectively.

The World Gross Product is estimated to grow 4.2% per year to 2010, then by 3.3% to 2030, 2.9% to 2050, and 2.25% to the end of the century. Such decline expresses the expected maturation of developing economies as the gap between them and already industrialised countries reduces over time and the demographic growth levels off. These assumptions are slightly different from those in *Energy Technology Perspectives 2008* (4.2% growth to 2015, then 3.3% to 2030, then 2.6% to 2050) but lead to almost exactly the same WGP by 2050: a four-fold increase over the 2005 level.

The rate of autonomous energy efficiency improvements (AEII) is set constant at 1.7% per year as in *Energy Technology Perspectives 2008*, almost 1% expressing technical improvements, and the remainder expressing structural changes.

The carbon intensity of the energy supply slowly augments till 2030, then more rapidly as coal starts being used on a massive scale to produce liquid fuels, from 2.38 t CO_2/toe in 2011-2020 to 2.4 in 2021-2030, 2.55 in 2031-2040, 2.7 in 2041-2050 and 2.8 t CO_2/toe from 2051 to 2100.

The resulting best-guess CO_2 emissions postulated by the model in this baseline scenario are 42 Gt CO_2 by 2030, 62 Gt CO_2 by 2050 and 90 Gt CO_2 by 2100. The first number is consistent with the *World Energy Outlook 2007* projection and the median projections of the most recent IPCC scenarios (IPCC 2007, p. 32). The second is consistent with the projection in the *Energy Technology Perspectives 2008*. The third number is close to the 75th percentile of the recent IPCC scenario (see Figure 6.2).

We then introduced uncertainty, with “Beta general” probability functions centred on the best guess values of the GDP growth rates. Minima and maxima are specified at 1.5% and 5.1% to 2030, 1.2 % and 4.6% for the next two decades, 1% to 4% for the rest of the century.

We also introduced “Beta general” probability functions for the carbon intensity values, reflecting a growing uncertainty over time. Minima and maxima were specified as follows:

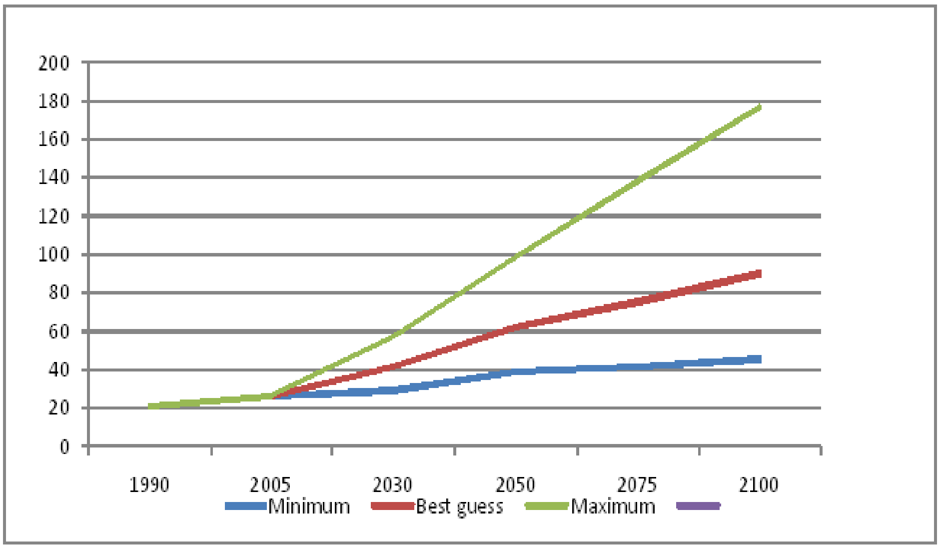
Table 6.1: Carbon Intensity Values

Timeframe	Range of minimal and maximum carbon intensity values*
2011-2020	2.28 → 2.48
2021-2030	2.2 → 2.6
2031-2040	2.5 → 2.9
2041-2050	2.6 → 3

* tonnes of CO_2 per tonne of oil equivalent

Running 3000 Monte Carlo simulations produced minima and maxima business-as-usual emissions. By 2030, the range is 29 – 58 Gt CO_2, by 2050 it is 39 – 99 Gt CO_2, and by 2100 it is 46 – 177 Gt CO_2 (Figure 6.1).

Figure 6.1: Business-as-usual energy-related CO_2 emissions



While some may deem our estimates of the uncertainty of the global economy growth rate to be rather large, they somehow compensate for the absence of explicit uncertainty relative to the AEEI — and our relatively optimistic assumptions about it. The IPCC quotes values between 0.5 to 1.9%; further, Pielke *et al.* (2008) have criticised the IPCC for being overly optimistic about both energy efficiency and carbon intensity evolutions.

However, these possible biases seem to cancel each other out in forecasting global energy-related CO_2 emissions. The match with the post-SRES scenarios shown in Figure 6.1 looks good (industrial CO_2 emissions are small compared to energy-related CO_2 emissions, accounting for respectively 2.8% and 56.6% of the total GHG emissions in 2004, and thus do not blur the comparison). Indeed, our uncertainty range is narrower than in the IPCC report, in part because the IEA expertise gives little credibility to spontaneous decreases in energy-related CO_2 emissions before the end of this century, given the relative abundance and low costs of coal.

Figure 6.2: Energy-related and industrial CO_2 emission scenarios (IPCC, 2007)

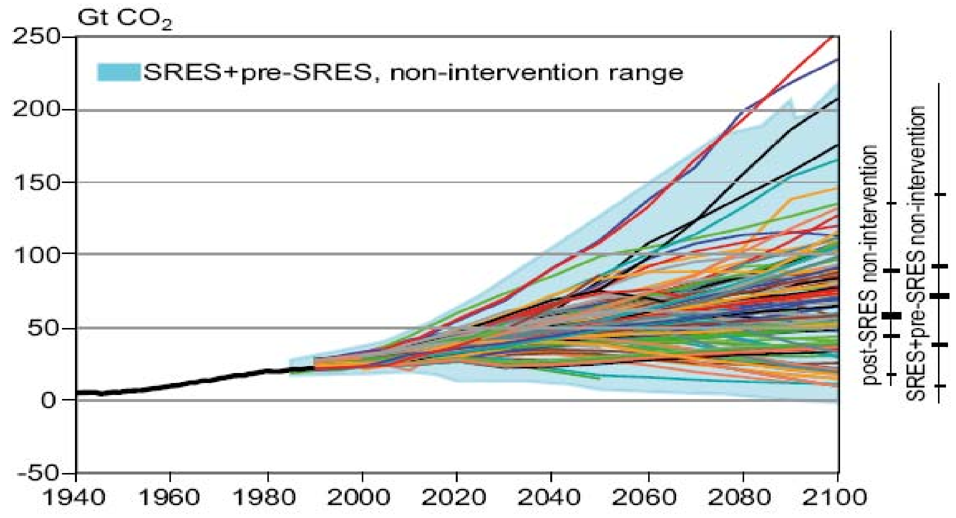


Figure TS.7: *Comparison of the SRES and pre-SRES energy-related and industrial CO_2 emission scenarios in the literature with the post-SRES scenarios [Figure 3.8].*

Note: Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios and indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions by 2100.

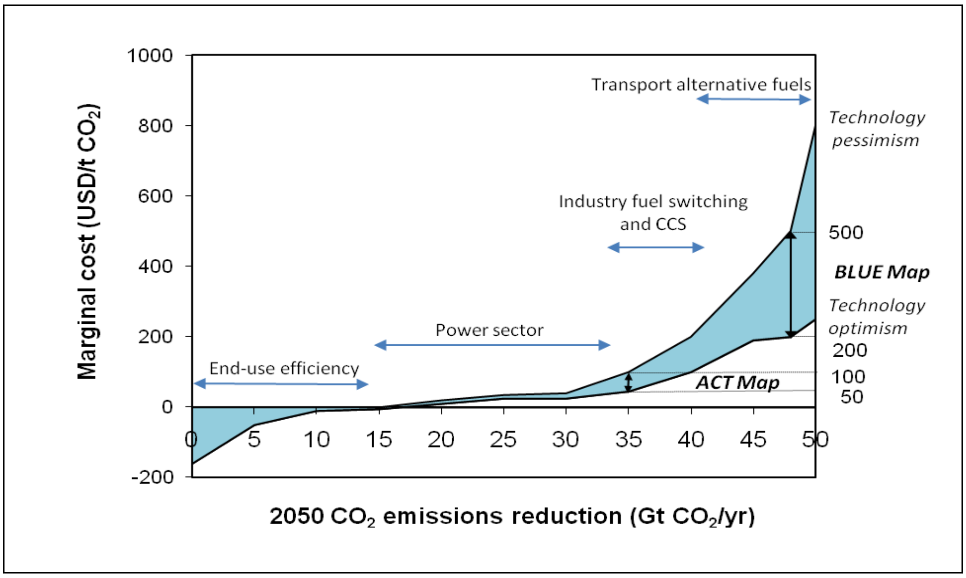
6.4 Abatement cost functions

In constructing the abatement cost function, our main assumption was that abatement costs would rise relatively rapidly with the amount of abatement undertaken in a short period of time – while they could possibly diminish over time. Hence, the first choice was to decide on the length of these periods. They could be seen either as “commitment periods”, or more appropriately, as the time lag between the setting of an objective and the end of the period in which this objective must be achieved. The Kyoto Protocol has an initial five-year commitment period – and a fifteen-year time lag between its adoption at Kyoto and the end of its first period (although one would only count seven years and ten months from its entry into force). In any case, the long time lag between Kyoto and the end of the first period may remain an exception. Meanwhile, many have suggested that longer time periods would be more effective (Buchner, 2007). Hence, we took ten-year periods in round figures, starting 1st January 2011.

6.5 Marginal abatement curve for 2041-2050

Our guide in shaping the abatement cost function was the abatement cost curve proposed in the *Energy Technology Perspectives 2008* (the most recent and accurate global study on abatement technologies) for emission reductions below baseline by 2050, as represented – with its uncertainty range – in Figure 6.3. This figure is a greatly simplified schematic representation. The curve, consisting of hundreds of options conveys two important messages. First, costs are relatively flat up to the ACT Map scenario objective to stabilise emissions at 2005 levels in 2050. But they rise quickly as the additional emissions reduction technologies implicit in the BLUE Map scenario are required. Second, although there is a high degree of uncertainty about the cost of the cheapest reduction measures, they are clearly negative. There is less uncertainty about the cost of technologies needed to achieve the ACT Map target. But costs become more uncertain again as the measures needed to achieve the BLUE Map scenario emission reduction objectives come into play. Nonetheless, *ETP 2008* makes clear that on the right-hand side of the picture mostly representing abatement in the transport sector, “the lower end of the range of [marginal costs] has a much higher likelihood than the upper end”.

Figure 6.3: ETP 2008 Abatement Cost Curve by 2050



How would costs evolve over time? Endogenous technical changes due to learning and increased R&D efforts responding to carbon prices and emission reduction policies tend to reduce long-term costs. But these cost reductions from technical progress might be counteracted by resource exhaustion. Contrary to common belief, exhaustion also applies to renewable energy sources, when good sites get more scarce or remote, or when the proportion of intermittent sources in electric generation makes it hardly manageable.

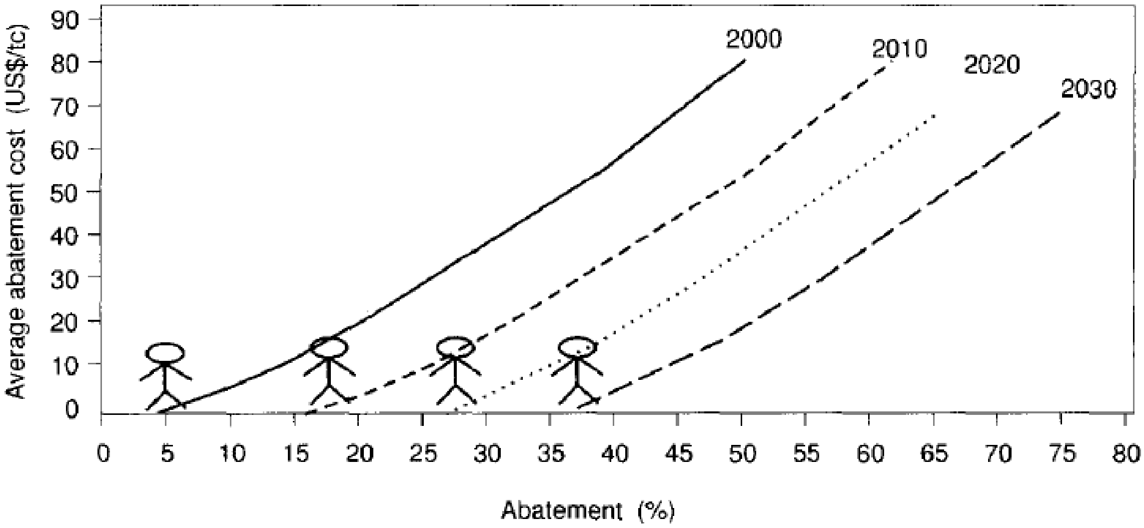
We needed to take into account the counter-balancing of these effects and introduce them into the ACTC model. The simplest method was to pile up our emission reductions from one period to another. In other words, in period *n* we took the business-as-usual trend and deducted the emissions that had been abated in period *n*-1. Thus we made sure to take full account of the long-lasting effects of the previous investments made to reduce emissions. Moreover, we applied the very same function to the next period.

This may be questioned. Is it realistic to consider that the first tonne to be reduced in a new period – say, January the 1st, 2021 – could cost much less than the last tonne to be reduced in the former period – say, 31st December, 2020? The answer is clearly yes – as the question is not properly framed. What matters is not so much time as the amount of emission reductions in a given period of time. The “last” reduction in one period is the more expensive, not necessarily the latest. New technical improvements and new opportunities arising from the optimal rotation of capital stock provide in all periods large potential for cheap reductions. The simplest way to mimic this is to re-start our cost function at the beginning of each “period”, following somehow the scheme suggested on Figure 6.4, which describes how R&D and learning processes constantly recreate cheap abatement opportunities (after Grubb, 1997). This is exactly what we endeavoured to reproduce.

We then had to derive abatement cost curves for our four ten-year periods to 2050 from this bulk of information. Indeed, instead of considering the wide difference between emissions in, say, the period 2041-2050 with a theoretical business-as-usual baseline, as if nothing will happen between now and 2041, we added emission reductions from one period to another.

To do this we multiplied quantities by 10, but we cannot expect that all cheap cost options – such as profitable energy savings – all come first in the first period, leaving only costlier reductions to the next. In particular, capital stock turnover and new technology developments would likely provide new cheap options in each period. Hence we could, for example, consider that the negative to rather low cost potential for a ten-year period would amount to a fourth of the total potential, or 37.5 Gt CO_2, *i.e.* 3.75 Gt CO_2 per year.

Figure 6.4: Technical improvements recreate cheap opportunities



Source: after Grubb, 1997. Reprinted from *Energy Policy* with the publisher's permission.

While this may be true in the last period, when business-as-usual emissions would be more than half that of today, should we keep such numbers for shorter term negative-to-no cost potential? Keeping that volume constant over the four periods is in fact assuming a decreasing availability (in proportion to unabated emission trends), as the low-hanging fruits get collected first. But other IEA estimates confirm these numbers. For example, the IEA in its Energy Efficiency Policy Recommendations in support of the G8 Plan of Action (IEA, 2008a) assumes a 8.2 Gt CO_2 amount of negative to no cost reduction, while our modelling would put the total over 20 years at 7.5 Gt CO_2 – seemingly not an overestimation.

Another interesting point of comparison here might be the Alternative Policy Scenario in the *World Energy Outlook 2006 (IEA, 2006).* Annual energy-related CO_2 emissions are reduced from baseline in this scenario by 6.3 Gt CO_2 per year by 2030. Energy end-users would have spent a cumulative amount of USD 2.4 trillion in energy savings but would save USD 8.1 trillion in their energy bills – an overall negative cost of USD 5.7 trillion.

Similarly, we could expect that in each cost range we will find a potential for a ten-year period that is 2.5 times the size of the potential indicated on the MAC per year suggested in *ETP 2008*. Hence, essentially, we first changed the scale of this graph so that the negative-to-zero (or very low) cost would correspond to a potential of 37.5 Gt CO_2 in 10 years, and the USD 200 to 500 range goes for 125 Gt CO_2.

As a result, the negative-to-zero (or very low) cost potential seen on the ETP MAC curve by 2050 can still be fully realised, provided that 25% is achieved in each of the four decades leading up to 2050. The same applies to each reduction potential corresponding to each MAC level on the curve.

When we selected optimal targets for the four decadal periods to 2050, however, we found that technical progress and discounting made the optimal abatement levels uneven between periods. The required total abatement of the last decade was pushed to about 160 Gt CO_2 depending on the exact parameters retained for the abatement cost function. As a consequence, the marginal cost in the last period would increase significantly and, while still in the range USD 200 to 500 it does not set a best guess value close to the lower end of the range, as it should according to *ETP 2008*. Hence, we modified the cost function for this period so as to make it conform more to the existing information – in practice we ended up, with a marginal cost of USD 253 (best guess) for a total emission reduction of 160 Gt CO_2 in the 2041-2050 period (as is shown below).

We wanted to approximate this curve with functions that would provide us with equations expressing the amount of abatement for a given marginal cost (in case of taxes or price caps) that are easily "solvable" algebraically – if possible. This is to avoid the complications of using the pure force of computers for heuristically seeking solutions while we are performing thousands of Monte Carlo simulations. Fortunately, some relatively simple functions provide an acceptable approximation.

We used a composite function in two segments. When abatement was less than 37.5 Gt CO_2 (over ten years) we used a biquadratic function, that is:

$$F(x) = -\ 2.5*10^{-6}*(x-37.5)^4-0.02*(x-37.5)^2+5$$

where x represents the amount of abatement in Gt CO_2.

When abatement was more than 37.5 Gt CO_2 we used another biquadratic function, that is:

$$F(x) = 0.9*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+5$$

This function yields the following values in Table 6.2 (in round numbers) for the indicated values of *x.*

The 112 Gt CO_2 abatement value is set to represent the effort of bringing emissions back to their 2005 level in the *ETP 2008* ACT scenario with a calculation derived from the adjustment made for the 2041-2050 curve (under best guess). The amount of yearly reductions that corresponds to the ACT scenario, or 35 Gt CO_2, was multiplied by 10 to get a decadal figure, then divided by four (because of four ten-year periods), then multiplied by 160/125 for adjustment. *ETP 2008* gives USD 50 for the most likely value of the marginal abatement costs by 2050 in the ACT scenario.

Table 6.2: Significant marginal abatement cost values for a 10-year period

x (Gt CO_2)	1	38	112	160
F(x) (USD)	-66	5	49	253

We introduced uncertainty on this 2041-2050 marginal abatement cost curve, calibrating a low and a high abatement cost functions for 160 Gt CO_2 over the 2041-2050 year-period so as to get the minima and maxima suggested by *ETP 2008* for 50 Gt CO_2 per year in 2050 – USD 200 and 500. This is rendered by the following functions:

- F_{high}:
  - If $x<37.5$, $f_{high}(x) = 5$;
  - If $x>37.5$, $f_{high}(x) = 2*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+5$
- F_{low}:
  - If $x<37.5$, $f_{low}(x) = -5*10^{-6}*(x-37.5)^4-0{,}04*(x-37.5)^2+5$;
  - If $x>37.5$, $f_{low}(x) = 0.64*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+5$

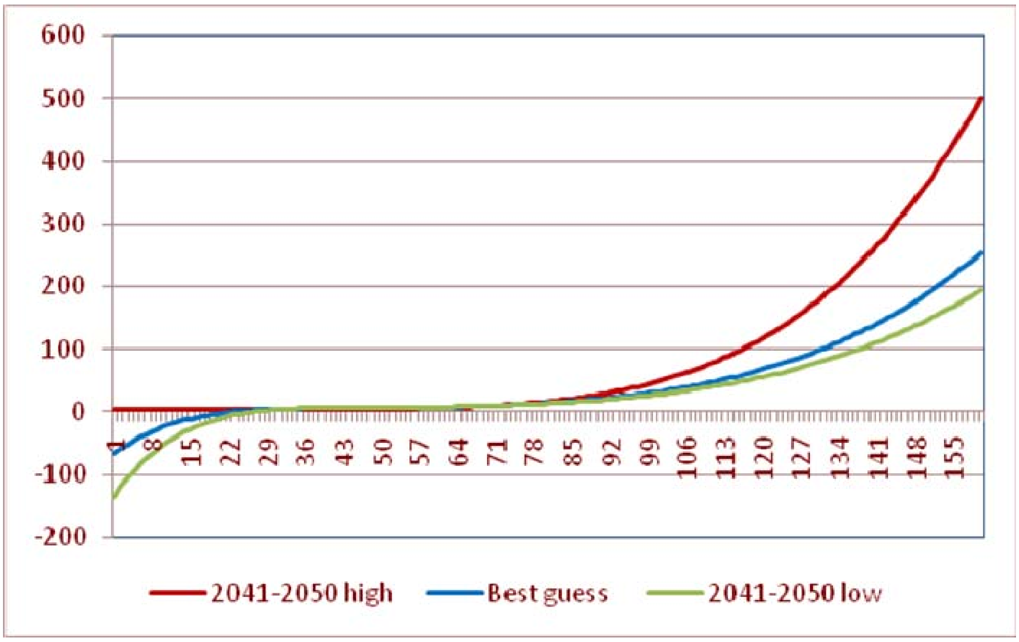
Using the same values for *x* as in Table 6.2, these low and high functions return the values shown in Table 6.3 (in round numbers) and are represented on Figure 6.5 by the red and green lines, respectively. The blue line represents the best guess marginal abatement cost curve, and is closer to the lower end of the uncertainty range than to its upper end, as suggested in ETP 2008.

The negative to very low cost potential varies from negative values to the value of USD 5, taking into account the possibility that negative or even zero costs were illusory. The horizontal axis was rescaled in comparison to Figure 6.3.

Table 6.3: Minimal and maximal MAC values 2041-2050

X (Gt CO_2)	1	38	112	160
$F_{high}(x)$ (USD) (red)	5	5	83	500
$F(x)$ (USD) (blue)	-66	5	49	253
$F_{low}(x)$ (USD) (green)	-137	5	41	195

Figure 6.5: Minimal and maximal MAC values 2041-2051



Uncertainty about abatement costs have been introduced in the model as “Pert” probability functions between the high and low MAC curves for the period 2041-2050. Pert functions are elaborated on Beta general functions but facilitate the specification of best guess values that are not necessary equal to the mean values. Proportionate uncertainty ranges have been introduced for previous and following periods.

6.6 Marginal abatement cost curves 2011-2020, 2021-2030, 2031-2040

While we can take this curve as a proxy for the MAC in the decade 2041-2050, we cannot assume that technical improvements only "re-create" low-cost options all along – indeed, this happens mostly due to capital stock turnover. What technical improvements are expected to do is to move down the costs of the expensive options – from carbon dioxide capture and storage to solar electricity to fuel cells for transport and the like. The cost curve at the end of the first half of this century is expected to result from intensive R&D efforts and learning-by-doing processes – and the whole ETP modelling effort is based on learning rates for all these technologies, *i.e.* rates at which costs are being reduced when cumulative production is doubled.

Hence, we could expect that if we were trying to factor in much of these technologies in today's energy mix, we would be confronted to much higher MAC. For example, in the BLUE scenario of *ETP 2008*, which would halve global energy-related CO_2 emissions by 2050, the cost of deploying carbon dioxide capture and storage (CCS) technologies or the costs of concentrating solar electricity are divided by four by comparison to current levels, the cost of photovoltaic (PV) modules by six, the cost of fuel cells for vehicles probably by even greater numbers. The costs of associated CO_2 emissions reductions are likely to be reduced by even greater factors in some cases. For example, when, or if the costs of grid-connected renewable energy technologies are sufficiently reduced to make them competitive, the cost of associated emission reductions becomes null or negative.

Hence we can make reasonable assumptions that our cost curve should be moved up for earlier periods. We used the following functions for abatement beyond 37.5 Gt CO_2 per decade:

Period 2041-2051: $F(x) = 0.9*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+5$

Period 2031-2040: $F(x) = 1.8*10^{-6}*(x-37.5)^4+0.0018*(x-37.5)^2+6$

Period 2021-2030: $F(x) = 3*10^{-6}*(x-37.5)^4+0.004*(x-37.5)^2+8$

Period 2011-2020: $F(x) = 5*10^{-6}*(x-37.5)^4+0.006*(x-37.5)^2+10$

The parameter choices for these MAC functions have been fine-tuned to fit the information available in the IPCC AR4, and in particular, the yearly abatement potential by 2030 at various cost levels seen in Figure 6.6.

At a cost of USD 20/t CO_2, the ACTC model indicates that 50 Gt CO_2 may be avoided from the first decade (2011-2020), and 54 Gt CO_2 from additional efforts during the second decade (2021-2030). As the effects of the abatement in the first decades are added to those of the second, the total potential during the period 2021-2030 amounts to 104 Gt CO_2, or, on average 10.4 Gt CO_2 per year. The IPCC AR4 (Contribution of Working Group III, p. 77) reports from bottom up studies an economic potential from 9 to 17 Gt CO_2-eq and from top-down studies 9 to 18 Gt CO_2-eq. Arguably, if abatement potentials are proportionate to emissions shares, as energy-related CO_2 emissions represent 56.6% of all GHG emissions,[4] these potentials would include abatement potential of energy-related CO_2 emissions of 5.1 to 10.2 Gt CO_2. It thus seems that the model errs a little on the high side of the abatement potential, *i.e.* the low side of marginal abatement costs.

At a cost of USD 50/t CO_2, the ACTC model indicates that roughly 62 and 69 Gt CO_2 may be avoided in the decades 2011-2020 and 2021-2030, respectively, *i.e.* a total of 131 Gt CO_2, or 13.1 Gt CO_2 per year. The IPCC gives 13 to 26 Gt CO_2-eq per year from bottom-up studies, 14 to 23 Gt CO_2-eq from top-down studies. This may represent energy-related CO_2 abatement potential of 7.8 to 15.6 Gt CO_2. Our model is close to the middle of those estimates.

Finally, at USD 100/t CO_2-eq, the ACTC model indicates abatement potential of 74 and 82 Gt CO_2 respectively, or a decadal total in the second period of 156 Gt CO_2, or 15.6 Gt CO_2 per year. The IPCC indicates abatement

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[4] IPCC AR4, Contribution of Working Group III, p.28.

potentials of 16 to 31 Gt CO_2-eq from bottom-up studies, 17-26 Gt CO_2-eq from top-down studies, likely to represent about 8.9 to 17.2 Gt energy-related CO_2 abatement potential, and again our model is well in the range, though on the upper side (of potential).

Figure 6.6: Global economic mitigation potential in 2030 from bottom-up studies (left) and top-down studies (right), as reported by the IPCC Fourth Assessment Report (2007)

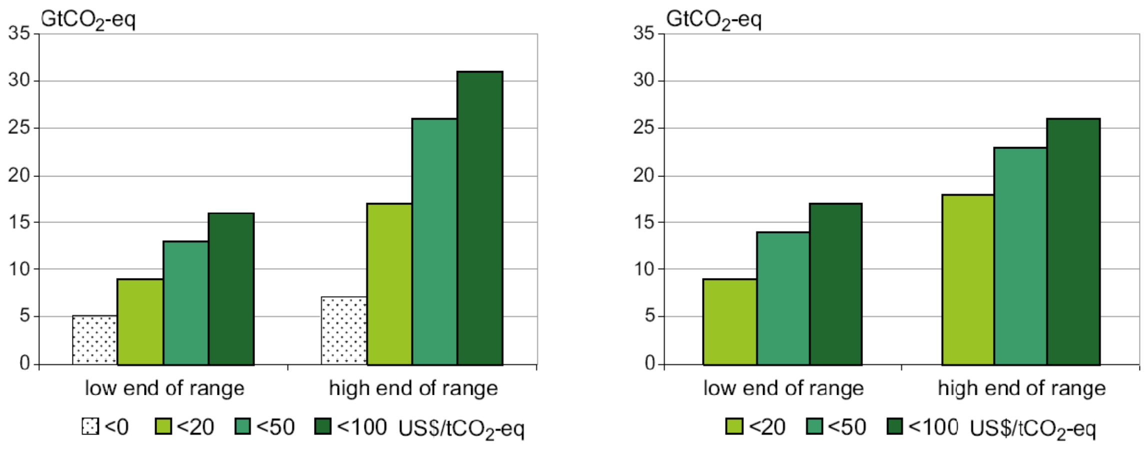
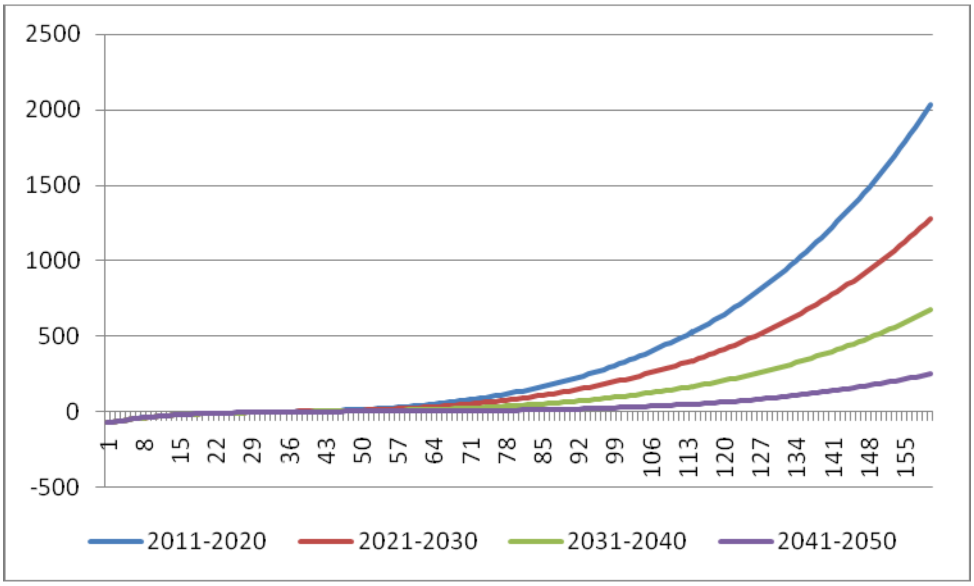


Figure TS.26A: *Global economic mitigation potential in 2030 estimated from bottom-up studies. Data from Table TS.15. [Figure 11.3].*

Figure TS.26B: *Global economic mitigation potential in 2030 estimated from top-down studies. Data from Table TS.16. [Figure 11.3].*

The various MAC curves (best guess values) for the next four ten-year periods are represented in Figure 6.7. The left-hand sides of the curves merge, as the function when abatement is less than 37.5 Gt CO_2 per decade is the same for all periods. On best-guess values, these MAC curves end up close to USD 680 for the 2031-2040 period, to USD 1 284 for the 2021-2030 period, and to USD 2026 for the 2011-2020 period. These values would be the marginal cost of abating 160 Gt CO_2 in ten years – which will only happen in the 2041-2050 period.

Figure 6.7: Marginal Abatement Cost curves for the four 10-year periods



We introduced uncertainty ranges and probability density functions for each of the other MAC curves. As for the period 2041-2050, whose functions are repeated below for the sake of immediate comparisons, the uncertainty range for other periods is skewed towards the high side, though to a lesser extent. The functions for decadal abatement quantities (*x*) over 37.5 Gt CO_2 are the following:

- **2011-2020:**
    - F_{low}: $= 4*10^{-6}*(x-37.5)^4+0.005*(x-37.5)^2+10$
    - F_{high}: $= 7*10^{-6}*(x-37.5)^4+0.0075*(x-37.5)^2+10$
- **2021-2030:**
    - F_{low}: $= 2*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+8$
    - F_{high}: $= 5*10^{-6}*(x-37.5)^4+0.006*(x-37.5)^2+8$
- **2031-2040:**
    - F_{low}: $1*10^{-6}*(x-37.5)^4+0.0015*(x-37.5)^2+6$
    - F_{high}: $3*10^{-6}*(x-37.5)^4+0.0025*(x-37.5)^2+6$
- **2041-2050:**
    - F_{low}: $= 0.64*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+5$
    - F_{high}: $= 2*10^{-6}*(x-37.5)^4+0.003*(x-37.5)^2+5$

6.7 Correlating uncertainties

Some combinations of scenarios are more likely to happen than others, however. For example, more rapid growth, while it pushes emissions up, also provides for a more rapid turnover of capital stock and thus more frequent opportunities to implement technical improvements, and eases the funding of research and development. Conversely, slower economic growth would slow down the turnover of capital stock and make the financing of research and development more difficult. To account for these, we introduced a relatively strong degree of negative correlation (-0.7, on a scale that could be from 0 to -1) between the uncertainty about economic growth and the uncertainty about marginal abatement costs – making it more likely that abatement costs would be low if growth were to be fast, and that abatement costs would be high if growth were to be slow. For simplicity, this correlation was only introduced for abatement with positive costs.

Introducing this correlation reduced the overall uncertainty (everything else being constant). Rapid growth increases baseline emissions and thus the amount of abatement, moving up the marginal cost curve, but this cost curve is less likely to be shaped by the highest coefficient. Conversely, slow growth reduces baseline emissions and thus keeps the amount of abatement close to the low beginning of the cost curve, but this is less likely to be shaped by the lowest coefficient. This should help avoid overestimating the possible benefits of introducing price caps.

6.8 Discounting

Discounting is one of the most disputed areas in the economic assessment of climate change.[5] The Stern report has been both praised and criticised for its use of a very low discount rate in assessing the costs of climate change. However, a growing body of literature, dating back to Krutilla (1967), Fisher and Krutilla (1974) and Boiteux (1976), points out that environmental assets which are not reproducible nor substitutable by the means of our industry should be given a value that grows over time at a rate close to the discount rate.[6] Thus, the Stern report may be “right for the wrong reasons”, and there would be no need to set an arbitrarily low discount rate to perform an acceptable assessment of climate change damage. Still, one must pick a value for some “ordinary” discount rate.

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[5] Discounting is the process of finding the present value of an amount of cash at some future date. It thus plays an important role in the economic assessment of climate change, given the long-term perspective implied.

[6] For a discussion, see Philibert, 2006b; for an assessment of the Stern report along these lines, see Sterner and Persson, 2007.

France revised its official discount rate in 2005, down from 8% to 4% as a basis for the first 30 years, then slowly declining to 2% until it reaches about 3% for 100-year horizons. The main argument for making the discount rate declines the uncertainty about long-term per capita economic growth. The report that led to that decision also pointed out that "*the discounting procedure must be understood as a whole that comprises the discount rate and a system of relative prices in which the price of the environment, in particular, grows significantly faster than other prices."* (Lebègue, 2005). The United Kingdom has come to relatively similar conclusions; its discount rate is 3.5% for the first 30 years, 3% for the next 40 years, 2.5% for the next 50 years, 2% for years 126 to 200, 1.5% for the following century, and then 1% forever.

However, these rates are for France or United Kingdom, two highly developed countries, and they may not apply to developing countries, where capital is scarcer and growth rates higher. For example, the Great Britain H.M. Treasury's (2003) "Green Book" makes clear that *"for international development assistance projects, a discount rate derived from estimates of the social time preference rate appropriate to the recipient economy should be used".* Not only has climate mitigation many aspects of an "international development assistance project", but the growth rate of the global economy is greater than that of industrialised countries alone.

Hence, we took 5% as an overall discount rate, which is consistent with *World Energy Outlook* analysis for the four decades from 2010 to 2050, and very close to the discount rates embodied in Nordhaus' Dice model (Nordhaus, 2007). Indeed, relatively small variations around this value would change some numbers, but not the insights provided by the ACTC Model.

In any case, the discounting issue has a relatively smaller importance in this study than in studies aiming at establishing the absolute level of (avoided) damage or policy benefits. As we are not trying to estimate the value of climate damage but focus instead on temperature changes to compare various policies, results are much less dependent on choices relative to discounting.

6.9 Total costs, price caps and floors

The ACTC model calculates total abatement costs for each period by integrating the marginal abatement cost function(s) and the net present values of abatement costs to 2050 and 2100, using the discount rate of 5% mentioned above.

Introducing price caps is relatively straightforward. Depending of the value taken by stochastic parameters during the simulation with respect to economic growth, carbon intensity and marginal abatement costs,, the model returns for actual abatement either the value of the target – if the marginal cost has not reached the level of the price cap – or the business-as-usual emission level, minus actual reductions in earlier periods, minus the level of abatement that corresponds to the level of the price cap.

Introducing price floors follows essentially the same process. It necessitates setting a minimum level that brings in the totality of the negative to low cost abatement potential. We set that level at USD 10, which is twice the postulated "low cost" level. If the marginal abatement cost is between the price floor and the price cap, the model returns the target value for actual emissions. If the marginal abatement cost is below the floor price, the model returns the business-as-usual emission level, minus the actual reductions in earlier periods, minus the level of abatement that corresponds to the level of the price floor.

6.10 Concentration levels and temperature changes

The ACTC model constantly adds 60% of the CO_2 emissions to the CO_2 content or the atmosphere. According to the IPCC AR4 (Contribution of Working Group I, Chapter 2, p.139) the apparent "airborne fraction", defined as the ratio of the annual increase in atmospheric CO_2 to the CO_2 emissions from annual fossil fuel and cement manufacture combined has averaged about 60% since the 1950s. This ratio may of course evolve over time, either decreasing if global emissions were to significantly decrease, or increasing as a result of some climate feedback – so that the sense of the forthcoming evolution can hardly be predicted. In any case, this simple relationship is sufficiently precise for the next 40 years and the purpose of this study.

The estimated equilibrium temperature change (relative to pre-industrial times) in the ACTC Model is directly derived from the probability density function of the equilibrium climate sensitivity provided by the IPCC AR4 (Contribution of Working Group I, Chapter 10, p. 798) – Figures 6.8 and 6.9. If C is the atmospheric CO_2 concentration (in ppm), s the climate sensitivity, 275 ppm the pre-industrial CO_2 concentration and ΔT the temperature change, the model computes as follows:

$$\Delta T = s * \frac{LOG(\frac{C}{275})}{LOG2}$$

Figure 6.8: Climate sensitivity in the ACTC Model

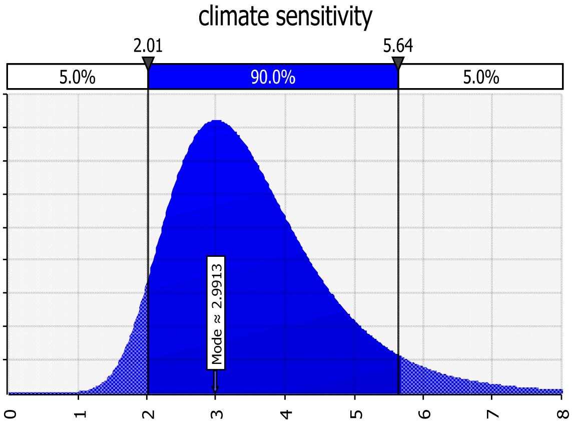
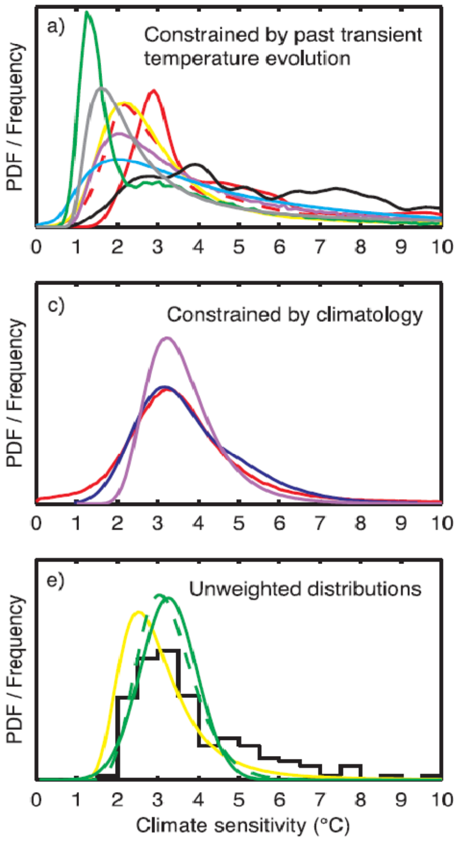


Figure 6.9: Equilibrium climate sensitivity in the IPCC AR4



The analysis focuses on the "warming committed by 2050", that is, the warming already in the "pipeline", the climate system at that time. Realised ("transient") warming at that time will be lower, as thermal inertia of the Ocean slows it. However, this committed warming takes no account of emissions subsequent to 2050. The warming committed by 2100 will likely be greater, but its computation would require not only estimating the emissions (and captures) of CO_2 from energy and industry, but also land use and land use change, which are beyond the scope of this study. Furthermore, the ultimate, very long-term warming may be even greater than the warming committed by 2100, as the equilibrium climate sensitivity provided by the IPCC AR4 does not include all "slow feedbacks"; for a discussion, see Hansen *et al*., 2008.

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