Les Cahiers du GERAD ISSN: 0711–2440

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G–2008–30

April 2008

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Abstract

The partial equilibrium technology rich global 15-region TIMES Integrated Assessment Model (TIAM) is used to assess climate policies in a very uncertain world. Stochastic optimizations are run with four possible climate sensitivities and two development rates, and full resolution of uncertainties in 2040. These assumptions are in line with those of the Energy Modeling Forum.

While a 3°C target – for both the peak and the long term equilibrium temperatures – is achievable at moderate cost, the smallest achievable temperature increase is close to 1.9°C, albeit at a very large cost. More severe temperature targets would require additional CO_2 abatement potential that is currently not yet seen as realistic.

The more detailed analysis of the optimal hedging strategy with a 2.5°C target reveals that hydroelectricity, sequestration by forests and CH_4/N_2O reduction are optimal early robust actions. However, nuclear plants and capture and storage of CO_2 do not belong to robust abatement strategies. Moreover, the uncertainty on the GDP growth rates has very little impact on robust decisions. Finally, no perfect forecast strategy is able to reproduce the hedging strategy, hence the relevance of using stochastic programming.

Sensitivity analyses are undertaken on: the date of resolution of uncertainties, the exogenous radiative forcing, the very long term emissions, the price elasticities of demands, and nuclear development.

Key Words: Energy modeling; Uncertainty; Hedging strategies; Stochastic programming; Climate policies; Technology.

Résumé

L’analyse stochastique des politiques climatiques mondiales est réalisée avec le modèle d’équilibre partiel *TIMES Integrated Assessment Model* (TIAM), tenant compte des incertitudes sur la sensibilité du climat (quatre valeurs possibles) et sur la croissance économique (deux trajectoires possibles), en accord avec les hypothèses proposés par le *Energy Modeling Forum*.

Le respect d’une augmentation maximale de la température de 3°C (température d’équilibre à long terme et pic maximal observé) est possible à coût modéré, tandis que l’augmentation minimale de température atteignable est de 1.9°C, selon les options de réduction disponibles dans le modèle.

L’hydroélectricité, la séquestration du CO_2 par les forêts et les options de réduction du CH_4/N_2O sont robustes, au contraire du recours aux centrales nucléaires et à la capture et séquestration du CO_2. Par ailleurs, les incertitudes sur la croissance économique présentent peu d’impact sur les décisions robustes. Finalement, aucune stratégie en contexte d’information parfaite ne réussit à reproduire la stratégie robuste, démontrant la pertinence de la programmation stochastique.

Des analyse de sensibilité sont effectuées sur : la date de résolution des incertitudes, le forçage radiatif exogène, les émissions à très long terme, l’élasticité des demandes, et les stratégies futures de développement de l’énergie nucléaire.

Acknowledgments: This work is the main contribution of the Energy Technology Systems Analysis Programme (ETSAP) to the EMF-22 program of research. ETSAP is the principal sponsor of the development of the TIMES Integrated Assessment Model (TIAM) used to conduct our analysis.

1 Introduction

Recent studies show that the range of global temperature increase caused by a doubling in CO_2 concentration relative to pre-industrial times. The range is now believed to extend from 1˚C to 9˚C. It is therefore more important than ever to take this large uncertainty into account when assessing climate stabilization strategies.

The partial equilibrium technological global 15-region TIAM (TIMES Integrated Assessment Model) is used to assess climate policies in a very uncertain world. When facing uncertainty, a good hedging strategy takes into account the possible outcomes, and strikes an optimal compromise between the negative effects of "guessing wrong" (Loulou and Kanudia, 1999). More particularly, the main objectives of this work are: a) to assess the impact of two major uncertainties on climate policies, i.e. the climate sensitivity and the future economic growth, and b) to analyze hedging strategies, i.e. a set of early robust actions capable of maintaining the global temperature within specified bounds, in spite of the uncertainty.

Robust actions are those actions chosen in the hedging strategy but not in the Base case. In fact, hedging is deemed relevant if decisions prior the resolution of uncertainty are different from those in the base case. Otherwise, "*wait and see*" is a good policy. Hedging is even more useful when it is not identical to *any* of the perfect forecast strategies, since such a situation clearly shows that the optimal technology and energy decisions are not easily predictable without an explicit treatment of uncertainty.

Sensitivity analyses were undertaken on: the date of resolution of uncertainties (helps reduce the expected surplus loss), the exogenous radiative forcing, the very long term emission profile, the price elasticities of demands, and decisions taken about the amplitude of development of nuclear power plants.

Among the results obtained, the fact that no perfect forecast is able to reproduce the hedging strategy confirms the relevance of using stochastic programming in order to analyze preferred climate policies in an uncertain world.

Section 2 contains a brief discussion of climate uncertainties. Section 3 describes the model and the methodology used to represent the uncertainties and to compute hedging strategies with stochastic programming. Sections 4 and 5 present results, including several sensitivity analyses, and Section 6 concludes the article.

2 Uncertainty and climate change

The impact of greenhouse gas (GHG) emissions on climate may be sketched as a chain of causal relationships, where GHG emissions provoke an increase in the concentration of GHG's in the atmosphere and in oceans; the increased concentrations provoke an increase of the atmospheric radiative forcing by the various gases, which in turn has an impact on the global temperature of the atmosphere and oceans. Nordhaus and Boyer (1999) proposed simple and well-documented linear recursive equations for calculating concentrations and temperature changes. The climate module to TIAM is based on these equations. The detailed dynamic equations used to represent these links are presented in Appendix A.

Two parameters of the climate equations are considered as highly uncertain: the climate sensitivity (C_s), defined as the equilibrium response of global surface temperature to a doubling of equivalent CO_2 concentration; and the inverse of the thermal capacity of the atmospheric layer and the upper oceans, also called "lag parameter", key determinant of transient temperature change. While C_s has received a great deal of attention, its value is still highly uncertain (Andronova and Schlesinger, 2001; Forest et al., 2002). Until recently, a range between 1.5oC and 4.5oC was commonly quoted (Houghton et al., 2001). More recent studies have strongly argued for a wider range of 0.5oC to 9oC or even 10 oC (Andronova and Schlesinger, 2001). Regarding the lag parameter, its value may either be considered approximately independent of C_s, or it may be assumed to vary inversely with C_s.[1] The latter case results in higher transient temperature increases than with a fixed value of the lag parameter (for example, in our results, we observed that, when using a fixed lag parameter, the smallest achievable temperature increase is 0.5°C higher that when assuming a variable lag value). In the main analyses presented here, we adopt the values adopted by the EMF-22 group[2] for the purpose of conducting comparative analyses of climate stabilization strategies with different models (Table 1). It is also assumed that the uncertainty on C_s and on the lag parameter will only be resolved in 2040, and that no significant additional knowledge will be obtained before the resolution date.

Table 1: Uncertain values of the climate sensitivity and the lag parameter

Climate Sensitivity	**Likelihood**	**Corresponding Lag Parameter**
1.5°C	0.25	0.065742
3°C	0.45	0.014614
5°C	0.15	0.010278
8°C	0.15	0.008863

Another potential source of uncertainty besides C_s is the annual rate at which the World economy develops, as this has a direct impact on economic demands and thus on GHG emissions. In this research, we also use the EMF-22 assumption that the base case annual rate is known until 2040. After that date, the annual growth rate is assumed to be revealed and may have one of two equally probable values: a high value (equal to 4/3 of the base case rate), and a Low value (equal to 2/3 of the base case rate). The same simple-to-double growth rate assumption is used for the GDP growth rate of each region of the TIAM. It affects the growth rate of each energy service demand having GDP as a driver (see Appendix B). World GDP starts from 32 trillion \$ in 2000 and reaches 260 trillion \$ (Base), 181 trillion \$ (Low) or 385 trillion \$ (High) in 2100.

2040 corresponds to the beginning of the period 2040–2060 of the TIMES model. This period is called "2050" in results provided by TIMES. Therefore, all the results presented for years 2050 and after correspond to the part of the event tree after uncertainty is resolved, while results presented for years 2030 and before correspond to the part of the event tree before uncertainty is resolved.

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[1] By linking C_s and σ_1, Yohe et al. (2004) assume a deterministic relationship between the two parameters. Fussel (2006) criticizes this relationship, since it results in values for the thermal capacity of the atmosphere and the upper oceans that are outside the physically plausible range. Moreover, the probabilistic relationship underestimates the true uncertainty about the transient climate response.

[2] The Energy Modelling Forum is an international forum on energy and environmental markets. The EMF-22 ongoing study, "Climate Policy Scenarios for Stabilization and in Transition", focuses on comprehensive analyses of long-run climate stabilization policies under uncertainty as well as intermediate-term transition policies.

3 Methodology

3.1 The TIMES Integrated Assessment Model (TIAM)

TIAM (TIMES Integrated Assessment Model) is a detailed, technology-rich Global TIMES model. It is a multi-region partial equilibrium model of the energy systems of 15 regions covering the entire World. The 15 regional models are: Africa, Australia-New Zealand, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Mexico, Middle-East, Other Developing Asia, South Korea, United States, and Western Europe. In addition, the upstream and energy trade sectors in each country are split into OPEC/Non-OPEC. The regional modules are linked by trade variables of the main energy forms (coal, oil, gas) and of emission permits. Thus, impacts on trade (terms of trade) of environmental policies are taken into. TIAM's planning horizon extends from 2000 to 2100, divided into 7 periods of varying lengths, suitably chosen.

TIAM is a global instance of the TIMES model generator (Labriet et al., 2005; Kanudia et al., 2005; full documentation in www.etsap.org/documentation.asp.), where a bottom-up, detailed technological representation of each economic sector is combined with key linkages to the macroeconomy. TIMES has evolved from its MARKAL forebear (Fishbone and Abilock, 1981, Berger et al., 1992, Loulou and Lavigne, 1996), and has benefited from many improvements sponsored by ETSAP over the last 8 years.

In TIMES, an intertemporal dynamic partial equilibrium on energy markets is computed, where demands for *energy services* are exogenously specified (only in the reference case), and are sensitive to price changes via a set of own-price elasticities at each period. The equilibrium is driven by the maximization (via linear programming) of the total surplus (sum of producers and suppliers surpluses) which acts as a proxy for welfare in each region of the model. Although TIMES does not encompass all macroeconomic variables beyond the energy sector, accounting for price elasticity of demands captures a major element of feedback effects between the energy system and the economy. The maximization is subject to many constraints, such as: supply bounds (in the form of supply curves) for the primary resources, technical constraints governing the creation, operation, and abandonment of each technology, balance constraints for all energy forms and emissions, timing of investment payments and other cash flows, and the satisfaction of a set of demands for energy services in all sectors of the economy.

The construction of the base case demands for energy services is done via the global General Equilibrium model GEM-E3 (http://www.gem-e3.net/), which provides a set of coherent *drivers* for each region and for the World as a whole, such as population, households, GDP, sectors outputs, and technical progress. These drivers are then transformed into growth rates for each of the 42 demands for energy services, via the generic relationship:

$$demand\_rate = driver\_rate \times decoupling\_factor.$$

The decoupling factors account for phenomena such as saturation (factor is then less than 1) and suppressed markets (factor is then larger than 1), and are in part empirically based. Most demands have economic growth as their driver. Note also that the demands of TIAM are user-specified only for the reference scenario, and are subject to endogenous changes in every alternate scenario, in response to endogenously changing prices. Elasticities of demands to their own price range from 0 to -0.6, with a majority in the range -0.2 to -0.3.

TIAM comprises several thousand technologies in all sectors of the energy system (Figure 1). A technology may represent any process that produces, transforms, conveys, and/or consumes energy and/or emissions (and some materials). It is characterized by several technical and economic parameters and by emission coefficients for the three main GHG's: CO_2, CH_4, and N_2O. The model constructs a coherent image of the future energy system by choosing a mix of technologies to invest in and operate at each future period, with the objective of maximizing total surplus, while respecting the many constraints of the model. A complete description of TIAM's technological database is not possible within the limits of an article, but we wish to mention some options for GHG emission reductions available in the model: first, emission reductions may be done via the numerous fuel and technology switching options that are available in each sector, and via specific CH_4 and N_2O abatement options[3] (e.g. suppression and/or combustion of fugitive methane from landfills, thermal destruction of N_2O in the adipic acid industry, etc.). Also, CO_2 emissions may in some cases be captured and stored (CCS options) before their release into the atmosphere (e.g. CO_2 capture from the flue gas of fossil fueled power plants, from hydrogen production processes, and from oil extraction processes; storage in depleted oil fields, deep saline aquifers, deep oceans, etc.). Finally, atmospheric CO_2 may be partly absorbed and fixed by biological sinks such as forests; the model has six

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[3] Non-energy CH_4 and N_2O emissions are included in the model (e.g. CH_4 from landfills, manure, rice culture, etc.).

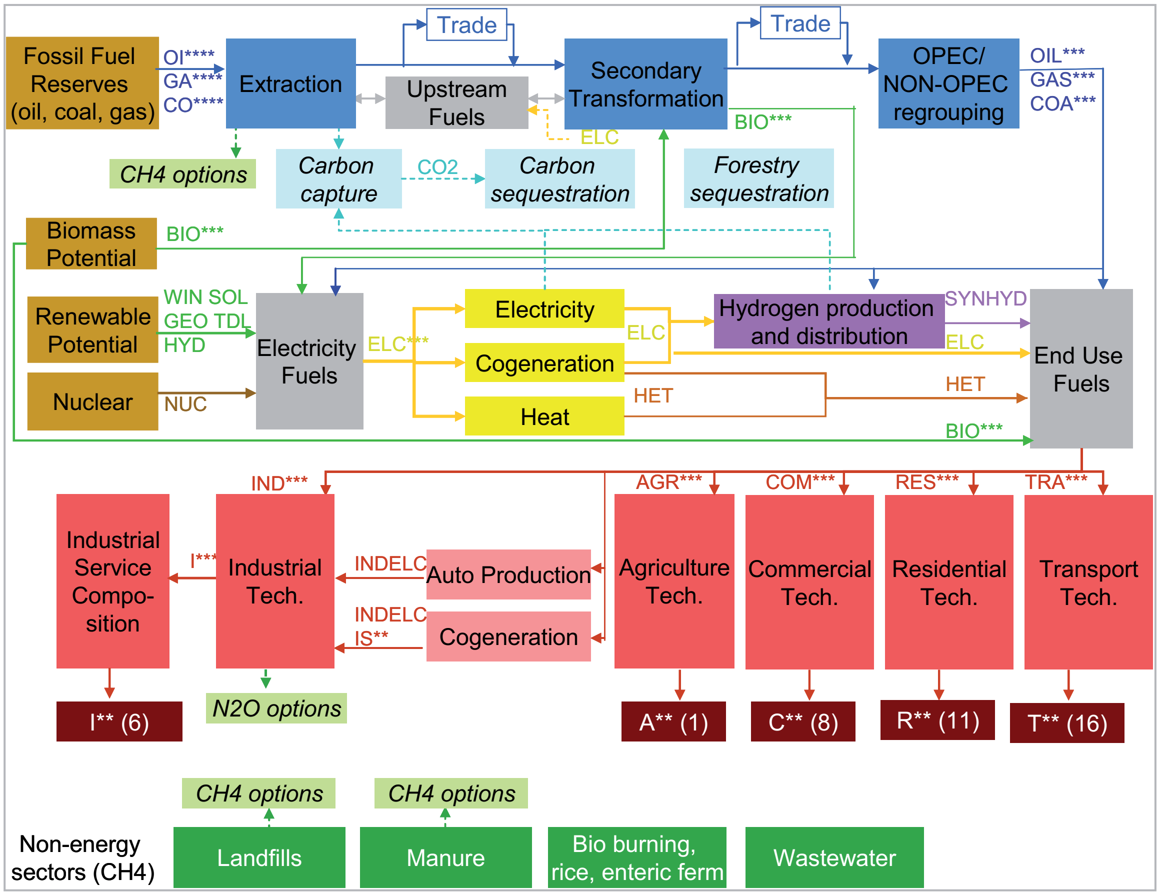

Figure 1: TIAM Reference Energy System

options for forestation and avoided deforestation, as described in Sathaye et al. (2005) and adopted by the EMF-22 group. Note also that methane emissions from the agriculture sector are fully accounted for, even if no abatement options are considered.

3.2 Using the Model

As noted before, climate equations from Nordhaus and Boyer (1999) have been integrated into the model. Following a commonly accepted approximation, TIAM uses these CO_2 equations also to calculate the impact of other gases (CH_4 and N_2O) on climate, using their Global Warming Potentials.

TIAM may be used to evaluate different kinds of climate targets: emission limits directly, concentration bounds, bounds on radiative forcing, and finally, limits on global temperature change. However, the non-convexity of the radiative forcing equation included in the climate module (equation 1) precludes using the temperature equations as regular constraints of the TIAM model. We explain in this subsection how to eschew this limitation.

$$\Delta F(t) = \gamma * \frac{ln(M_{atm}(t)/M_0)}{ln2} + FEX(t) \tag{1}$$

where:

- $\Delta F(t)$ is the increase of the radiative forcing at period t relative to pre-industrial level
- M_0 is the pre-industrial (circa 1750) reference atmospheric concentration of CO_2
- γ is the radiative forcing sensitivity to the doubling of atmospheric CO_2 concentration (4.1 W/m^2)
- $FEX(t)$ is the exogenous forcing component (W/m^2), due to anthropogenic GHG's not accounted for in the computation of CO_2 emissions.

We first note that, *at equilibrium* (assuming an equilibrium is reached), forcing and temperature change are linked by the very simple linear relationship, given by the climate equations:

$$\Delta T_{eq} = \Delta F_{eq}/\lambda \tag{2}$$

where

- ΔT_{eq} and ΔF_{eq} are respectively the temperature (°C) and forcing (W/m^2) increases at equilibrium (over some pre-existing equilibrium)
- $\lambda = \gamma/C_s$ with γ the radiative forcing resulting from a doubling of CO_2 concentration (4.1 W/m^2) and C_s the climate sensitivity parameter

Since ΔF_e is related to the change in atmospheric concentration M_e/M_0 via equation (1), it follows that the following direct relationship between ΔT_e and M_e/M_0, holds:

$$\Delta T_e = C_s \cdot \left(\frac{\log(M_e/M_0)}{\log 2} + \frac{FEX_e}{4.1} \right) \tag{3}$$

where FEX_e is the exogenous forcing not explicitly modeled (if any), at equilibrium.

Of course, since (3) is only valid at equilibrium (i.e. after a very long time, assuming an equilibrium climate is reached), it provides only an approximate method for setting the concentration target that achieves a desired temperature target. This is so for two reasons:

a) because the relationship is only true at equilibrium - whereas a concentration target may only be imposed within the 2100 planning horizon, and b) because the modeler may well want to impose a temperature limit not only at equilibrium, but *at all times*.

Our approach described below solves these two difficulties at once, via a mixture of (i) running the model over the 2000–2100 horizon, and (ii) simulating temperature change over the very long run (10000 years). The following algorithm describes the approach:

Step 1 (initialization): Starting from the desired temperature target T, calculate an equivalent concentration target M via (3);

Step 2 (model run): Use M as target in 2100, and run the model;

Step 3 (simulation): Observe the resulting temperature change not only within the 2100 horizon, but throughout a very long horizon, by using the dynamic climate equations (this is possible only if an assumption on emissions post-2100 is explicitly made; in this research, we assume that emissions after 2100 decline linearly to 0 over one century - years 2101 to 2200). **IF** the simulated temperature throughout the long term reaches but does not exceed T, **STOP**. **OTHERWISE,** adjust M accordingly (increase M if temperature stays below T at all times, decrease M if simulated temperature exceeds T at any time), and **GOTO Step 2**.

In practice, this approach was quite effective, and quickly converged in very few iterations in all cases.

3.3 The computation of hedging strategies

3.3.1 Stochastic programming

The treatment of uncertainty is done via Stochastic Linear Programming in extensive form (Dantzig, 1955; Wets, 1989). In this method, the model takes a single *hedging* route in the short term (before the resolution of uncertainty) so as to be best positioned to adapt to any of the possible long term futures (after resolution). In our application, the optimization is done on the *expected value*[4] of the total surplus. A typical stochastic LP is written as follows, in the simpler two-stage case where all uncertainties are resolved at a single date θ:

$$\textbf{Maximize} \sum_t \beta(t) \sum_{s=1 \text{ to } S} C(t,s) \cdot X(t,s) \cdot p(s) \tag{4}$$

Subject to:

$$A(t,s) \times X(t,s) \geq b(t,s) \tag{5}$$

and $X(t,1) = X(t,2) = \ldots = X(t,s)$, if $t <$ resolution date θ

where

- s represent the possible *states of the world* (sow), $s = 1, 2, \ldots, S$
- $p(s)$ is the probability that *sow* s realizes

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[4] Other optimizing criteria may be preferred, see Loulou and Kanudia (1999) for an application using the Minimax Regret criterion. Another approach is available in TIMES, in which the criterion to maximize is a combination of the expected surplus and of a risk term calculated as the semi-variance.

- C and b are respectively the surplus and the RHS vectors of the LP
- A is the matrix of LP coefficients
- $X(t, s)$ is the vector of decision variables at time t, under state-of-the-world s.
- $\beta(t)$ is the discounting factor that converts 1$ from time t to time 0.

Remark: It is exceedingly important to understand that the main interest of a hedging strategy resides in its description of *what to do prior to the resolution date* (in contrast, traditional deterministic scenario analysis computes multiple strategies even prior to the resolution date, leaving the decision maker in a quandary. Once uncertainty is resolved, the decision maker no longer faces uncertainty, and her decisions result from optimizing a deterministic problem from θ onward. Nevertheless, the computation of the hedging strategy must also take into account all possible outcomes *after* the resolution date. In other words, short term decisions are devised while taking the uncertain long term into consideration. This is the essence of decision under risk, and in particular of stochastic programming.

3.3.2 The two uncertain parameters

For a given temperature target, the uncertain parameters are,), as illustrated by Figure 2: i) the climate sensitivity C_s (four possible values), and ii) the vector of energy service demands resulting from the future economic growth (two possible values).

However, after conducting stochastic optimizations with the 8 sow's, it was observed that the impact of economic uncertainty on the hedging strategy before 2040 was negligible. In other words, the hedging decisions taken *before* 2040 are quite insensitive to the values of economic demands (and therefore the emission levels) *after* 2040 (there is no anticipation effect). This observed insensitivity of the hedging strategy to demands post 2040 may be due in part to the fact that the two demand levels have equal probability (and thus to some extent cancel out). Therefore, we decided to eliminate economic growth as an explicit uncertainty in our main runs reported in Section 4 (and to assess the impact of uncertain economic growth on the hedging strategy as one kind of sensitivity analysis in Section 5). The resulting event tree, with only C_s as the uncertain parameter, has 4 branches, as shown in Figure 3.[5]

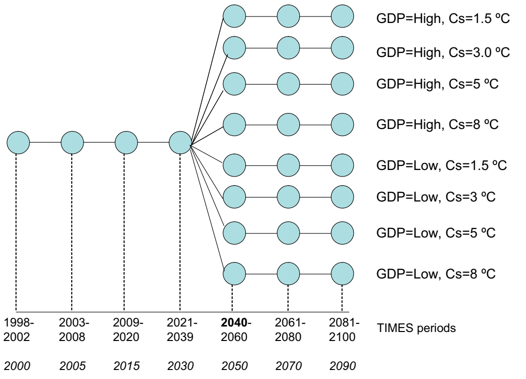

Figure 2: The event tree

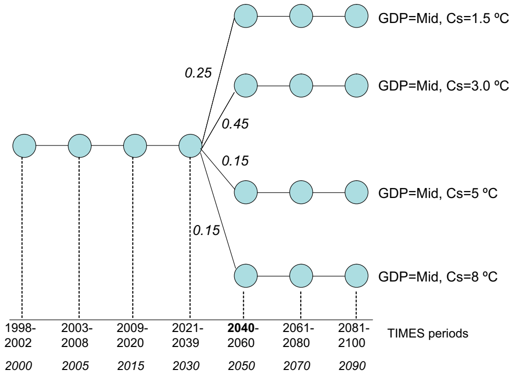

Figure 3: The reduced event tree

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[5] Reducing the number of sow's has a direct impact on the computational time to resolve the LP. Typical time for solving the 8 sow problem was 440 minutes versus only 80 minutes for the 4 sow problem.

4 Hedging Strategy and Perfect Forecast Strategies for the 2.5°C scenario

Our initial objective was to calculate hedging strategies for two alternative targets of temperature change: 2°C and 3°C. As it turned out, with the options present in the model, the 3°C target is achievable at very moderate cost, while the more severe 2°C target is achievable at very high cost. Therefore, only the intermediate 2.5°C scenario will be discussed in detail in this paper. Moreover, the model reveals that the smallest achievable temperature increase is close to 1.9°C, albeit at a very large cost, given the options for GHG control present in the model and the GPD trajectory. This means that more severe temperature targets would require additional CO_2 abatement potential that is currently not yet seen as realistic.[6] Figure 5 shows that the trajectory of CO_2-eq concentration must remain almost constant throughout the 21st century in order to keep global temperature change below the 1.9°C upper bound.

In addition to the hedging strategy, we also computed four (deterministic) perfect forecast strategies (noted PF), each assuming that the value of C_s is known as early as the first period. The theoretical interpretation of the four PF strategies is that of an optimal strategy if one assumes that the uncertainty is resolved at the beginning of the horizon. The PF's may be used to compute the Expected Value of Perfect Information (EVPI), which is the expected gain in welfare accrued if perfect information if available, i.e.:

$$EVPI = \sum_{s=1 \text{ to } S} p(s) \cdot \left[O_{PF(s)} - O_{HEDG}\right] \tag{6}$$

where

- $O_{PF(s)}$ is the surplus of the PFs strategy ($s = 1$ to S)
- O_{HEDG} is the expected surplus of the hedging strategy

Another finding of the research is that when C_s turns out to be 1.5°C, the Base case happens to satisfy the 2.5°C temperature constraint at all times, provided emissions after 2100 decline linearly to 0 by 2200 as assumed in Section 3.3. Therefore, the $\text{PF}_{C_s = \text{ } 1.5^\circ\text{C}}$ strategy is not different from the Base case, and no concentration target is required for the corresponding Hedging branch.

In the detailed analysis of results for 2.5°C, we compare the results of the hedging strategy with those of a Base case where no climate target is imposed, but we also compare them with those of the Perfect Forecast strategies defined above. The rationale for this comparison stems from the following important remark: Apart from its theoretical meaning as a perfect forecast strategy, any given PF strategy may be re-interpreted as a possible set of actions *until the resolution date*. After that date, decisions taken in the PF strategy are not realistic, since they ignore the fact that the value of C_s has indeed been revealed.

Therefore, we shall discuss PF results only before 2040.[7] One finding is that $\text{PF}_{C_s = \text{ } 5^\circ\text{C}}$ is the deterministic strategy that is closest to the optimal hedging one, although some significant

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[6] No abatement options are available for rice production, enteric fermentation and biomass burning, whose CH_4 emissions are included in the model. This contributes to the infeasibility of any target smaller than 1.9°C.

[7] With some additional effort, each PF strategy may also become a complete strategy as follows: freeze all PF decisions until 2040 at their observed values in the solution, and then re-optimize the system over periods post-2040 periods with each of the C_s values. In this way, each PF strategy gives birth to four post-2040 trajectories, which, taken together, constitute a bona fide complete strategy. This approach was not implemented in this research, but is illustrated Loulou and Kanudia (1999).

differences between $\mathrm{PF}_{C_s = 5^\circ\mathrm{C}}$ and hedging exist in some areas, as we shall see. Therefore, when comparing Hedging with deterministic strategies, we shall always use $\mathrm{PF}_{C_s = 5^\circ\mathrm{C}}$ (and then only before 2040).

4.1 Cost analysis

The overall *cost* of a strategy is the Net Present value of the loss of expected surplus relative to that of the base case. This provides a convenient indicator of the difficulty of reaching a particular target, and therefore a convenient way to compare various strategies. In addition to the NPV, we are interested in the marginal cost of one tonne of GHG.

4.1.1 Loss of surplus and expected value of perfect information

The overall net present value of the surplus attached to a climate strategy represents a compact measure of the social welfare associated with that strategy. Table 2 shows the expected loss of total surplus of the hedging strategy and of the perfect forecast strategy, relative to that of Base taken as reference. The loss of surplus when following Hedging is 35% higher than the expected loss for the perfect information strategy.[8] This difference represents the expected value of perfect information (210 B$ in NPV).

Table 2: Loss of surplus and expected value of perfect information

Strategy	**Loss of surplus** (NPV5% in B$)	**Probability**	**Expected loss** (NPV in B$ and annuity in B$/year)	**EVPI** (NPV in B$ and annuity in B$/year)
BASE	0	1	–	–
PF Cs=1.5°C	0	0.25	–	–
PF Cs=3°C	43	0.45	–	–
PF Cs=5°C	580	0.15	–	–
PF Cs=8°C	3353	0.15	–	–
Total PF			610 (31)	–
HEDGING	820		820 (41)	210 (11)

EPVI = Expected loss $_{\text{HEDGING}}$ – Expected loss $_{\text{PERFECT FORECAST}}$

4.1.2 Marginal cost of GHG

We first recall that the environmental constraint is defined in terms of global atmospheric CO_2-equivalent concentration. Thus, CO_2, CH_4 and N_2O have the same marginal cost in all regions and all sectors of the model.

Before 2040, the marginal cost of GHG in the hedging strategy remains low (Table 3). The analysis of preferred abatement options before 2040 shows that relatively inexpensive forestry measures contribute to this low price. The fact that no abatement option is available for methane from rice production, enteric fermentation and biomass burning, contributes to the observed high GHG price, and methane represents the most important GHG in the late horizon (up to more than 1200\$/tCO_2). We may conclude that none of the perfect forecast strategies is

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[8] The corresponding annuities represent less than 0.1% of the World GDP (33000 B$ in year 2000). However, the stream of expenditures would clearly be lower in early years and higher in later years. Furthermore, equity issues might dictate an uneven imputation of the overall cost among the regions.

able to provide a good approximation of the expected GHG price under uncertainty, although $\mathrm{PF}_{C_s = 5^\circ\mathrm{C}}$ is the closest to hedging in that respect.

Table 3: Marginal cost of GHG ($\$/\mathrm{tCO}_2$)

Year	2000	2005	2015	2030	2050	2070	2090
TIMES periods	*1998–2002*	*2003–2008*	*2009–2020*	*2021–2039*	*2040–2060*	*2061–2080*	*2081–2100*
HEDGING Cs=1.5°C	1	2	4	10	0	0	0
HEDGING Cs=3°C					0	2	3
HEDGING Cs=5°C					11	40	80
HEDGING Cs=8°C					176	620	1236
PF Cs=3°C	0	0	0	1	2	7	14
PF Cs=5°C	0	1	2	4	12	43	86
PF Cs=8°C	3	7	12	28	84	296	589

4.2 Global emissions and climate results

The base case GHG emission trajectory (Figure 4) as well as the atmospheric GHG concentration reached in 2090 (Figure 5) are fairly close to the B2 Emission Scenario proposed by the Intergovernmental Panel on Climate Change (Houghton et al., 2001; Nakicenovic, 2000). CO_2 remains the most important GHG (around 79%), followed by CH_4 (around 19%) and $\mathrm{N}_2\mathrm{O}$ (less than 2%).

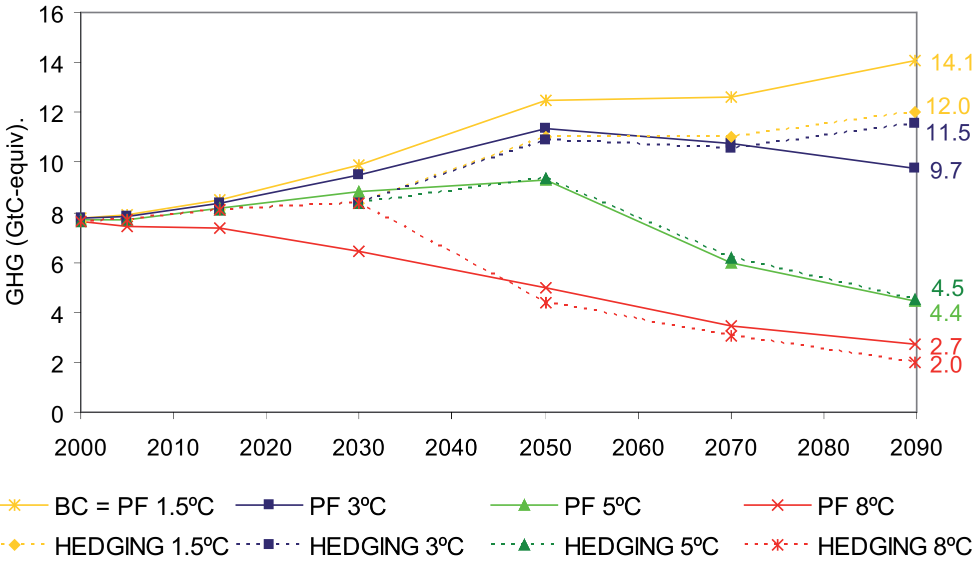


Figure 4: GHG emissions of hedging and perfect forecast strategies

As for sector emissions in the base case, the electricity and transportation sectors are the highest GHG contributors in 2000 (more than 40% of total GHGs), and the electricity and industry sectors become the highest contributors at the end of the horizon (more than 48% of total GHG). The situation is radically different under the 2.5°C temperature constraint, since both the electricity and industry sectors are able to reduce to almost zero (less than 3% of total GHG) their emissions in the most stringent branch, mainly thanks to CCS in the

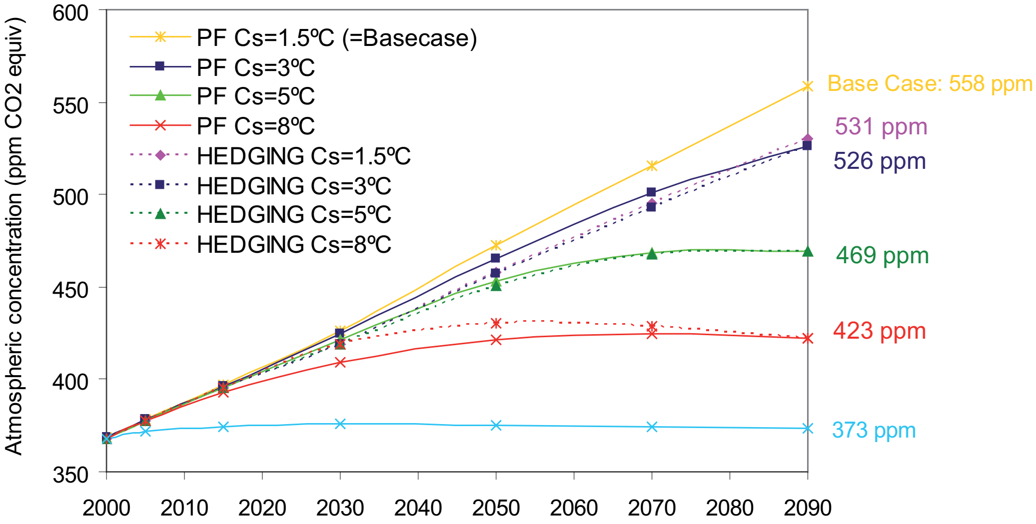


Figure 5: Atmospheric concentration (CO_2-equiv) under hedging and perfect forecast strategies

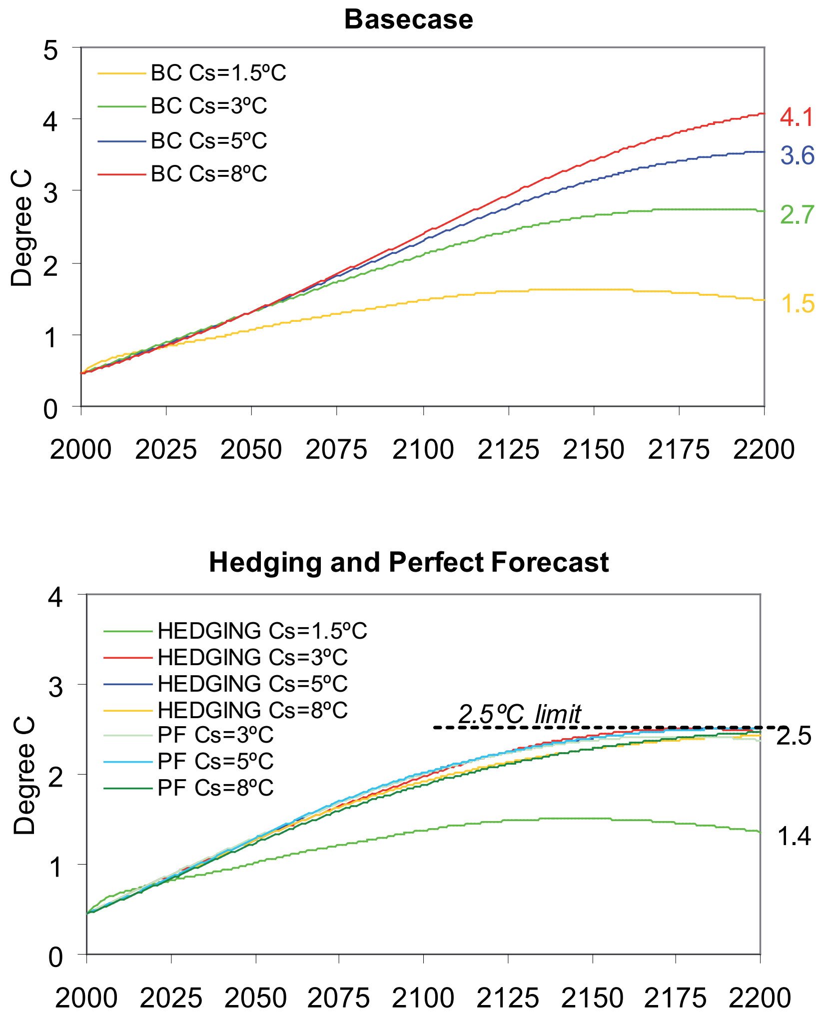
electricity sector, and switching to electricity in the industrial sector. In this most stringent branch, transport and agriculture are the highest remaining GHG contributors (30% and 41% of total GHG). No such drastic decrease of CH_4 emissions is possible because some non-energy agriculture-related sources have no abatement options in the model. Based on emissions, the $\mathrm{PF}_{C_s = \, 5^\circ\mathrm{C}}$ strategy is also the deterministic strategy that is closest to the optimal hedging strategy before 2040.

Atmospheric concentration obtained with the lowest value of C_s (Figure 5) is lower in Hedging than in Base although no target was imposed on this branch of the Hedging. This is because hedging actions taken pre-2040 push concentration downward. Again, $\mathrm{PF}_{C_s = \, 5^\circ\mathrm{C}}$ is the PF strategy that is closest to Hedging before 2040.

The increase of base case temperature varies from 1.4 to 2.4°C in 2090 depending on C_s (Figure 6). In all hedging branches, temperature peaks within the 22nd century, and then declines, so that the equilibrium temperature is always lower than the maximum observed temperature from 2000 to 2200, assuming emissions decline linearly to 0 from 2100 to 2200. This might not necessarily be the case for other temperature scenarios, or if a slower emission decline was assumed after 2100.

4.3 Preferred abatement options

The most important changes in primary energy production in the hedging strategy until 2030 concern the decrease of coal and the increase of hydro and gas (Figure 7), mainly explained by changes in the structure of electricity production (Section 4.5.2.). These trends as well as several other changes, such as the increase of nuclear and biomass, the decrease of oil (transportation), are more drastic after 2030, more particularly under the most stringent target. More detailed results are provided in the sectoral analysis below.

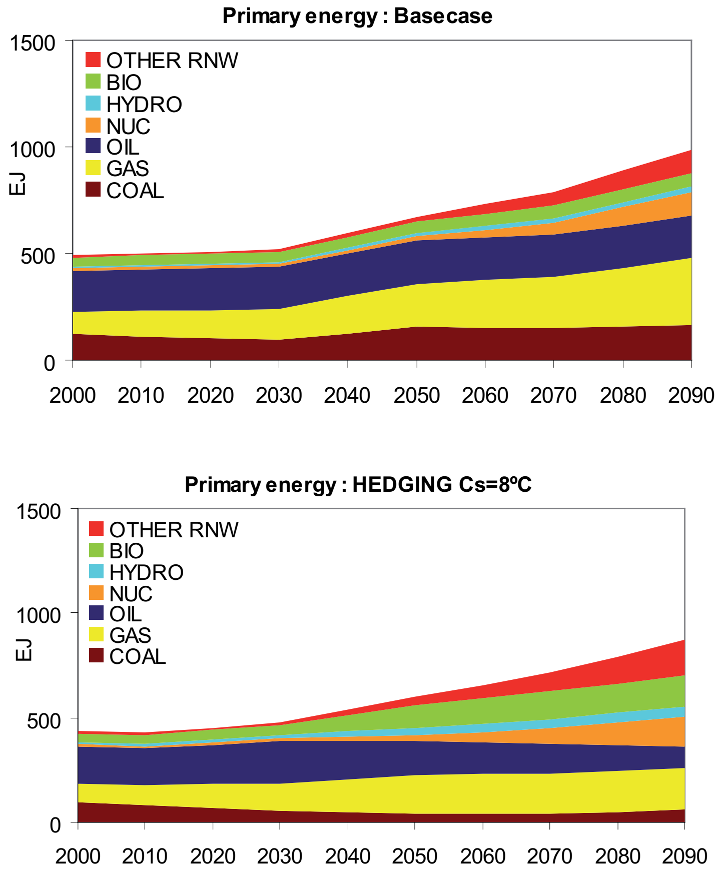


* Assuming emissions linearly decrease to 0 from 2100 to 2200

Figure 6: Temperature increase 2000-2200*

4.3.1 CO_2 sequestration

Sequestration by forests appears to be a very robust abatement option, since it penetrates in the hedging strategy as early as 2005 (Table 4) and uses its full potential, given its low cost. In fact, it plays a transitional role until less expensive energy options become available. As regards CCS options (with sequestration in deep oceans, saline aquifers, coal bed methane recovery, depleted oil and gas fields, enhanced oil recovery), they are much less robust, as they penetrate only slightly in 2030 in the hedging strategy, while they are used much earlier (in 2005) and at a higher level in $PF_{C_s=\,8^\circ C}$, and used only after 2040 in the other PF strategies. In other words, no perfect forecast strategy is able to reproduce the hedging strategy.



* Only the most stringent hedging branch is included. From 2050, other hedging branches lie between the Base case and the most stringent one. Recall that before 2050, all hedging branches are the same.

Figure 7: Primary energy supply in the base case and the hedging strategy*

4.3.2 Electricity sector

Electricity production is shown in Table 5. The first observation is that, as expected, electricity production up to 2030 takes a middle-of-the-road course up to 2030, compared to the PF strategies.

In the pre-2040 periods, we note significant differences in the Hedging and PF$_{C_s=\,5^\circ\mathrm{C}}$ strategies mainly in two categories: first, the PF strategy widely overestimates the amount of coal based electricity production (with CCS) compared to Hedging. In contrast, it underestimates the optimal amount of biomass fueled electricity and also the amount of hydroelectricity, compared to Hedging. For other types of electricity (from gas and nuclear), PF$_{C_s=\,5^\circ\mathrm{C}}$ production levels are quite close to the optimal hedging amounts over the entire pre-2040 period.

Table 4: Contribution of CCS and forestry to the total GHG reduction

Contribution of CCS to GHG (CO_2 equiv) reduction

Year	2005	2015	2030	2050	2070	2090
TIMES periods	2003–2008	2009–2020	2021–2039	2040–2060	2061–2080	2081–2100
HEDGING Cs=1.5°C	0.0%	0.0%	2.9%	0.0%	0.0%	0.0%
HEDGING Cs=3°C				0.0%	0.0%	0.0%
HEDGING Cs=5°C				1.0%	5.3%	10.8%
HEDGING Cs=8°C				17.0%	10.6%	10.7%
PF Cs=1.5°C	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
PF Cs=3°C	0.0%	0.0%	0.0%	0.0%	1.9%	3.7%
PF Cs=5°C	0.0%	0.0%	0.0%	1.1%	6.6%	10.9%
PF Cs=8°C	7.3%	3.7%	5.6%	17.7%	13.3%	11.9%

Contribution of forestry sequestration to GHG (CO_2 equiv) reduction

Year	2005	2015	2030	2050	2070	2090
TIMES periods	2003–2008	2009–2020	2021–2039	2040–2060	2061–2080	2081–2100
HEDGING Cs=1.5°C	35%	53%	29%	65%	99%	97%
HEDGING Cs=3°C				61%	85%	78%
HEDGING Cs=5°C				31%	27%	21%
HEDGING Cs=8°C				12%	18%	16%
PF Cs=1.5°C	0%	0%	0%	0%	0%	0%
PF Cs=3°C	85%	86%	77%	53%	61%	41%
PF Cs=5°C	44%	65%	43%	29%	26%	20%
PF Cs=8°C	25%	27%	16%	13%	19%	17%

Moreover, hydroelectricity (and, to a lesser extent, wind power too) and the shutdown of coal plants without CCS might qualify as hedging actions, since they appear before 2040. This is not the case of either power plants with CCS or nuclear plants.

In conclusion, the hedging strategy is significantly different from any of the PF strategies, which confirms the relevance of using stochastic programming.

4.3.3 End-use sectors

In *transportation*, Hedging stays close to the PF strategies and even to the Base case before 2040 (Figure 8). This is due to two causes: first, vehicles have a rather limited technical life, so that pre-2040 decisions do not have a lasting effect after resolution time. The other important cause of the observed insensitivity of this sector is that the CO_2 price signal is simply not strong enough before 2040 to warrant a large departure from traditional fuels. After resolution time, of course, the strategies do differ, and they do so in a fairly predictable way: the larger C_s values entail smaller market shares for RPP's and larger for alcohols and natural gas. Electricity keeps a very limited market share, and hydrogen (mainly produced by plants with CCS) makes a belated and small appearance in 2090 only in the most extreme branch of the Hedging).

The hedging strategy in *residential and commercial* buildings is characterized by very few energy changes compared to base case before 2040, and by an increase of electricity after 2040 (replacing natural gas and RPPs) in the most severe branches of the Hedging, mainly for space heating purposes.

In *industry*, differences between Hedging and Base case actions are slight before 2040. The exception being that N_2O abatement options in adipic and nitric acid industries penetrate as

Table 5: Electricity production (EJ/year)

Plant Type		2000	2005	2015	2030	2050	2070	2090
COAL FIRED	BASE, PF Cs=1.5ºC	18	17	17	15	28	22	24
	PF Cs=3ºC	18	17	17	15	25	18	15
	PF Cs=5ºC	17	17	17	9	5	3	8
	PF Cs=8ºC	16	17	11	0	12	12	14
	HEDGING Cs=1.5ºC	16	17	17	5	25	24	23
	HEDGING Cs=3ºC					25	21	20
	HEDGING Cs=5ºC					5	3	8
	HEDGING Cs=8ºC					14	10	12
OIL+GAS FIRED	BASE, PF Cs=1.5ºC	5	10	18	34	54	57	61
	PF Cs=3ºC	5	10	18	34	52	56	54
	PF Cs=5ºC	6	10	18	34	56	39	29
	PF Cs=8ºC	8	10	20	29	34	27	30
	HEDGING Cs=1.5ºC	7	10	18	36	51	58	61
	HEDGING Cs=3ºC					51	56	62
	HEDGING Cs=5ºC					59	38	29
	HEDGING Cs=8ºC					29	23	25
NUCLEAR	BASE, PF Cs=1.5ºC	9	8	10	11	20	59	109
	PF Cs=3ºC	9	8	10	11	20	59	109
	PF Cs=5ºC	9	8	10	11	20	73	128
	PF Cs=8ºC	9	8	10	13	28	74	136
	HEDGING Cs=1.5ºC	9	8	10	11	20	59	109
	HEDGING Cs=3ºC					20	59	109
	HEDGING Cs=5ºC					20	73	128
	HEDGING Cs=8ºC					28	74	138
HYDRO	BASE, PF Cs=1.5ºC	9	9	10	11	13	22	26
	PF Cs=3ºC	9	9	10	11	19	26	38
	PF Cs=5ºC	9	9	10	15	30	39	44
	PF Cs=8ºC	9	9	12	25	35	42	49
	HEDGING Cs=1.5ºC	9	9	10	17	19	19	27
	HEDGING Cs=3ºC					19	24	28
	HEDGING Cs=5ºC					28	39	44
	HEDGING Cs=8ºC					35	44	53
BIOMASS	BASE, PF Cs=1.5ºC	0	0	0	0	1	1	1
	PF Cs=3ºC	0	0	0	0	1	1	1
	PF Cs=5ºC	0	0	0	0	1	1	1
	PF Cs=8ºC	0	0	0	1	6	4	3
	HEDGING Cs=1.5ºC	0	0	0	0	1	1	1
	HEDGING Cs=3ºC					1	1	1
	HEDGING Cs=5ºC					1	1	1
	HEDGING Cs=8ºC					8	7	7
OTHER RENEWABLES	BASE, PF Cs=1.5ºC	0	0	0	0	1	1	1
	PF Cs=3ºC	0	0	0	0	1	1	1
	PF Cs=5ºC	0	0	0	0	1	1	2
	PF Cs=8ºC	0	0	0	1	1	3	7
	HEDGING Cs=1.5ºC	0	0	0	0	1	1	1
	HEDGING Cs=3ºC					1	1	1
	HEDGING Cs=5ºC					1	1	2
	HEDGING Cs=8ºC					3	7	22
TOTAL	BASE, PF Cs=1.5ºC	41	45	56	72	118	162	222
	PF Cs=3ºC	41	45	56	72	118	161	219
	PF Cs=5ºC	42	45	56	70	114	155	214
	PF Cs=8ºC	42	44	54	68	115	162	239
	HEDGING Cs=1.5ºC	42	45	56	70	117	162	222
	HEDGING Cs=3ºC					117	162	222
	HEDGING Cs=5ºC					114	155	214
	HEDGING Cs=8ºC					117	166	257

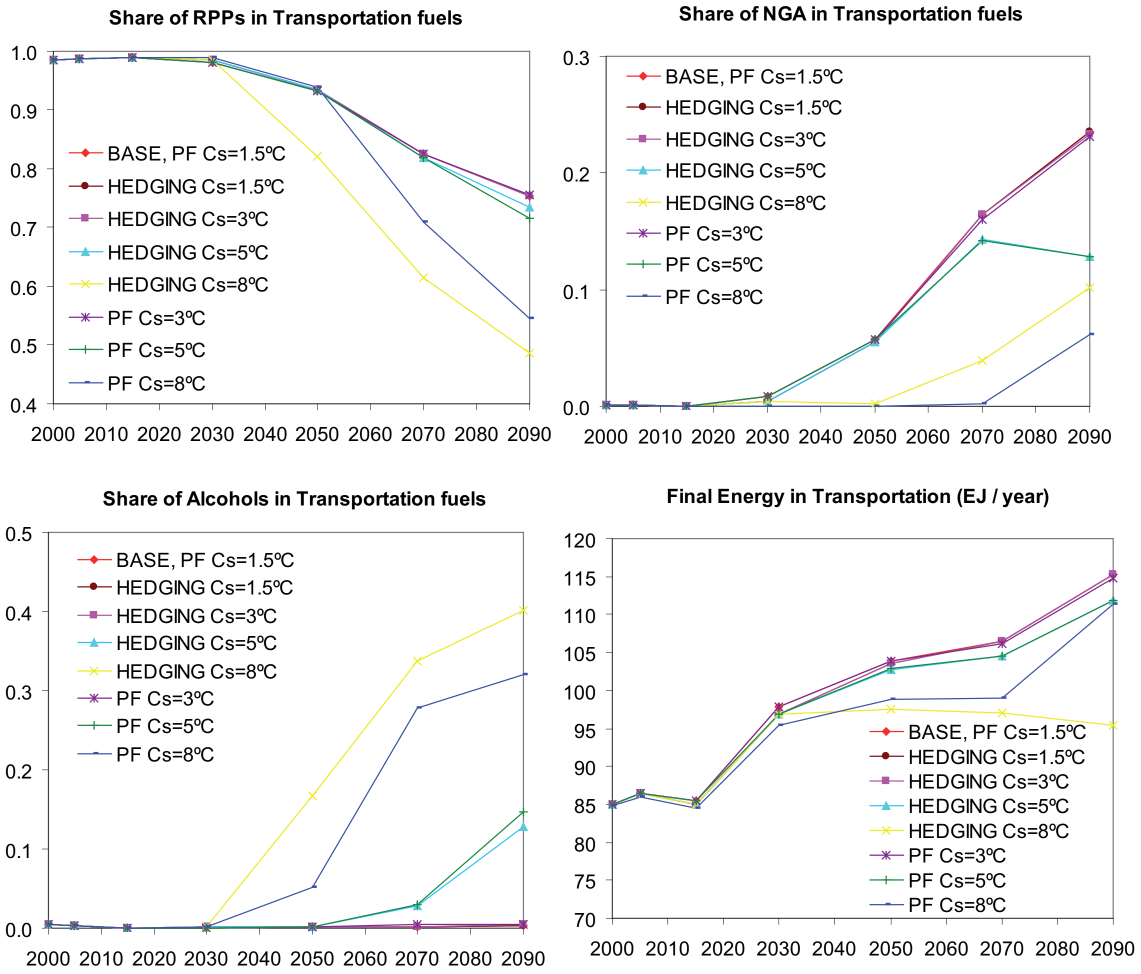


Figure 8: Evolution of transportation fuels

early as 2005 in the hedging strategy and thus are are robust decisions. After 2040, natural gas and, to a lesser extent, electricity, replace coal after 2040 in the most stringent branches of the hedging, mainly in chemical and other industry sub-sectors.

Demands are affected by the introduction of the climate target, since the rising GHG price induces a rise in demand prices, and thus a decrease in demand levels. Their reduction starts as soon as 2005, remaining small until 2030 and reaching up to 5% in buildings and 6% in industry in the longer term (Figure 9).

The reduction of *upstream* emissions until 2030 is the result of both changes in the primary energy structure driven by final energy changes (for example, CO_2 and CH_4 reduction in coal extraction), and of specific GHG abatement measures (for example, degasification and pipeline injection of CH_4 in coal sector, inspection and maintenance of gas distribution facilities, flaring instead of venting, etc.) In fact, a few CH_4 reduction options appear to be non-regret measures and penetrate even in the base case.

Finally, CH_4 capture options in *landfill* and, to a lesser extent, *manure* emission abatement measures also appear to be either non-regret or robust (penetration before 2040 in the hedging strategy). In fact, we observe that the relative CH_4 reduction is more important than the CO_2 reduction in the short term, due to the availability of these low-cost CH_4 capture options in upstream and landfills. This result is in line with the literature (e.g. Hyman et al., 2003).

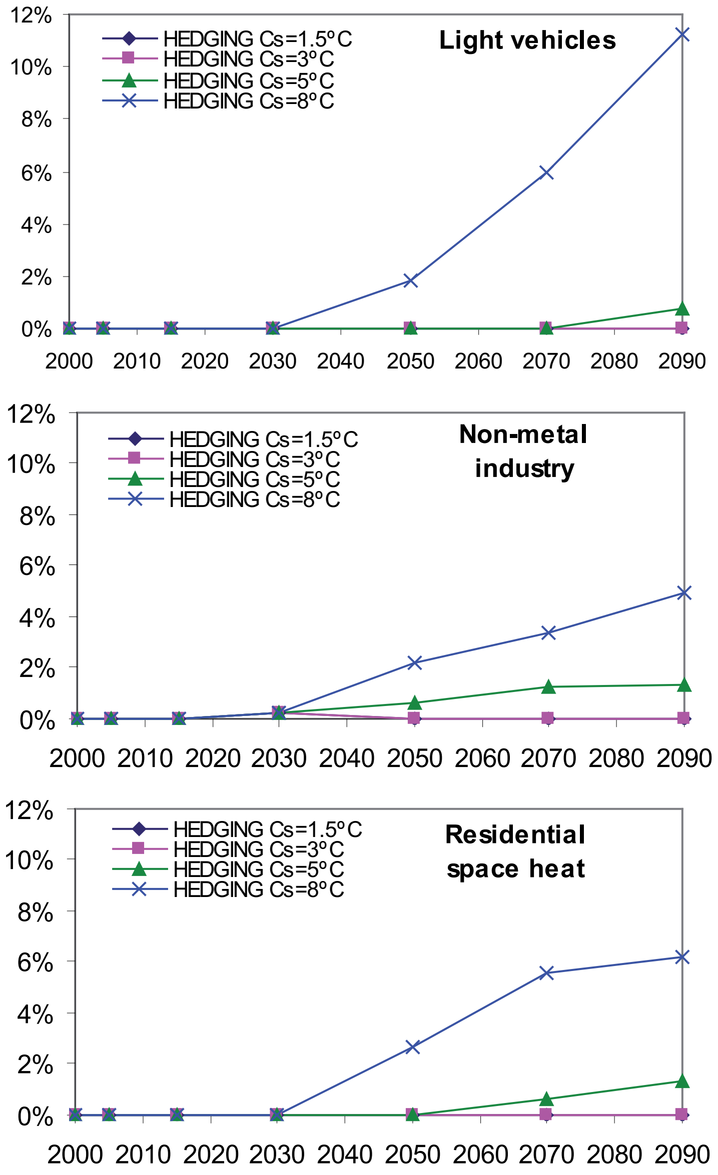


Figure 9: Example of demand reduction relative to base case

4.4 Super-hedging actions

A “super-hedging” action is an action that penetrates more in the hedging strategy than in any of the perfect forecast strategies. Such an action appears to be counter-intuitive, since it lies outside limits defined by the perfect forecast strategies, which confirms that stochastic analysis of future climate strategies may propose decisions that are beyond any combination of the deterministic strategies (Kanudia and Loulou, 1998).

Electricity production from renewables, fuel switches in industry (to biomass and gas), consumption of ethanol in several subsectors, consumption of geothermal in commercial buildings and biomass in residential buildings, and finally CH_4 abatement actions are all super-hedging actions.

5 Sensitivity analyses

Sensitivity analyses were undertaken on: the exogenous radiative forcing, the very long term emission profile, the date of resolution of uncertainties (helps reduce the expected surplus loss), decisions taken about the amplitude of development of nuclear power plants and the price elasticities of demands.

In our main experiment, the assumed value of *exogenous forcing* in the TIAM is 0.4 W/m^2 indefinitely. When the exogenous forcing value is allowed to vary within the range 0 to 0.8 W/m^2, the equilibrium temperature of the Hedging remains less than 2.5˚C across most of the range, reaching 2.8˚C for the highest value (0.8) of the exogenous forcing. The peak temperature also slightly exceeds the 2.5˚C target in this case. Although these temperature shifts are not negligible, they do not drastically depart from the temperature changes observed in the main hedging strategy.

Changing the assumption about the *post-2100 emission curve* (for instance extending the period of emission decrease to 200 years instead of 100 years), has of course no impact on the equilibrium temperature, but has an impact on the peak temperature (Table 6). However, this impact remains very small. This analysis is most reassuring, as it tends to confirm that emission policies beyond 2100 have a small impact on temperature increase, as long as a policy of eradicating all emissions is followed, irrespective of the speed of that eradication.

Table 6: Peak temperature increase for different post-2100 emission trajectories

	Emi 2200 = 0		Emi 2300 = 0	
Cs	Equilibrium temperature increase (˚C)	Peak temperature increase (˚C)	Equilibrium temperature increase (˚C)	Peak temperature increase (˚C)
1.5	0.5	1.5	0.5	1.6
3	1.0	2.5	1.1	2.7
5	1.4	2.5	1.5	2.6
8	2.0	2.5	2.1	2.5

Advancing the date at which the climate uncertainty is resolved to 2020 (instead of 2039) results in welfare savings of 159 B$, i.e. a full 3/4 of the EVPI. Such an analysis may provide a useful guide in deciding research expenditures in the climate change domain.

There may be societal and political reasons that may warrant limiting the degree of *penetration of nuclear power*. Therefore, we have undertaken sensitivity analyses on both the level of nuclear power in the base case and on the maximum allowed level of nuclear energy. In both cases, other reduction options (wind, solar, biomass etc.) penetrate to replace the nuclear loss, and the loss of surplus of the new hedging strategy is moderately increased. This confirms that nuclear does not qualify as a robust abatement option but also that the limitation of nuclear penetration does not seriously compromise the possibilities to satisfy a 2.5°C target at an “acceptable” cost.

Finally, if *demand elasticities* are set to 0, the expected loss of total surplus of the hedging strategy increases by almost 15%, and the marginal cost of GHG reduction is around 19% higher compared to the hedging strategy with elastic demands (higher electricity consumption, higher penetration of hydrogen and natural gas in the transportation sector, higher penetration of low emitting power plants etc.). Moreover, the reduction of emissions starts earlier, so that emissions are smaller before 2040 and higher in the long term compared to the hedging strategy with elastic demands.

6 Summary of conclusions

In this article, a new Integrated Assessment Model (TIAM) is used to conduct a long term analysis of climate stabilization strategies under high uncertainty of climate sensitivity C_s (in the range 1.5 to 8°C) and of economic growth (simple-to-double GDP growth rates from 2040). Both uncertainties are assumed to be resolved in 2040. The methodology relies on the computation of a hedging strategy based on the maximization under uncertainty (via Stochastic Programming) of total World surplus over the 21st century.

Amongst the most noticeable results, the model reveals that the smallest achievable temperature increase is close to 1.9°C, albeit at a very large cost, by a combination of energy switching, capture and storage of CO_2, CO_2 sequestration by forests and non-CO_2 emission reduction options. This means that more severe temperature targets would require additional GHG abatement potential that is currently not yet seen as realistic. Moreover, the impact of uncertainty of the climate sensitivity parameter C_s is major, requiring the implementation of early actions (before 2040) in order to reach the temperature target. In other words, the “wait and see” approach is not recommended. Robust abatement options include: substitution of coal power plants by hydroelectricity, sequestration by forests, CH_4 and N_2O reduction. Nuclear power plants, electricity production with CCS, and end-use fuel substitution do not belong to early actions. Among them, several options appear also to be super-hedging actions i.e. they penetrate more in the hedging strategy than in any of the perfect forecast strategies (e.g. hydroelectricity, CH_4 reduction), proving that stochastic analyze of future climate strategies might give insights that are beyond any combination of the deterministic strategies. In contrast, the uncertainty of the GDP growth rates has very little impact on pre-2040 decisions. This insensitivity is a pleasant surprise, as it shows that the hedging strategy for only one random parameter (C_s) is also a quasi-optimal strategy when the two types of uncertainty are present.

The comparison of hedging with perfect forecast strategies shows that a deterministic strategy with $C_s = 5$°C is closest to the hedging strategy. However, the two differ in several key aspects, and this confirms the relevance of using stochastic programming in order to analyze preferred climate policies in an uncertain world where the correct climate response is known only far into the future. In particular, the perfect forecast strategy provides a poor approximation of the optimal electricity production mix, of the price of carbon, and of the penetration of several sequestration options.

Amongst the sensitive parameters of the problem, resolving the uncertainties in 2020 rather than 2040 induces a 19% reduction in the loss of expected surplus, and keeping the same hedging strategy while assuming a doubling of the exogenous forcing has a non negligible (although moderate) raises global temperature by 0.3˚C.

Future work could aim at refining some technological options such as hydrogen, CO_2 capture and storage, and improved estimates of biomass potentials. Another possible improvement would consist in enhancing the TIAM model with feedbacks from climate to the economy. Examples of such feedbacks are: the decreased demand for space heating (and the increased demand for cooling) as global temperature increases, the impact of changing climate on hydro potentials, and the release of methane from permafrost as a result of temperature increase at higher latitudes.

Appendix A: Climate Equations in TIAM

Concentrations (accumulation of CO_2)

CO_2 accumulation is represented as the linear three-reservoir model below: the atmosphere, the quickly mixing upper ocean + biosphere, and the deep ocean. CO_2 flows in both directions between adjacent reservoirs. The 3-reservoir model is represented by the following 3 equations when the step of the recursion is equal to one year:

$$M_{atm}(y) = E(y-1) + (1-\varphi_{atm-up})M_{atm}(y-1) + \varphi_{up-atm}M_{up}(y-1) \tag{A1}$$

$$M_{up}(y) = (1-\varphi_{up-atm}-\varphi_{up-lo})M_{up}(y-1) + \varphi_{atm-up}M_{atm}(y-1) + \varphi_{lo-up}M_{lo}(y-1) \tag{A2}$$

$$M_{lo}(y) = (1-\varphi_{lo-up})M_{lo}(y-1) + \varphi_{up-lo}M_{up}(y-1) \tag{A3}$$

Where:

- $M_{atm}(y), M_{up}(y), M_{lo}(y)$: concentrations (masses) of CO_2 in the atmosphere, in a quicly mixing reservoir representing the upper level of the ocean and the biosphere, and in deep oceans (GtC), respectively, at period t (GtC)
- $E(y-1)$ = CO_2 emissions in previous year (GtC)
- φ_{ij}, transport rate from reservoir i to reservoir $j(i, j = atm,\ up,\ lo)$ from year $y-1$ to y

Radiative forcing

The relationship between CO_2 accumulation and increased radiative forcing, $\Delta F(t)$, is derived from empirical measurements and theoretical climate models.

$$\Delta F(T) - \gamma * \frac{ln(M_{atm}(t)/M_0)}{ln2} + FEX(t) \tag{A4}$$

Where:

- M_0 is the pre-industrial (circa 1750) reference atmospheric concentration of CO_2
- γ is the radiative forcing sensitivity to the doubling of atmospheric CO_2 concentration: $\gamma = 4.1$ W/m^2
- $FEX(t)$ is the exogenous forcing component, i.e. the increase in total radiative forcing at period t relative to pre-industrial level, due to anthropogenic GHG's not accounted for in the computation of CO_2 emissions. Units = W/m^2. In Nordhaus and Boyer (1999),

only emissions of CO_2 were explicitly modeled, and therefore $FEX(t)$ accounted for all other GHG's. In TIAM, the main GHG's (CH_4, N_2O) are fully converted into CO_2-equivalents, but some are not (e.g. CFC's, aerosols, ozone, black and organic carbon). In our experiments, we have used a constant exogenous forcing of 0.4 indefinitely into the future, following the indications of IPCC scenarios (Houghton et al., 2001, Table 6.14).

The parameterization of the forcing equation is not controversial and relies on the IPCC Second Assessment Report by Working Group I (1996). The major assumption made in RICE is also made here: a doubling of CO_2 concentrations leads to an increase in radiative forcing $\gamma = 4.1$ W/m^2. The IPCC Third Assessment Report by Working Group I (Houghton et al., 2001) provides a slightly smaller value of 3.7 W/m^2 (based on Table 6.2, Chapter 6).

Temperature increase

In the TIMES Climate Module as in many other integrated models, climate change is represented by the global mean surface temperature. The idea behind the two-reservoir model is that a higher radiative forcing warms the atmospheric layer, which then quickly warms the upper ocean. In this model, the atmosphere and upper ocean form a single layer, which slowly warms the second layer consisting of the deep ocean.

$$\Delta T_{up}(y) = \Delta T_{up}(y-1) + \sigma_1\{F(y) - \lambda \Delta T_{up}(y-1) - \sigma_2[\Delta T_{up}(y-1) - \Delta T_{low}(y-1)]\} \quad (A5)$$

$$\Delta T_{low}(y) = \Delta T_{low}(y-1) + \sigma_3[\Delta T_{up}(y-1) - \Delta T_{low}(y-1)] \quad (A6)$$

Where

- ΔT_{up} = globally averaged surface temperature increase above pre-industrial level,
- ΔT_{low} = deep-ocean temperature increase above pre-industrial level,
- σ_1 = 1-year speed of adjustment parameter for atmospheric temperature (also called lag parameter)
- σ_2 = coefficient of heat loss from atmosphere to deep oceans,
- σ_3 = 1-year coefficient of heat gain by deep oceans,
- λ = feedback parameter (climatic retroaction) ($\lambda = 4.1/C_s$, C_s being the temperature sensitivity to CO_2 concentration doubling).

Appendix B: Energy service demands in TIAM

DEMAND	**DRIVER**	
Transportation	**All regions**	
Automobile travel	GDP/capita	
Bus travel	POP	
2 & 3 wheelers	POP	
Rail passenger travel	POP	
Domestic aviation travel	GDP	
International Aviation travel	GDP	
Trucks	GDP	
Fret rail	GDP	
Domestic Navigation	GDP	
Bunkers	GDP	
Residential	**All regions after 2050 + Non-OECD before 2050**	**OECD regions before 2050**
Space heating	HOU	HOU
Space Cooling	HOU	GDPP
Water Heating	POP	POP
Lighting	GDPP	GDPP
Cooking	POP	POP
Refrigeration and Freezing	HOU	GDPP
Washers	HOU	GDPP
Dryers	HOU	GDPP
Dish washers	HOU	GDPP
Other appliances	GDPP	GDPP
Other	HOU	GDPP
Commercial	**All regions**	
Space heating	SPROD-Services	
Space Cooling	SPROD-Services	
Water Heating	SPROD-Services	
Lighting	SPROD-Services	
Cooking	SPROD-Services	
Refrigeration and Freezing	SPROD-Services	
Other electric demands	SPROD-Services	
Other	SPROD-Services	
Agriculture	SPROD-Agriculture	
Industry	**All regions**	
Iron and steel	SPROD-I	
Non ferrous metals	SPROD-I	
Chemicals	SPROD-I	
Pulp and paper	SPROD-O	
Non metal minerals	SPROD-O	
Other industries	SPROD-O	

HOU: households
POP: population
GDP: gross domestic product
GDPP: GDP per capita
SPROD-X: production of sector X related to GDP

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