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Climate policies as a hedge against the uncertainty on future oil supply
Supplementary Material

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This Supplementary Material is a complement to the Climatic Change Letter "Climate policies as a hedge against the uncertainty on future oil supply." It presents in a first Section the model IMACLIM-R that is used in the main text, with a full description of all modelling assumptions. Then, a second section describes the sensitivity analysis that is conducted, and the 8 parameter sets varied in the analysis. The third section presents results with more details than the main article, including in particular an analysis of variance to identify the main sources of uncertainty among the 8 parameter sets, and a regional analysis to highlight the distribution of Gross World Product (GWP) losses among the different regions. Finally, a last section proposes an estimation of the "risk premium," i.e. the economic value of the hedging that climate policies provide with respect to oil scarcity.

1 Modelling framework: the imaclim-r model

1.1 The IMACLIM-R model and the dialogue between economists and engineers

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy divided into 12 regions and 12 sectors (see table 1).

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(a) It is a hybrid model in the classical sense: its structure is designed to combine Bottom-Up information in a Top-Down consistent macroeconomic framework. Energy is explicitly represented in both money metric values and physical quantities so as to capture the specific role of energy sectors and their interaction with the rest of the economy. The existence of explicit physical variables (e.g. the efficiency of cars) allows indeed a rigorous incorporation of sector based information — coming from bottom-up models and experts' judgement[1] — about how final demand and technical systems are transformed by economic incentives. This dual vision of the economy is a precondition to guaranteeing that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and relative prices.

(b) It is hybrid in the sense of Solow (2000)[2] , i.e. it tries and bridges the gap between long-run and short-run macroeconomics, as efforts were devoted not only to model long-term mechanisms but also focus on transition and suboptimal pathways through possible underutilization of production factors. We seek, indeed, to capture the transition costs with a modeling architecture that allows for endogenous disequilibrium generated by the inertia in adapting to new economic conditions. This inertia arises from imperfect foresight and non flexible characteristics of equipment vintages available at each period (putty-clay technologies). In the short run, the main available flexibility lies in the rate of utilization of capacities, which may induce excess or shortage of production factors, unemployment and unequal profitability of capital across sectors.

Regions	Sectors
USA	Coal
Canada	Oil
Europe	Gas
OECD Pacific(JP,AU,NZ,KR)	Liquid fuels
Former Soviet Union	Electricity
China	Air Transports
India	Water Transports
Brazil	Other transports
Middle-East Countries	Construction
Africa	Agriculture
Rest of Asia	Energy-intensive industry
Rest of Latin America	Composite (services and light industry)

Table 1 Regional and sectoral disaggregation of the IMACLIM-R model

[1] Expert opinion includes *inter alia* data from Bottom-Up models such as POLES (LEPII-EPE, 2006), from the IEA (Fulton and Eads, 2004; IEA, 2008) and from private business experts on technological potentials.

[2] Solow (2000): "I can easily imagine that there is a "true" macrodynamics, valid at every time scale. But it is fearfully complicated[...]. At the five-to-ten-year time scale, we have to piece things together as best we can, and look for a hybrid model that will do the job."

Technically, the model can be labeled as "recursive dynamic", since it generates an energy-economy trajectory by solving successive yearly static equilibria of the economy, interlinked by dynamic modules.

(a) Within the static equilibrium, in each region, the demand for each good derives from households' consumption, government consumption, investment and intermediate uses from the production sectors. This demand can be provided either by domestic production or imports, and all goods and services are traded on world markets. Domestic and international markets for all goods — except factors such as capital and labour — are fully cleared by a unique set of relative prices that depend on the behaviours of representative agents on the demand and supply sides. The calculation of this equilibrium determines the following variables: relative prices, wages, labour, quantities of goods and services, value flows.

Within each yearly static equilibrium, producers are assumed to operate under short-run constraints of (i) a fixed maximal production capacity $Cap_{k,i}$ (for a good i in region k), defined as the maximum level of physical output achievable with the equipment built and accumulated previously, and (ii) fixed input-output coefficients representing that, with the current set of embodied techniques, producing one unit of a good i in region k requires fixed physical amounts $IC_{j,i,k}$ of intermediate goods j and $l_{k,i}$ of labour. In this context, the only margin of freedom of producers is to adjust the utilization rate $\frac{Q_{k,i}}{Cap_{k,i}}$ according to the relative market prices of inputs and output, taking into account increasing costs when the production capacities utilization rate approaches one. This represents a different paradigm from usual production specifications, since the "capital" factor is not always fully operated.

(b) Between two static equilibria, the dynamic modules shape the accumulation of capital and its technical content; they are driven by economic signals (such as prices and sectoral profitability) that emerge from former static equilibriums. They include the modelling of (i) the evolution of capital and energy equipment stock described in both vintage and physical units (such as number of cars, housing square meter, transportation infrastructure), (ii) the technological choices of economic agents described as discrete choices in explicit technology portfolios for key sectors such as electricity, transportation and alternative liquid fuels, or captured through reduced form of technology-rich bottom-up models, and (iii) endogenous technical change for energy technologies (with learning curves).
The dynamic modules therefore represent flexible technical choices, but they modify only at the margin the input-output coefficients and labour productivity embodied in existing equipment vintages that result from past technical choices. This general putty-clay assumption is critical to represent the inertia in technical systems, and allows to distinguish short-term rigidities and long-term flexbilities (Johansen, 1959).

Our model growth engine is composed of exogenous demographic trends (UN World Population Prospects, medium scenario, United Nations, 2005) and exogenous trends of labor productivity, as in Solow's neoclassical model of economic growth (Solow, 1956). To build these trends we draw on stylized facts from the literature, in particular the convergence assumption (Barro and Sala-i Martin, 1992) and two empirical analyses on economic convergence, one investigating the past trends by Maddison (1995), and the other one looking at future trends, by Martins et al (2005). We retained a "leader," the US, whose labor productivity growth trend lies between 2% today and 1.65% in the long run. The other regions labor productivity trends catch up with the leader's, i.e. their labor productivity growth is higher when their absolute labor productivity is farther from the leader's level.

The two sets of assumptions on demography and technical change, although exogenous, only prescribe potential growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labor and capital).

The next section describes the methodology we used to build prospective scenarios, carry out a sensitivity analysis and explore the key uncertainties. In the third section, we present our modeling choices for some critical dynamics modules that are relevant for the sensitivity analysis. For more details on these modeling choices, the reader should refer to Appendix A and Sassi et al (2010).

2 Scenarios: neither "best guess" nor arbitrary "storylines"

IMACLIM-R is able to produce long-term scenarios of the world economy evolution. But these scenarios are highly uncertain as they depend on unknown exogenous trends (e.g., future population) and parameter values that are debated or encompass poorly understood mechanisms (e.g., penetration of new technology through investment). To get a better understanding of this uncertainty, we computed a large number of scenarios from the combination of hypotheses on selected exogenous parameters. These hypotheses are derived from experts judgment and represent possible values for the parameters.

Decisions for large scale technological projects like the EV (Electric Vehicle), the nuclear power or the bioenergy have to be made in a context of radical uncertainty. The approach selected in this study tries and avoids both the traps of the "best guess" or "most likely" scenarios, which come to an illusory reduction of uncertainty and the symmetric trap of defining somewhat arbitrary "storylines" amongst the many possible ones. It aims in some way at giving a structure to uncertainty in order to disentangle the role of:

(a) exogenous uncertainty about critical parameters;

(b) regulatory uncertainty (such as the existence of climate policies);
(c) endogenous uncertainty created by the interplays between the parameters in the modeling structure.

The detailed representation of the dynamics that drives the energy system and the material content of the economic growth in the IMACLIM-R model allows us to describe in a consistent manner:

(a) the interplay between consumption styles (C), technological choices (T) and localization patterns (L) (Hourcade, 1993) that drive the mobility needs and global energy demand;
(b) critical technical uncertainty (e.g. carbon capture and sequestration (CCS) availability, ultimately recoverable fossil resources availability and accessibility).

At each level, uncertainty on different topics is translated into a wide set of uncertain parameters. For CCS for example, these parameters include the date of availability in each region, capital costs, technology learning rate, maximum socially and technically achievable market shares. These parameters take part in the calibration of the model and define the macro-energetic context in which the model run is performed. They must be distinguished from endogenous outputs that result from model runs. For example, the maximum possible share of CCS-equipped coal plants over the whole electric sector is a parameter, but the actual CCS equipment rate is an endogenous variable that is consistent with carbon prices, or electricity demand for example. To put it in another way, a scenario defined with optimistic parameters about the ultimate performance of a technology may result in a non penetration of this technology if the economic conditions of this penetration are not met.

One difficulty arises from the multiplicity of parameters; we identified hundreds of parameters on which a sensitivity analysis can be useful, and each parameter can take an infinite number of values. To avoid combinatorial explosion, the parameter domain has been simplified. First, the selected parameters are aggregated into a few consistent parameter sets. For instance, all parameters describing the future availability of oil and gas are aggregated into an "oil and gas markets" parameter set. Then, two or three sets of values (referred to as "Assumptions") are associated to each parameter set. For instance, the "oil and gas market" parameter set has three possible Assumptions of increasing scarcity for both oil and gas; each of these Assumptions consists of values for the parameters that compose this set.

Eventually, we distinguish seven parameters sets covering the major drivers of macro-energetic contexts as a combination of assumptions on natural resources, technology availabilities and international economic trends. These sets are described in details in Appendix A and are summarized here:

1 - Oil and gas markets (3 Assumptions): this set describes (i) the amount of ultimately recoverable resources[3]; (ii) the extend of Middle-East invest-

[3] conventional and non conventional oil

ment to postpone depletion at the oil field scale; (iii) the inertia in non conventional production development; and (iv) the indexation of gas prices on oil prices. In Assumption 1 all parameters are combined so that the resources are abundant and easily extracted, while in Assumption 3 oil and gas supplies are very constrained. In Assumption 2, most parameters are the same as in Assumption 3, except that investments to postpone the depletion phase are sustained.

2 - Middle-East strategy (2 Assumptions): in IMACLIM-R, the Middle-East is a "swing producer" (Rehrl and Friedrich, 2006) that benefits from market power and can adjust its production to manipulate the oil price over the short-run. In Assumption 1, Middle-East producers has a target price of 40$, versus 80$ in Assumption 2.

3 - Coal markets (2 Assumptions): this set describes the coal price growth sensitivity with respect to the coal production growth.

4 - Alternative liquid fuels supply (2 Assumptions): this set describes the ability of biofuels and coal-to-liquid (CTL) to penetrate the energy markets.

5 - Carbon free options for power generation (2 Assumptions): this set describes the ability of carbon-free technologies to penetrate the electricity-generation capacities. The three technologies involved are renewable electricity generators, carbon capture and sequestration (CCS) and nuclear plants.

6 - Energy end-uses technologies (2 Assumptions): this set describes the more and less rapid deployment of new technologies in the transportation and residential sectors.

7 - Development patterns (2 Assumptions): this set describes either a "mimetic" development pattern for developing countries, who want to catch up with the western lifestyle, or a less carbon-intensive one. We take into account infrastructure policies and the agents' preferences for automobile transport and vast individual dwelling.

All the possible combinations of the modalities in those variables lead to 3×2^6 (i.e. 192) contexts that we call baselines. In each of these baselines, we assess the effects of climate policies implementations:

8 - Implementation of climate policies (3 Assumptions): the model represents (i) a "Business As Usual" (BAU) world with no constraint on emissions, or (ii) two possibilities of "stabilization" worlds in which a carbon tax reduces emissions such that CO_2 concentration is stabilized at 450ppm in the long run. The two possibilities regard tax income recycling: this income is either entirely given back to households, or recycled based on a lump sum principle in which each sector receives back what they have paid, except for the power generation sector whose payoff is given to the consumer. As a consequence, there are twice as many scenarios in the stabilization case (450ppm) as in the BAU case.

Therefore, we introduce an eighth critical parameter set covering the existence of climate policies, which leads to 576 ($3^2 \times 2^6$) scenarios. In the next section, we detail the content of each parameters set.

3 Scenario variables and uncertain parameters

This section provides a detailed list of all uncertain parameters that we use in our sets. In Appendix A, we explicit the equations in which these parameters can be found, and shed some light on the underlying modeling principles.

Sets		Parameters	Assumption 1	Assumption 2	Assumption 3
Oil and gas markets	Oil	**Amount of ultimately recoverable resources (total conventional and non conventional)***	3.6 Tb	3.1 Tb	3.1Tb
		Inertia in the deployment of non conventionals (spread of the bell-shaped curve: see Equation 1)	no inertia (b=0.061)	inertia (b=0.041)	inertia (b=0.041)
		Maximum growth rate of Middle-East capacities	0.8Mbd/year	0.7Mbd/year	0.7Mbd/year
		Remaining resources before depletion starts	25%	25%	50%
	Gas	Indexation of gas price on oil price (see Equation 3)	Until 80$/bl	Always indexed	Always indexed

Sets		Parameters	Assumption 1	Assumption 2
OPEC behavior		Target oil price	40$/bl	80$/bl
Coal		Price growth elasticity to production decrease (see α_1 in Equation 5a)	1.5	1
		Price growth elasticity to production increase (see α_2 in Equation 5a)	1	4
		Production growth rate which cancels out price growth rate (see g_{lim} in Equation 5b)	2%	0,05%
Power generation decarbonization	Nuclear	**Maximum market shares [min - max]****	[5% - 40%]	[2.5% - 20%]
	Renewables	Maximum market share of renewables	25%	15%
		Learning rate for renewables investment costs (see Equation 6)	7%	3%
	Carbon capture and storage	CCS learning rate (see Equation 6)	13%	7%
		CCS start date (see Figure 5)	2010	2015
		CCS “bottleneck phase”	7 years	10 years
		CCS maximum market share at the end of the bottleneck phase	5%	3.5%
		CCS growth phase	8 years	8 years
		CCS maximum market share at the end of the growth phase	90%	63%
		CCS maturation phase	8 years	8 years
		CCS maximum market share at the end of the maturation phase	100%	70%
Low carbon end-use technologies	Electric vehicles	EV start (see Figure 5)	2010	No significant market penetration before 2050
		EV "bottleneck phase"	3 years	
		EV maximum market share at the end of the phase	2.5%	
		EV growth phase	15 years	
		EV maximum market share at the end of the phase	45%	
		EV maturation phase	16 years	
		EV maximum market share	50%	
	Industry	Capital lifetime in the industry	20 years	30 years
	Energy efficiency	Freight energy consumption (see μ_f in Equation 8)	Trend extracted from POLES data (LEPII-EPE, 2006): starts at 1 reaches 1.1 in 2030 and stays at 1.1 until 2050	1
		Freight fuel consumption elasticity to fuel prices (see ϵ in Equation 8)	-0.4	-0.35
		Buildings energy consumption per m^2* (see μ_h in Equation 9)	1	Trend which starts at 1, reaches 1.2 in 2030 and stays at 1.2 until 2050

The parameters in bold are multiple parameters.
(*): different parameters according to the region.
(**): different parameters according to the region and horizontal slice in the annual monotonous load curve (between base load and peak load).
(***): different parameters according to the region and category of oil.

			Assumption 1	Assumption 2
Alternative liquid fuel supply	**Biofuels**	Time scale of reactive anticipation for biofuels production	4 years	6 years
		Biofuels supply: multiplier coefficient of the supply curves (see Figure 6 for the default value)	50% increase w.r.t Assumption 2 value	Value from IEA curves
	Coal-to-liquids	Oil price threshold for CTL production start (see Equation 10)	120 $/bl	200 $/bl
		Time scale of reactive anticipation for CTL production	0	8 years
		Maximum production growth in 2030, 2035 and in 2050 (see p_{growth}^{CTL} in Equation 11)	0.20 Mbd - 1.5 Mbd - 3 Mbd	0.05 Mbd - 0.10 Mbd - 0.10 Mbd
Development patterns	**Transport**	**Motorization rate growth with GDP per capita*** (see λ in Equation 12)	Value from IEA data (Fulton and Eads, 2004)	50% increase w.r.t Assumption 1 value
	Buildings	Income elasticity of buildings stock growth (see μ_s^{ini} in Equation 13)	0.7	1
		Asymptote to surface per capita in China and India (see A in Equation 13)	40	60
		Start year and fuel price for a forced decline of oil consumption in this sector	2010 - 1000$/tep	2020 - 1300$/tep
	Industrial goods	**households industrial goods consumption saturation level [min-max]*** (multiplier factor of the calibration year consumption volume: see η in Equation 14)	[1-2]	[1.5-3]

The parameters in bold are multiple parameters.

(*): different parameters according to the region.

4 Results

As an illustration of our methodology, Figure 1 shows the 576 world oil production (right panel) and GWP curves (left panel) between 2001 and 2050 resulting from all scenarios, with different colors corresponding to the three possible “oil and gas market” set Assumption. This parameter set critically determines the shape of oil production, especially when the amount of recoverable resources is low, i.e. in Assumption 3 (delayed investment) or Assumption 2 (sustained investment). Other sets clearly play a secondary role in oil production.

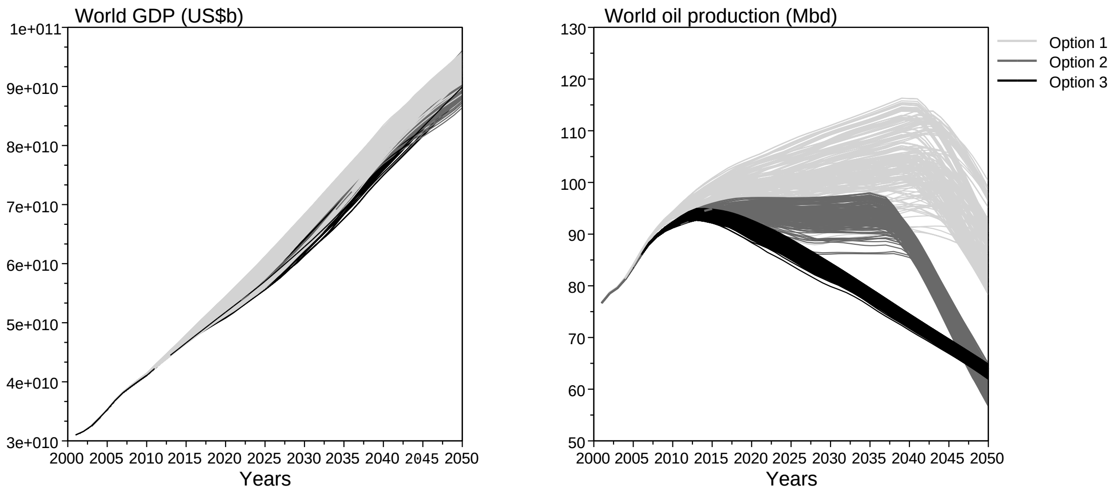

Fig. 1 World real GDP (in US$b) and oil production (in Mbd) for all scenarios, sorted according to the 'oil and gas' parameters' set

The analysis of GWP curves is less obvious. To understand the contribution of each parameter set to GWP pathways, we performed an analysis of variance (ANOVA) on the GWP discounted sum between 2010 and 2050, using a 3% discount rate. Figure 2 represents the relative contribution of each parameter set on the GWP variance (for baseline scenarios, and then for all scenarios, including the ones with climate policies) and classifies them.

While keeping in mind that we only compare the contribution of the considered parameters (for example population uncertainty is disregarded but would have a large impact on GWP), two important conclusions can be drawn from Figure 2. First, three significant sources of uncertainty on BAU GWP can be identified: (i) a technological set (the “end uses technologies” set); and (ii) the fossil fuel availability sets, namely the “coal market” and “oil and gas market” sets. Second, the relative importance of those sets is modified with

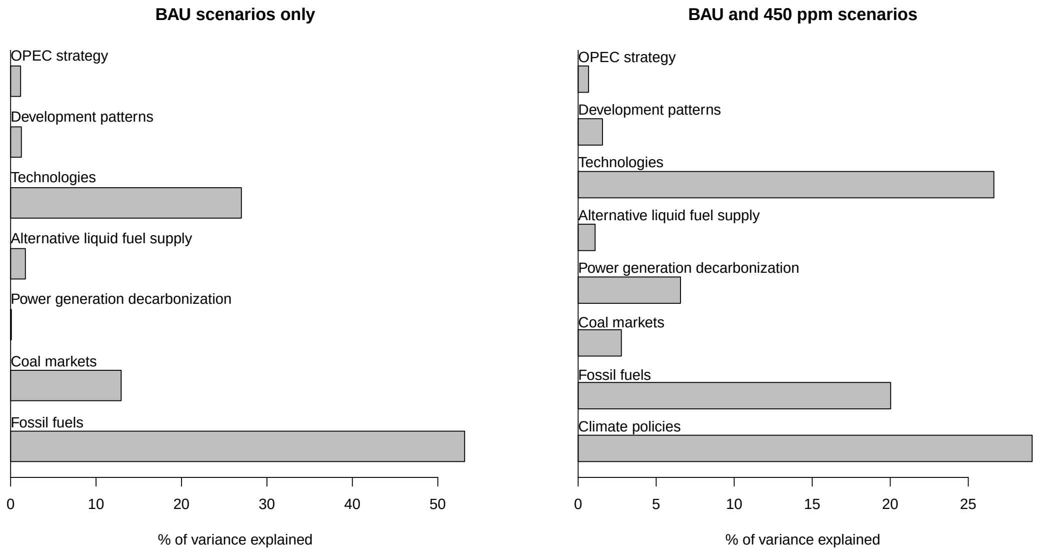

Fig. 2 Classification of the parameter sets with an analysis of variance (ANOVA) on world real GDP between 2010 and 2050, for scenarios with no climate policies (left), and for all scenarios (right) (discount rate 3%)

the introduction of climate policies: they lower the impact of oil scarcity and coal markets on GWP, while they increase that of end-use technologies and power generation decarbonization.

In our BAU scenarios, the largest source of uncertainty arises from the oil and gas availability. Figure 3 represents GDP per capita in different regions, according to the oil and gas parameter set: the more constrained is oil supply, the lower is oil-importing countries GDP per capita. Among oil-importing countries however, non-OECD countries suffer from more important losses than OECD countries. This regional difference can be explained by the energy intensity of non-OECD countries GDP, since these countries happen to be in an energy-intensive equipment phase when the peak oil occurs. Indeed, while the OECD economies are based on services, developing countries are in an industrialization process that requires more energy. The case of oil exporters is different, since the high oil prices induced by oil scarcity lead to high oil profits. Note that although the oil exporting countries' profits are higher in Assumption 2 and 3 than in Assumption 1 (thanks to higher oil prices) their GDP per capita is lower in Assumption 3 because of a weaker global context.

Considering the high level of uncertainty and controversy about oil and gas and the sensitivity of GWP to it, it appears highly misleading to assess the cost of climate policies assuming a unique possibility for future oil and gas supply. It is even more misleading if this unique possibility is assumed to be common knowledge for all economic actors, as in most optimization models.

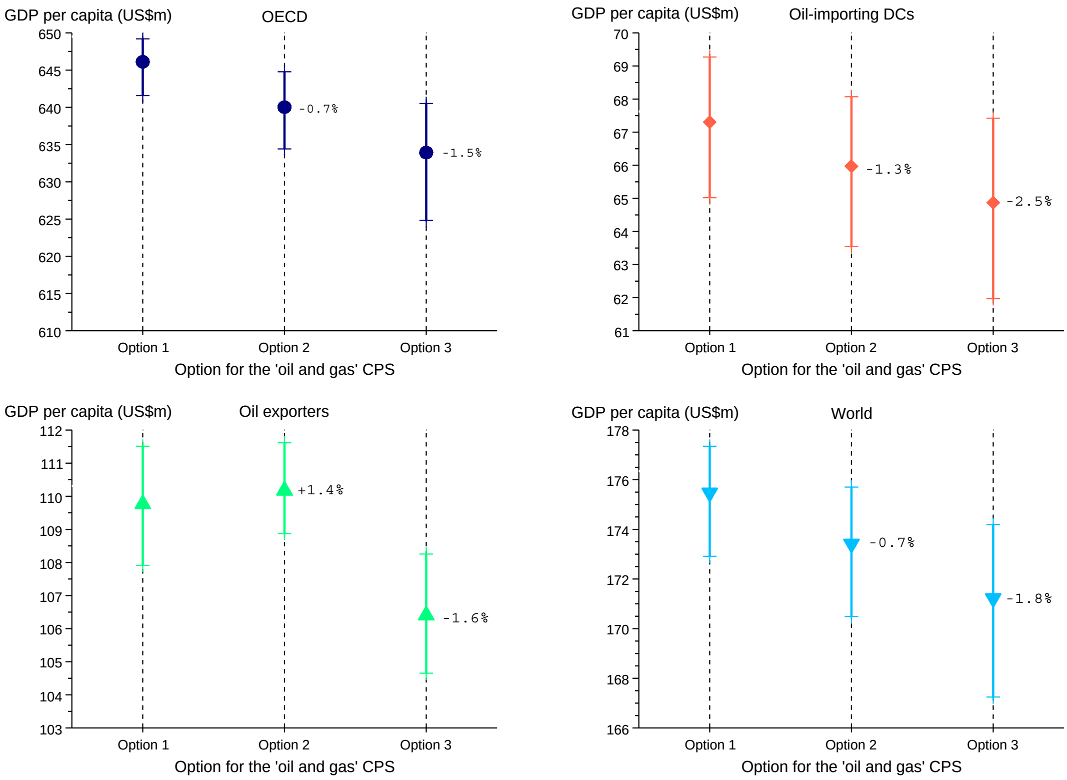

Fig. 3 Baselines GDP per capita, by region, sorted according to the 'oil and gas' parameters' set (discounted sum, 3% discount rate). Max, mean and average are represented.

This is why this study focuses on the link between climate policy costs and future oil supply.

5 Risk reduction and assessment of the risk premium

Figure 5 represents the GWP changes due to oil scarcity, i.e. the GWP change between each scenario with Assumption 1 parameterization for oil and gas, and the same one with Assumption 2 or 3. These variations are aggregated between 2010 and 2050 with a 3% discount rate, and shown separated according to the climate target (BAU vs. stabilization).

Two important results emerge: first, the 450 ppm histogram is shifted to the left, indicating that the mean loss due to oil scarcity is reduced by climate policies; second, the large right tail of the BAU distribution disappears in the 450 ppm distribution, meaning that climate policies eliminate a large number of scenarios with high GWP losses (larger than 3% and reaching up to 3.7%).

These large mitigation co-benefits can be explained by earlier and more regular increases in final oil price. In a second-best world where anticipations are imperfect, indeed, brutal increases in energy prices cause larger welfare losses than slower increases (Nordhaus, 2007). Here, the more regular increase in energy price with climate policies prevents economic lock-ins in oil-dependent schemes and promotes the development (induced technical change) and diffusion (investment incentive) of oil-free technologies before the beginning of the depletion phase in oil production.

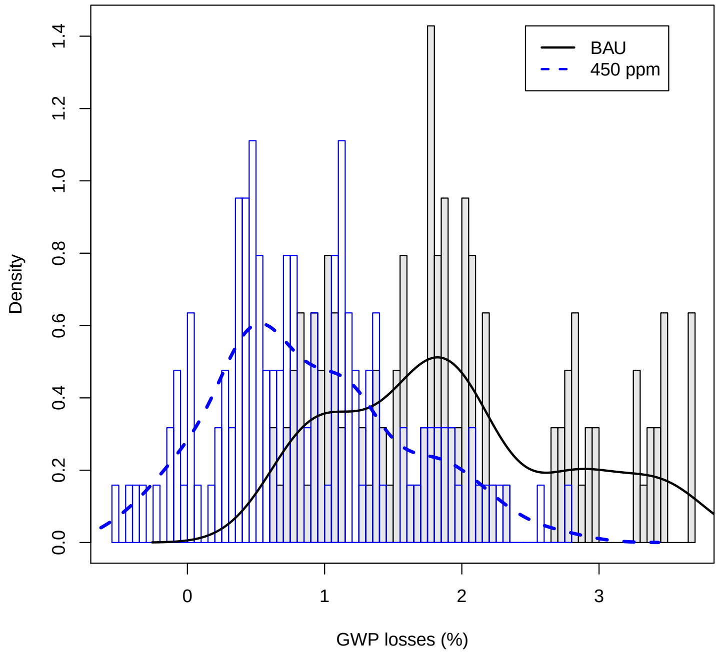

Fig. 4 Histogram and smoothed densities of GWP losses (in %) due to constrained oil supply (discounted GWP between 2010 and 2050, with a 3% discount rate). Black filled bars and plain line for BAU scenarios; blue empty bars and dashed line for 450ppm-stabilization scenarios. Losses from oil scarcity are larger in absence of climate policies.

Mean co-benefit of climate policies

For scenarios with no climate policies, we calculated the discounted GWP losses (from 2010 to 2050) due to oil scarcity, that is the losses between each scenario with a large amount of oil resources and the corresponding one with low amount of oil resources (i.e. with Assumption 2 and 3).

$$Loss^{BAU}_{Opt2or3} = \sum_{i=0}^{40} \frac{GWP^{BAU}_{Opt2or3}}{(1+\delta)^i} - \sum_{i=0}^{40} \frac{GWP^{BAU}_{Opt1}}{(1+\delta)^i}$$

The same calculation for stabilization scenarios gives:

$$Loss^{450}_{Opt2or3} = \sum_{i=0}^{40} \frac{GWP^{450}_{Opt2or3}}{(1+\delta)^i} - \sum_{i=0}^{40} \frac{GWP^{450}_{Opt1}}{(1+\delta)^i}$$

Eventually, we compared the oil scarcity losses without climate policies to the same losses with climate policies. For each scenario, the co-benefit is

$$\mathsf{Co-benefit} = Loss^{450}_{Opt2or3} - Loss^{BAU}_{Opt2or3}$$

The mean co-benefit, across all scenarios, is 0.78% of the GWP discounted sum over the 2010-2050 period (with a 3% discount rate), that is 11.5T$. This very large value shows that the co-benefit of climate policies —in terms of reducing the world's vulnerability to peak oil— should be a major incentive to implement ambitious climate policies.

Risk premium

In presence of risk aversion, this benefit can also be associated to a risk premium, i.e. the value of reducing the uncertainty on future GWP. In insurance markets, the risk premium is the difference between the insurance premium (the price the buyer is ready to pay to be insured) and the expected loss (i.e. the average loss the buyer would have to support in absence of insurance). According to the Arrow-Lind theorem Arrow and Lind (1970), the effect of risk aversion is small when considering public policy choices that affect all individuals homogeneously, but we claim that reducing the uncertainty on future growth may appear, nevertheless, as a significant side-benefit of climate policies to many decision-makers.

In the following calculations, we assume that global welfare is linked to the GWP through a simple welfare function $\mathsf{U} = \frac{GWP^{1-\Phi}}{1-\Phi}$, with $\Phi = 2$. We use the pure time-preference rate ($\rho = 1\%$) for the discounted sums of global welfare.

The model provides a first set of scenarios in the BAU case, i.e. in absence of climate policies. These 192 scenarios are referred to as $GWP_i^{BAU}(t)$, where t is the year between 2010 and 2050, and i is the number of the scenario (between 1 and 192). In the climate policy case, the scenarios are labeled in the same way: $GWP_i^{450}(t)$.

Let us define C_{ra} as the cost of climate policies with a risk aversion. This cost is the monetary loss occurring in 2010 in all BAU scenarios that would equalize average welfare in the BAU scenarios (with the loss) and in the 450 ppm scenarios (without the loss caused by climate policy). Let us also define

C_{no} as the cost of climate policies in absence of risk aversion. This cost is the monetary loss occurring in 2010 in the average BAU scenario that would equalize the welfare from average GWP in the BAU scenarios (with the loss) and the welfare from average GWP in the 450 ppm scenarios (without the loss). Basically, in the first one we average the welfare derived from GWP in all scenarios, while in the second one we calculate the welfare derived from the averaged GWP.

Let us define $GWP^{BAU}_{C_{ra}}$ and $GWP^{BAU}_{C_{no}}$ such that the costs are entirely paid in 2010:

$$\begin{cases} GWP^{BAU}_{C_{ra}}(2010) = GWP^{BAU}(2010) - C_{ra} \\ GWP^{BAU}_{C_{ra}}(2011:2050) = GWP^{BAU}(2011:2050) \end{cases}$$

$$\begin{cases} GWP^{BAU}_{C_{no}}(2010) = GWP^{BAU}(2010) - C_{no} \\ GWP^{BAU}_{C_{no}}(2011:2050) = GWP^{BAU}(2011:2050) \end{cases}$$

C_{ra} is such that

$$\left\langle \sum_{\rho=1\%} \mathsf{U}(GWP^{BAU}_{C_{ra}}) \right\rangle = \left\langle \sum_{\rho=1\%} \mathsf{U}(GWP^{450}) \right\rangle$$

The $\langle . \rangle$ symbol is for the mean. We look for C_{no} (the average loss in absence of insurance), such that

$$\sum_{\rho=1\%} \mathsf{U}\left(\langle GWP^{BAU}_{C_{no}} \rangle\right) = \sum_{\rho=1\%} \mathsf{U}\left(\langle GWP^{450} \rangle\right)$$

Then the risk premium is

$$RP = C_{ra} - C_{no} = 42\mathsf{G\$}\ ,$$

which means that climate policies are less expensive by 42G$ when risk aversion is taken into account.

Therefore, the uncertainty-reducing role of climate policies through the reduction of the uncertainty on future GWP, can be estimated at a net present value of 42G$, in addition to the main benefit of 11.5 T$. This low value is consistent with the Arrow-Lind theorem, which states that risk aversion can be disregarded for public policies as its effect is of second order.

6 Conclusion

Much larger efforts have been devoted to the assessment of the cost of climate policies than to the cost of a possible scarcity in oil supplies. We used a global energy-economy model to assess these two costs in a common framework, and it showed that both costs can be significant. Moreover, our results suggest that, in the context of a limited and uncertain amount of ultimately recoverable oil resources, climate policies reduce the world vulnerability to peak oil. Climate policies, therefore, appear as a hedging strategy against the uncertainty on oil resources, in addition to their main aim of avoiding dangerous climate change. This co-benefit is as a major incentive to implement ambitious climate policies. Moreover, simple calculations suggest that it has a net present value of about 11 500 US$b. Reducing the risk of future economic losses due to oil scarcity may thus appear as a significant side-benefit of climate policies to many decision-makers.

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A Parameter sets, modelling choices and equations

This appendix is not an exhaustive list of all equations in IMACLIM-R dynamic modules, but it presents the equations concerned by the parameters in Section 3, and some modelling choices. For more details, the reader should refer to Sassi et al (2010).

A.1 The "Oil and gas markets" parameter set

First subset : Oil

In this parameter set we built three Assumptions describing different levels of oil scarcity.

The modeling structure of oil supply in IMACLIM-R is based on 3 general principles. First, a physical description of oil resources with an explicit differentiation by region and nature (conventional vs. non-conventional) is used into the dynamic set-model describing the evolution of oil producing capacities (see Equation 1). Oil resource availability is based on data from USGS (2000); Greene et al (2006); Rogner (1997) and was corrected according to estimations from Total[4] about oil resources and future field production profile. Secondly, an explicit differentiation is made between fourteen (seven conventional and seven non conventional) categories of resources in each region according to the cost of exploration and exploitation. As oil must be discovered before it is produced, the temporal availability for production of a given category of oil resource depends on the characteristics of the discovery process, which is subject to two main effects: the information effect (the more an oil slick is exploited, the more information about the localization of remaining resources is obtained) and the depletion effect (the more a slick is exploited, the less oil remains in the soil). Following Rehrl and Friedrich (2006), inertias in the deployment of oil producing capacities resulting from the combination of these technical constraints on the discovery process are captured through independent bell shaped curves that shape the time-evolution of oil producing capacities for each category of oil in each region.

Equation 1 : Oil production.
We distinguish the regional oil resources into different categories according to their production costs (*i.e.* including exploration and exploitation costs) and the nature of the resource (conventional or non-conventional). To do so, we associate with each resource category a bell-shaped time profile of its production:

$$\frac{Q_\infty b e^{-b(t-t_0)}}{(1+e^{-b(t-t_0)})^2} \tag{1}$$

where t is the current date, t_0 is the starting date of oil production for this category, Q_∞ is the amount of ultimate resources and b a parameter that captures the intensity of constraints slowing down the production growth.

As to the dynamics of production capacities, IMACLIM-R makes a distinction between 2 types of oil producers according to their investment behaviors. All non Middle-East countries are supposed to be motivated by short-term return on investments, which implies that they will bring a category of oil reserve into production as soon as it becomes profitable (that is when the selling price on world market exceeds the total cost of exploration and exploitation). From then on, the deployment of production capacities is thus limited by geological constraints and strictly follows the corresponding bell shaped curve. These producers who do not adopt any strategic behavior are referred to as "fatal producers" (Rehrl and Friedrich, 2006). For Middle-East producers, the situation is different as the amount of their oil resource gives them a market power and allows them to adopt a strategy to fulfill a precise objective (either a price or a market share target). For a given year, the Middle-East production capacity is still bounded by a bell-shaped curve but its actual production can be below this limit if the chosen strategy requires a production restriction. This "swing producer" (Rehrl and Friedrich, 2006) behavior is consistent with past OPEC production, which has no longer fit the discovery trend since the 70's oil shocks (Laherrere, 2001).

[4] French oil company

Inside this oil supply module, we decided to explore the uncertainty on three major parameters components: the amount of ultimately recoverable resources, the investment behavior of OPEC oil producers to postpone the beginning of depletion at the oil field scale, and the level of inertia that will shape the development of non conventional production.

- In each region of the model, ultimately recoverable resources can have two values: the first value is such that the world total amount of ultimately recoverable resources is 3.1 Tb (conventional and unconventional oil); the second value is 15% higher.
- Then, to take into account in our analysis that, for a given oil field, the oil production shape will highly depend on the sequence of investments made to postpone the beginning of the depletion phase, there are two possible shares of the OPEC's amount of ultimately recoverable resources that can be extracted before depletion begins. The Middle-East oil production depletion can begin either when one half or three quarters of the resources have been extracted. The former leads to a bell-shaped production curve while the latter leads to a plateau-shaped curve.
- Furthermore, the shape of the curve modeling unconventional oil production capacity can differ, because of inertias in their diffusion. In our analysis, the deployment of unconventional oil can be easy, with the same curves modeling conventional and unconventional production capacities. Conversely, this deployment can be difficult, with a slower diffusion of unconventional oils because of specific additional inertias. In that case, unconventional oil production capacities are modeled with outstretched bell-shaped curves. Therefore, the third parameter of the 'oil and gas markets' subset is the spread of the bell-shaped curve modeling unconventional production capacities.

Assumptions on the amount of recoverable resources and on investments made to postpone the beginning of the depletion phase are combined to build three possibilities (instead of two) for conventional oil: when the amount of recoverable resources is low the production follows either a bell-shaped curve or a "plateau-shaped" curve (depending on the investments in the oil sector), while when the amount of recoverable resources is high the production always follows a "plateau-shaped" curve. In order to simplify the results section, we will call Assumption 1, Assumption 2 and Assumption 3 the three assumptions for this subset. Assumption 1 corresponds to the case with a high amount of recoverable resources ; Assumption 2 to the case with a low amount of recoverable resources and a plateau-shaped curve (sustained investments) ; and Assumption 3 to the case with a low amount of resources and a bell-shaped curve (delayed investments). The parameter modeling unconventional oil production capacities depends on the amount of recoverable resources: in Assumption 2 and 3 the deployment of unconventional oils is slower than for conventional oils, while in Assumption 1 there is no difference.

Second subset: Gas

In the model, gas world production capacities answer to demand growth until ultimately recoverable resources enter a depletion process. Gas prices variations are indexed on that of oil prices via an indexation coefficient (0.68, see Equation 3) calibrated on the World Energy Model IEA (2007). When oil prices increase by 1%, gas prices increase increase by 0.68%. In Assumption 1 for the "oil and gas markets" parameter set, this indexation disappears when oil prices reach 80$/bl: beyond this threshold, the evolution of gas prices only depends on production costs and possibly on the depletion effect, which leads to a sharp price increase (due to an augmentation of the producer mark-up rate). In Assumptions 2 and 3, gas prices remain indexed on oil prices whatever their evolution, but an additional price increase occurs when gas production enters its depletion phase.

Equations 3 : Gas price indexation on oil price.
Gas price in each region at year t is equal to :

$$p_{gas}(t) = p_{gas}^{ref} \cdot \tau_{gas}(t) \tag{2}$$

where:
p_{gas}^{ref} is the gas price in this region at year 1

While gas depletion has not started, $\tau_{gas}(t)$ in each region is:

$$\tau_{gas}(t) = 0.68 \times \left(\frac{1}{3} \times wp_{oil}(t) + \frac{2}{3} \times wp_{oil}(t-1)\right) \times \frac{1}{wp_{oil}^{ref}} \quad (3)$$

where:
$wp_{oil}(t)$ is the world oil price at year t;
wp_{oil}^{ref} is the world oil price at year 1

Moreover, if depletion has started in this region, $\tau_{gas}(t)$ is increased by 5% each year, regarless of oil prices.

A.2 "The OPEC strategy" parameter set

As presented in section A.1 the IMACLIM-R modeling structure makes a distinction between "fatal producers" (Rehrl and Friedrich, 2006) and the OPEC, who has market power. As a result, the OPEC strategy is a critical parameter whose evolution needs to be explored. The Middle-East countries can use their market power in two polar ways (and any combination in between). The first is to secure high price levels over the short-run by limiting the expansion of production capacities; but this strategy has the drawback of inciting the oil importing countries to accelerate their efforts to develop oil-free technologies and to adopt energy-sober consumption patterns. The second one is a "market flooding" strategy to maintain rather low prices over the short-term in order to favor oil consumption and discourage oil importing countries from sustaining oil-saving efforts. The trade-off is between low revenues in the next decades and higher rents in the long run, the lower price elasticity of the oil demand being due to the lack of large scale cheap substitutes to oil. The trade-off between these two assumptions does not depend only on the flows of export revenues, it also depends upon geopolitical considerations and long term objectives of the Middle-East governments, including the way they prepare the "post-oil" era. The conduct of these strategies will depend upon the internal cohesion among OPEC members and of Middle-East countries. In fact, when the OPEC's coordination is secure, they can agree to cut back production so that oil prices are high; conversely, when they are divided, they tend to produce more individually, resulting in lower oil prices. In Assumption 1 the low short-term price aimed at by the OPEC is 40$/bl while in Assumption 2 it is 80$/bl.

A.3 The "Coal market" parameter set

Coal is treated in a different way than oil and gas because of the larger amount of available resources which prevents coal production from entering into a depletion process before the end of the 21st century. We describe price formation on the world coal market with a reduced functional form which relates price variation to production changes. This choice allows us to capture the cyclic behaviour of this commodity market. In Assumption 1, coal price growth sensitivity with respect to coal production growth is quite low, so that the coal production growth can be absorbed without prices variations. On the contrary coal price growth is very sensitive to coal production growth in Assumption 2.

Equation 5 : Coal price growth rate.

Coal price each year is equal to:

$$p_{coal}(t) = p_{coal}^{ref} \cdot \tau_{coal}(t) \quad (4)$$

where:
p_{coal}^{ref} is the coal price in this region at year 1.

$\tau_{coal}(t)$ is defined as:

$$\tau_{coal}(t) = \tau_{coal}(t-1) \cdot (1 + \alpha_{1or2} \cdot g_{coal}(t)) \tag{5a}$$

$$with\ g_{coal}(t) = \frac{Q_{coal}^{world}(t) - Q_{coal}^{world}(t-1)}{Q_{coal}^{world}(t-1)} - g_{lim} \tag{5b}$$

where:
$Q_{coal}^{world}(t)$ is the world coal production at year t
g_{lim} is the production growth rate that would not lead to price fluctuation

We distinguish upwards and downwards movements of production growth, in order to introduce asymmetry in price response: we use α_1 when production growth is lower than g_{lim} and α_2 when production growth is greater than g_{lim}.

A.4 The "Power generation decarbonization" parameter set and new technologies learning curve

The electricity supply module in IMACLIM-R represents the evolution of power-generating capacities over time, depending on the amount of available investment and changes in fuel and production factors prices. The expectations are adaptative: the model anticipates ten years forward the potential future electricity demand, extrapolating from demand past trends, and computes an optimal mix of electricity-productive capacities to face future needs at the lowest cost, given anticipations of future fuel prices. Moreover, the modeling structure accounts for the physical constraints that – in absence of competitive technology for electricity storage – hamper the extensive deployment of renewable capacities within the electrical grid (e.g., the fact that production is intermittent, especially for solar and wind energy). Given that electricity decarbonization can have a strong impact on the oil sector through electric vehicles development, the uncertainty analysis is focused on carbon-free technologies such as renewable energy generators (simply called renewables), carbon capture and sequestration (CCS) and nuclear plants. The social acceptability and the future technological availability of these technologies spark off debates: future deployment, when technically possible, can be constrained by bottleneck phenomena (like the lack of technical skills) or political barriers (solidly grounded or not). Our approach implies that we do not pretend to settle these debates; rather, we test for each technology the resulting effective availability dates and the maximum penetration rates as critical parameters that can take higher or lower values (see Figure 5). There are two Assumptions in this parameter set: in Assumption 1, renewable energies, CCS and nuclear energy can penetrate the markets early and at a large scale, while their costs drop quickly thanks to learning-by-doing effects; in Assumption 2, they face strong constraints on their deployment.

Equation 6 : Learning curve for new technologies (including technologies in the electric sector).

We use the learning rate described as follows by McDonald and Schrattenholzer (2001): "In its most common formulation, unit costs decrease by a constant percentage, called the learning rate, for each doubling of experience". For each technology, the investment cost at year t is given by:

$$C_{inv}(t) = C_{inv}^{ref} \cdot (1-\gamma)^{\omega}\ \ with\ \omega = \frac{\log(I_{cum}(t)/I_{cum}^{ref})}{\log(2)} \tag{6}$$

where:
C_{inv}^{ref} is the investment cost for the technology in the reference year;

$I_{cum}(t)$ is the cumulated investment in the technology at year t;
I_{cum}^{ref} is the cumulated investment in the technology in the reference year;
γ is the technology learning rate.

Our modelling choice can be rewritten following Gillingham et al (2008) formulation:

$$C(K) = \alpha K^{-\beta}$$

where C is the unit cost of a technology, K is the cumulative installed capacity, α is the cost of the first unit (a normalization parameter), and β is the learning elasticity. This implies that a doubling of experience will reduce specific costs by a factor of $2^{-\beta}$. In our equation this factor is $(1-\gamma)$. From $2^{-\beta} = (1-\gamma)$, we get Eq. (6):

$$\beta = -\frac{\log(1-\gamma)}{\log(2)}$$

$$C(K) = C(K_0) \cdot e^{-\beta \log(K/K_0)} = C(K_0) \cdot (1-\gamma)^{\frac{\log(K/K_0)}{\log(2)}}$$

New technologies penetrate the markets according to their profitability, but are constrained by a maximum market share, represented in Figure 5 for CCS.

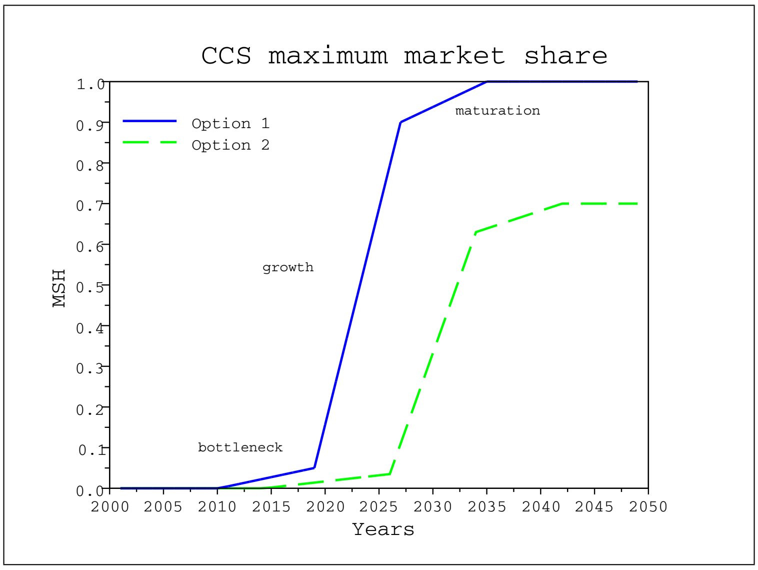

Fig. 5 Maximum market share for new technologies penetration, with the different phases

A.5 The "Energy end-use technologies" parameter set

Final demand for oil refined products arises from production sectors and household consumption. The evolution of this demand is of course related to the general level of activity but its ability to adjust to oil prices movements is highly impacted by inertias (i) on the renewal of equipments and (ii) on technical progress in the three major oil-consuming sectors (industry, residential and transport). In these sectors, inertias on equipments are captured by a description of capital vintages, each of them being characterized by an energy intensity and a final energy mix.

At each point in time, energy prices affect the selection of new equipments (that include technology-explicit portfolio for automobile transportation) but do not influence the existing production capacities.

Since IMACLIM-R relies on an endogenous technical change framework, the costs of equipments and production techniques are related to their cumulative production through the usual learning curves (see Equation 6). Thus, endogenous technical change parameters are driven by the cumulated effect of economic choices over the projected period. Because of the embodiment of technical change in equipments, endogenous technical change captured in IMACLIM-R has to be interpreted as encompassing both R&D and learning-by-doing.

For the transport sector (private cars and freight), technical change interacts with the overall demand for mobility trough the interplay between the following parameters: (i) the total user's costs of the vehicle (ii) the availability of road infrastructures and alternative assumptions (railways, soft modes) (iii) the saturation of the time budget the consumer can allocate to transportation (the so-called Zahavi law) (Zahavi and Talvitie, 1980). Other parameters control constraints on the electrical vehicle deployment (see Figure 5). This modeling choice allows us to capture (i) the possibility that progress on the efficiency of vehicles generates a rebound effect on mobility demand (Greening et al, 2000) and (ii) that additional transport demand can be induced by new transportation infrastructures (Goodwin, 1996).

Equation 8 : Freight energy consumption at year t, for each country.

$$CI_{freight}^{fuel}(t) = \mu_f(t) \cdot CI_{freight}^{fuel}(0) \cdot \left(\frac{pIC_{freight}^{fuel}(t)}{pIC_{freight}^{fuel}(0)} \right)^{\epsilon} \tag{8}$$

where:
$\mu_f(t)$ is a multiplier coefficient at year t;
$CI_{freight}^{fuel}(0)$ is the freight energy consumption for each country in the reference year, in each country;
$pIC_{freight}^{fuel}$ is the price for fuel consumption in the freight sector, in each country (it takes into account all taxes, including the carbon tax);
ϵ is the fuel consumption elasticity to fuel prices, in each country.

In the residential sector parameters rule the energy consumption of buildings (see Equation 9), as well as the decrease of oil consumption in case of high oil prices.

Equation 9 : Housing energy expenditure.

$$H_{Exp} = \sum_{e} \left(\mu_h(t) \cdot \alpha_{m2}^{e} \cdot b_{stock} \cdot pFD_e \right) \tag{9}$$

where:
H_{Exp} is the total energy expenditure in housing, for each country;
α_{m2}^{e} is the energy consumption of buildings e per m^2, in each country (exogenous trend calibrated on POLES: see LEPII-EPE (2006))
$\mu_h(t)$ is a multiplier coefficient at year t;
b_{stock} is the building stock in each country;
pFD_e is the price for final demand for energy e in each country (it takes into account all taxes, including the carbon tax).

Accordingly, in Assumption 1 for energy end-use technologies, the deployment of new technologies in the transportation and residential sectors is made easier than in Assumption 2, in which inertias prevents them from penetrating the markets effectively.

A.6 The "Alternative liquid fuel supply" parameter set

In our numerical exercises with the IMACLIM-R modeling framework, biofuels (first and second generation) and Coal-To-Liquid fuels represent the main alternatives to refined oil over the 21st century. The penetration of biofuels in energy supply is modeled according to worldwide supply curves published by the IEA (2006). These supply curves define the maximum amount of biofuels that can penetrate the liquid fuel market, at a given date and for a given oil refined products price (including taxes). Figure 6 shows these biodiesel supply curves for each level of oil refined products price. The same type of curves are used for ethanol.

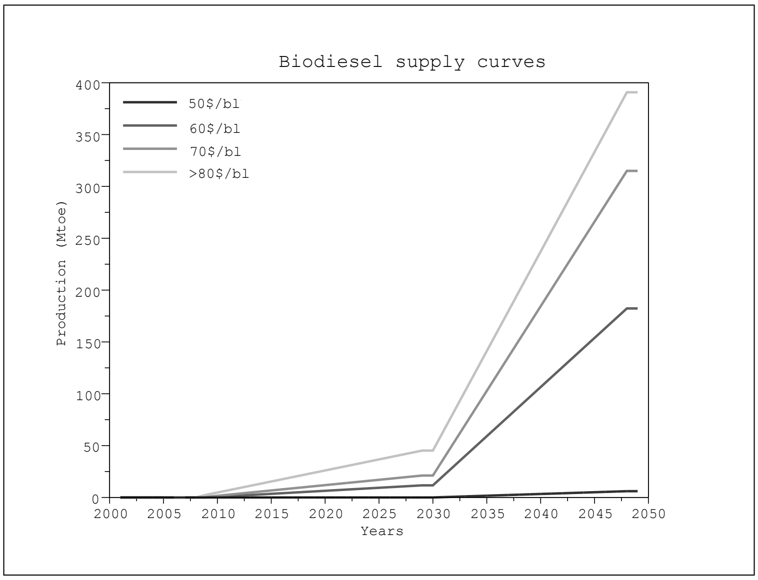

Fig. 6 Biodiesels supply curves in Mtoe. Each curve corresponds to a given price per barrel of Gasoline equivalent (including taxes).

They evolve over time to mimic technical improvements in production processes and account for limits to production due to constraints on land availability and conflicts with other uses of biomass (including food)[5]. In addition to that, an exogenous maximum constraint – which encompasses other kinds of inertias that could affect the deployment of these technologies – is imposed to the annual biofuel production growth. These constraints and their feedback on the cost of biofuels are one major reason why synfuels may become a potentially competitive alternative to oil.

In the simulations with IMACLIM-R, the main share of synfuels is taken by Coal-To-Liquid (rather than Gas-To-Liquid) because of the abundance of coal resources. The decision to initiate CTL production is captured through a threshold value for oil price p_{CTL} above which CTL producers take the risk of launching large scale production. If we note $D^{LF}(t)$ the estimated demand of liquid fuels and $RO(t)$ the supply of refined oil and biofuels, the desired CTL production ($\widetilde{CTL}$) is given by:

$$\widetilde{CTL}(t) = f(t) \cdot Max\left[D^{LF}(t) - RO(t), 0\right] \tag{10}$$

[5] For the treatment of this constraint see Hourcade et al. (2010)

CTL producers are willing to fill a growing fraction of the gap between total fuel demand and the supply of refined oil and biofuels. This fraction depends on investors' beliefs on profitability of CTL investments. We capture this effect through $f(t)$, defined as an increasing function of the cumulated oil prices from 2001 ($p_{oil}^{cum}(t) = \sum_{i=2001}^{t} Min\left[p_{oil}(i), p_{oil}^{max}\right]$ with $p_{oil}^{max} = 110\$/bl$): the higher the cumulated price, the higher the confidence in CTL profitability and the level of desired CTL production (see Figure 7).

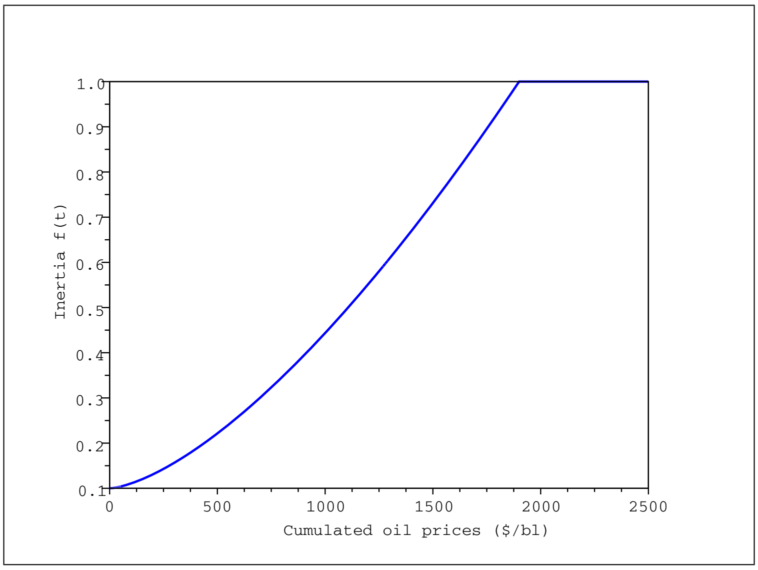

Fig. 7 Investors' beliefs on profitability of CTL investments (f(t))

Eventually, constraints on the delays of maturation of production investments and the time necessary to adapt distribution networks are captured by a limitation on CTL production growth, through the following equation:

$$CTL(t) = Max\left[CTL(t-1) + \Delta CTL^{IEA}(t), \widetilde{CTL}(t)\right] \quad (11)$$

Where ΔCTL^{IEA} represents the largest possible increase in CTL production and is calculated as a linear interpolation between three values from IEA scenarios, in 2030, 2035 and 2050, according to IEA values (IEA, 2008).

A.7 The "Development patterns" parameter set

In addition to the uncertainty surrounding technological changes, the IMACLIM-R model allows to include contrasted views on development patterns. These dynamics are not determined by pure economic decisions; they involve political bargaining, households' preferences and are far from the classical "carbonomics." Yet, these patterns are key in determining and describing economic growth, and more particularly its energy content, as they affect the need for energy services in sectors such as transport or dwellings. The articulation between consumption styles, technological and localization patterns is a critical parameter for the energy future with and without climate policies for any region in the world. However, the major uncertainty is about how this articulation will be made by developing countries in the next decades. Even though the economic context will matter in the shaping of development patterns, it will do so together with infrastructure decisions that involve political bargaining, as well with the evolution of households preferences in various cultural contexts. Our parameters set describes either a 'mimetic' development pattern, in which developing countries want to catch up with the western lifestyle (vast houses in spread and mobility-intense cities, high calorie intake per capita) and asymptotically the US development pattern, or a less carbon-intensive development pattern. To do so, we take into account infrastructure policies (which encourage or not urban sprawl), agents preferences for automobile transport and vast individual dwellings (through income elasticities), as well as a more limited role of the "just in time" and distributed industrial processes. The reader must keep in mind that endogenous outputs will be influenced by those parameters, but remain coherent with the economic context, thanks to the resolution of the economic equilibrium.

Equation 12: Number of cars per capita For each country, evolution of the number of cars per capita (with λ extracted from data from the IEA model MOMO (Fulton and Eads, 2004) in the reference case):

$$cars_{pc}(t) = cars_{pc}(t-1) + \lambda \cdot \Delta GDP_{pc} \tag{12}$$

where:
GDP_{pc} is the country real GDP per capita

Equation 13: evolution of dwelling surface per capita in each country at year t. The parameters are μ_s^{ini} (income elasticity of buildings stock growth) and A (asymptote to surface per capita in developing countries).

$$\mu_s(t) = Min\left[\mu_s^{ini}, \left(1 - \frac{b_{stock}(t-1)}{L_t(t-1)} \cdot \frac{1}{A}\right) \cdot \mu_s^{ini}\right] \tag{13a}$$

$$s_{pc}(t) = Min\left[A, \frac{b_{stock}(t-1)}{L_t(t-1)} \cdot \left(1 + \mu_s(t) \cdot Max\left[0, \left(\frac{R(t)}{L_t(t-1)} \cdot \frac{L_t(t-2)}{R(t-1)}\right) - 1\right]\right)\right] \tag{13b}$$

$$b_{stock}(t) = s_{pc}(t) \cdot L_t(t) \tag{13c}$$

where:
μ_s^{ini} is the income elasticity of buildings stock growth for each country at year 1;
$\mu_s(t)$ is the income elasticity of buildings stock growth for each country at year t;
b_{stock} is the building stock in each country;
L_t is the total population in each country;
s_{pc} is the surface per capita in each country;
b_{stock} is the building stock in each country;
R is the households net income in each country;
A is the asymptote to surface per capita in developing countries

Equation 14: households industrial goods consumption.
The parameter η describes the saturation level of household industrial goods consumption, expressed as a multiplier factor of the calibration year consumption volume.

$$Dpc_{indus}^{max} = \frac{D_{indus}^{ref}}{L_t^{ref}} \cdot \eta \tag{14a}$$

if $Dpc_{indus}(t) > Dpc_{indus}^{max}$ then

$$s_{indus}^{income}(t+1) = s_{indus}^{income}(t) \cdot Dpc_{indus}^{max} \cdot \frac{L_t(t)}{Dpc_{indus}(t)} \tag{14b}$$

where:
D_{indus}^{ref} is the final demand for industrial goods, in each country, at year 1;
Dpc_{indus} is the final demand per capita for industrial goods, in each country;
L_t^{ref} is the total population, in each country, at year 1;
$L_t(t)$ is the total population, in each country, at year t;
s_{indus}^{income} is the share of desired industrial goods w.r.t households' income in each country.

A.8 The "Implementation of climate policies" parameter set

The three Assumptions as regards to climate policies are the following: the model represents (i) a "Business As Usual" (BAU) world with no constraint on emissions, or (ii) two possibilities of "stabilization" worlds in which a carbon tax reduces emissions such that CO_2 concentration is stabilized at 450 ppm in the long run. To do so, the model calculates an endogenous carbon tax in order to comply with an exogenous trajectory of emissions, consistent with concentration level of 450 ppm in 2050.

This concentration level corresponds approximately to 550 ppm if all gases are included. It is close to the concentration targets investigated in the Working Group III of the IPCC (IPCC, 2007).

The carbon tax yields a government income which can be recycled in multiple ways. We thus added two possibilities as regards tax income recycling: this income is either entirely given back to households, or recycled based on a lump sum principle in which each sector receives back what they have paid, except for the power generation sector whose payoff is given to the consumer. As a consequence, there are twice as many scenarios in the stabilization case (450ppm) as in the BAU case.