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# Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations[☆]

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## ABSTRACT

Stabilizing the atmospheric concentrations of greenhouse gases (GHGs) at levels expected to prevent dangerous climate changes has become an important, long-term global objective. It is therefore crucial to identify a cost-effective way to achieve this objective. In this paper, we use WITCH, a hybrid climate–energy–economy model, to obtain a quantitative assessment of equilibrium strategies that stabilize $CO_2$ concentrations at 550 or 450 ppm. Since technological change is endogenous and multifaceted in WITCH, and the energy sector is modeled in detail, we can provide a description of the ideal combination of technical progress and alternative energy investment paths in achieving the sought stabilization targets. Given that the model accounts for interdependencies and spillovers across 12 regions of the world, equilibrium strategies are the outcome of a dynamic game through which inefficiency costs induced by global strategic interactions can be assessed. Our results emphasize the drastic change in the energy mix that will be necessary to control climate change, the huge investments in existing and new technologies implied, and the crucial role of breakthrough technological innovation.

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## 1. Introduction

Climate change may dramatically damage future generations. According to the latest International Panel on Climate Change report (IPCC, 2007), anthropogenic emissions of greenhouse gases (GHGs) are among the main causes of climate change, even though uncertainty remains as to their exact relevance in the overall climatic process: thus it is necessary to identify when, where and how these emissions ought to be controlled in order to avoid dangerous climate changes.

The many uncertainties that still permeate the debate about the relationship between GHG concentrations and temperature change or the existence of temperature thresholds beyond which irreversible changes could occur, make it difficult to use the standard cost–benefit framework for jointly identifying the optimal stabilization target and related investment mix. Scientific uncertainties aside, the long-term stabilization target is clearly a political decision, and policymakers worldwide are indeed discussing how to tackle the climate change problem. At the 2008 G8 Summit in Japan, the leading industrialized nations agreed on the objective of at least halving global $CO_2$ emissions by 2050. Such an agreement follows earlier resolutions of other countries, such as the European Union (EU), Canada and Japan.[1] There is therefore increasing interest in, and a need for, research efforts providing information on the best strategy that different regions of the world should adopt in order to minimize the cost of achieving their own emission reduction target. In particular, it is crucial to identify the long-term investment mix in the energy sector in different world regions, taking into account the role of investments in energy R&D and the future evolution of different technologies.

For analytical purposes, this paper considers two long-term stabilization targets, both expressed in terms of atmospheric carbon concentrations. The first target is a 550 ppm ($CO_2$ only) concentration target. The second one stabilizes emissions at 450 ppm ($CO_2$ only). These two reference targets roughly coincide with IPCC Post-Third Assessment Report (TAR) stabilization scenarios C and B respectively. Although the IPCC considers even more stringent emissions pathways, our current analysis focuses on the two that we consider more politically realistic. The first target is often advocated for in the United States (see *e.g.* Newell and Hall, 2007), whereas the second one is close to the EU objective of keeping future temperature changes within 2 °C. We then compute the welfare maximizing path of energy R&D expenditures, investments in energy technologies and direct consumption of fossil fuels that is consistent with the proposed stabilization targets.

The equilibrium R&D and investment strategies in a given region of the world depend upon many factors, such as the discount rate; the investment decisions taken in other regions or countries; and the effectiveness of R&D in increasing energy efficiency, or in providing new, low carbon, energy technologies. Equilibrium R&D and investment strategies also depend on the expected climate damages, on the pattern of economic growth in various regions of the world, and on other economic and demographic variables. In this paper, all these interdependent factors are taken into account.

To this purpose, we use WITCH (World Induced Technical Change Hybrid; see Bosetti et al., 2006a, 2007a), a climate–energy–economy model in which a representation of the energy sector is fully integrated into a top-down optimization model of the world economy. Thus, the model yields the equilibrium intertemporal allocation of investments in energy technologies and R&D that belong to the best economic and technological responses to different policy measures. The game theory set-up accounts for interdependencies and spillovers across 12 regions of the world. Therefore, equilibrium strategies are the outcome of a dynamic game through which inefficiencies induced by global strategic interactions can be assessed. In WITCH, technological progress in the energy sector is endogenous, thus enabling us to account for the effects of different stabilization scenarios on induced technical change, via both innovation and diffusion processes. Feedback from economic variables to climatic ones, and vice versa, is also accounted for in the dynamic system.

These features enable WITCH to address many questions that naturally arise when analyzing carbon mitigation policies. Among those that this paper aims to answer are the following: what are the

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[1] The European Union, for example, has identified both its long-term target (to keep the increase of global atmospheric temperature below 2 °C with respect to the pre-industrial level) and a short-term target consistent with the former (i.e. a reduction of 2020 emissions by 20% with respect to 1990, which may become a 30% reduction if a global agreement on climate change is achieved).

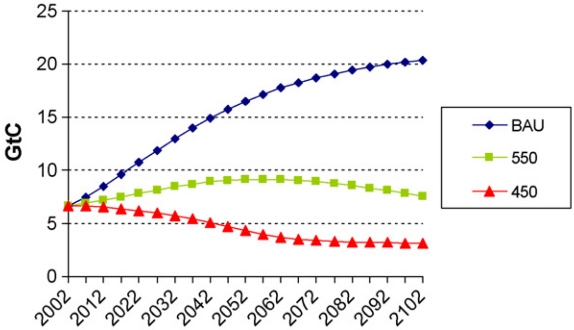

**Fig. 1.** World fossil fuel emissions in the three scenarios (2002–2102).

implications of the proposed stabilization targets for investment strategies and consumption of traditional energy sources vis-a-vis low carbon options? What is the role of public energy R&D expenditures for generating improvements in both energy efficiency and carbon intensity? And how sensitive are the economic costs of climate policies to different technological scenarios, and in particular, to hypotheses on major technological breakthroughs?

The structure of the paper is as follows. Section 2 describes the framework of our analysis and explores the implications of stabilization targets for the energy sector. Section 3 informs readers about investment needs for known technologies, while Section 4 focuses on innovation strategies. Section 5 provides estimates of the economic costs of climate policy with a focus on technological choices, and Section 6 concludes the paper. Appendix A provides background information on the WITCH model.

## 2. The challenge of stabilizing atmospheric GHG concentrations

As previously indicated, we investigate best response strategies, particularly in the energy sector, to achieve two stabilization targets. According to the first one, atmospheric concentrations must be stabilized at 550 ppm ($CO_2$ only) by the end of the century. This is roughly equivalent to a 650 ppm target if all GHG are included. The second target is more stringent and requires that $CO_2$ concentrations be stabilized at 450 ppm (550 ppm all gases included) at the end of the century. Fig. 1 shows Business as Usual (BaU) emissions together with emission time profiles for the two stabilization targets. These are optimal time profiles because they were obtained by computing the fully cooperative equilibrium of the game given the GHG concentration constraints, *i.e.* by solving a global joint welfare maximization problem where all externalities are internalized. Note that feedbacks from climate damage to the production of economic goods are taken into account when computing the optimal emission profiles.[2]

Current annual fossil fuel $CO_2$ emissions are roughly 7 Giga Tonnes of Carbon per year (GtC/yr). According to the model projections, without any stabilization policy (the BaU or "baseline" scenario), $CO_2$ emissions are expected to reach about 21 GtC by the end of the century, a value in line with the IPCC B2 scenario of the Special Report on Emissions Scenarios (SRES). In the case of the 550 ppm stabilization target, annual emissions slowly increase until 2060 (when they reach 10 GtC/yr) and then decrease to 8 GtC by the end of the century. If the target is 450 ppm, $CO_2$ emissions start decreasing immediately and reach 3 GtC by the end of the century. That is, the optimal emission profile does not allow for overshooting emissions which would trade off current and future abatement. The emission reductions required to meet the more stringent stabilization target are particularly challenging, given the expected growth rate of world population and Gross Domestic

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[2] We adopt the same damage function as in Nordhaus and Boyer (2000). Future damages are discounted at a declining discount rate (starting from 3% and declining to 2%).

**Table 1**
Ratio of future over past values of Kaya' s variables in the three scenarios (BAU, 450 and 550 ppm).

| | World | | | | |
|---|---|---|---|---|---|
| | ΔEMI | ΔGDP/POP | ΔEN/GDP | ΔEMI/EN | ΔPOP |
| 2032 vs. 2002 | | | | | |
| BAU | 1.94 | 1.92 | 0.74 | 1.04 | 1.31 |
| 550 | 1.28 | 1.91 | 0.61 | 0.84 | 1.31 |
| 450 | 0.86 | 1.89 | 0.49 | 0.70 | 1.31 |
| 2002 vs. 1972 | | | | | |
| Historical | 1.96 | 1.64 | 0.76 | 0.97 | 1.63 |

Product (GDP): per capita emissions in the second part of this century would have to decline from about 2 to 0.3 tC/cap per year.[3]

To achieve the two stabilization targets and the related optimal emission profile, it is assumed that all regions of the world agree on implementing a cap and trade policy. This is an obvious simplification which is useful in this paper to focus on differences in the technological make-up of the economy under the two stabilization scenarios, and on the difference in R&D portfolios. In two companion papers (Bosetti et al., 2008a,b), we analyze the implications of partial agreements, delayed action in developing countries, and uncertain stabilization targets. In this paper, the global cap and trade policy is implemented by assuming an equal per capita allocation of initial allowances.

Given the adopted climate policy, countries use the permit market to trade emissions (banking is also allowed) and determine their investments and R&D strategies, as well as their demand for permits, by maximizing their own welfare function (see Appendix A) given the strategy adopted in the other regions of the world. The intertemporal Nash equilibrium of the dynamic game defines the equilibrium investment strategies in each world region.

To assess the implications of the equilibrium of the game under the two concentration constraints, let us compare the impact of imposing the two stabilization targets on the dynamics of the main economic variables. Table 1 shows the changes in the variables belonging to the well-known Kaya's identity (emissions, per capita GDP, energy intensity, carbon intensity of energy and population) for two periods: 1972–2002 (historical values) and 2002–2032 (WITCH scenarios).

In the BaU, future changes of all economic variables, one of the main outputs of the model, are consistent with historical values observed in the past 30 years.[4] Baseline emissions, which are also an output of the model, almost double in 30 years time, due to the exogenous population growth and to the endogenous growth in income per capita. From basic assumptions on energy technologies and initial investment costs, we derive an endogenous path of energy use in which a looser economy–energy interdependence emerges, but not an energy–carbon decoupling. The endogenous dynamics of energy and carbon efficiency are comfortingly similar to observed trends over the past three decades. Given that the characteristics of the baseline have important implications in terms of efforts required to stabilize the climate (and therefore in terms of stabilization costs), the ability to reproduce history – at least over short time horizons – is an important feature of the WITCH model.

In the 550 ppm scenario, lesser growth in emissions stems mainly from energy efficiency improvements as testified by the decrease of energy intensity (ΔEN/GDP column), although some de-carbonization of energy is also needed. A more fundamental change is required in the 450 ppm scenario. Keeping carbon concentrations below this target can be achieved only if both energy intensity and carbon content of energy are significantly decreased.

Fig. 2 provides some additional interesting information on the modifications required in the energy sector, as it plots the evolution of energy intensity and carbon intensity of energy in 2030, 2050 and

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[3] Note that 0.3 tC $yr^{-1}$ $cap^{-1}$ is the amount of carbon emitted on a *one way* flight from the EU to the US East Coast.

[4] Long-term economic growth dynamics is endogenous in the model, as well as investment strategies, prices of all inputs and GHG emissions. The few exogenous variables are labor supply (which is equal to population in the model), and an exogenous total factor productivity trend. The interest rate, which measures the cost of capital, is also endogenous, as usual in Ramsey-type optimal growth models.

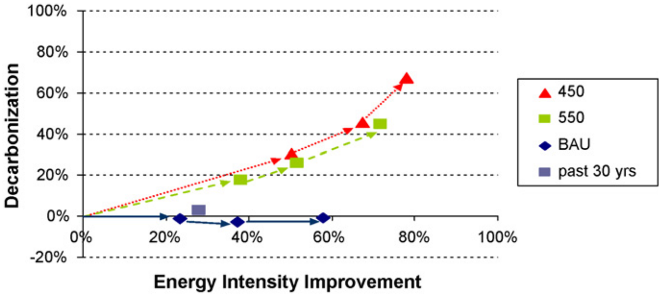

**Fig. 2.** Reductions of energy and carbon intensity in the next 30, 50 and 100 years, and over the past 30 years (changes w.r.t. 2002).

2100. The BaU scenario is characterized by an improvement of energy intensity, even though slightly less pronounced than the historical one. It also shows a slight carbonization of energy over the century: although small, this effect reflects the increasing share of coal in the energy mix in the absence of climate policy (this is also consistent with the Energy Information Agency's medium term projections; see EIA, 2007). This increase is mostly driven by the growing energy consumption of developing countries. Coming to the stabilization scenarios, they both show energy efficiency measures to be the most relevant in the short-term, but both call for the development of low carbon options in the long-term, especially for the more stringent 450 stabilization target.

The dynamic paths of energy intensity and carbon intensity of energy implied by the two stabilization scenarios require drastic changes in the energy sector. The next section will analyze the equilibrium investment paths in different energy technologies over the next century. This will allow us to identify the welfare maximizing investment strategies that different regions of the world ought to implement to achieve the two stabilization targets.

## 3. Equilibrium mitigation strategies with known energy technologies

The energy sector is characterized by long-lived capital. Therefore, the investment strategies pursued in the next two/three decades will be crucial in determining the emissions pathways that will eventually emerge in the second half of the century. The previous section highlighted the urgent need for a new strategy in the energy sector, targeted to de-carbonize energy production. This can be done through the extensive deployment of currently known abatement technologies (Pacala and Socolow, 2004) and/or through the development of new energy technologies. Let us analyze the equilibrium investment mix and the related shares of existing and innovative technologies in the stabilization investment portfolio.

Emission reductions can be achieved by increasing energy efficiency and by reducing carbon intensity. As shown in Fig. 2, energy efficiency improvements beyond the baseline scenario are an important component of a GHG control strategy. Many economic sectors are indeed characterized by the potential for large savings at relatively low costs. Yet, especially for ambitious emission reductions, energy efficiency improvements are not enough and energy de-carbonization is essential. Supply cost curves of abatement vary widely across sectors; for example they are believed to be especially steep in the transport sector. Power generation is comparatively more promising: it is a heavy weight sector in terms of emissions and one of the few for which alternative production technologies are available.

Not surprisingly, our scenarios show a significant contribution of electricity in mitigation, as illustrated in Fig. 3. To optimally achieve a 450 ppm concentration target, almost all electricity (around 90%) will have to be generated at low, almost zero, carbon rates by 2050 (left panel). The milder 550 target allows a more gradual transition away from fossil fuel based electricity, but nonetheless shows a noticeable departure from the no climate policy BaU scenario. The role of electricity is strengthened by its growing share with respect to primary energy supply. The substitution towards electricity is especially important for the more stringent 450 scenario (Fig. 3, right panel), since it makes it possible

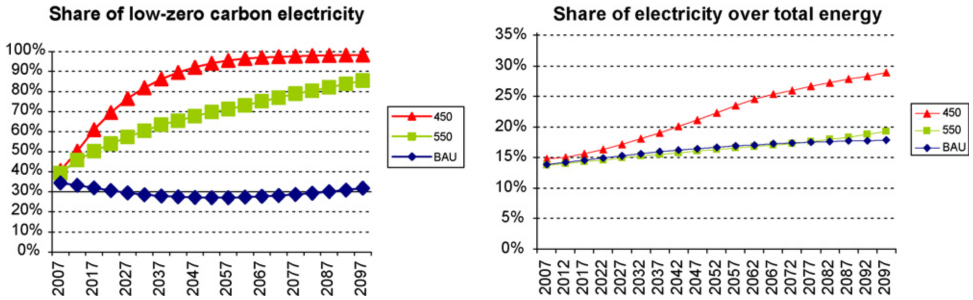

**Fig. 3.** The role of electricity in mitigation.

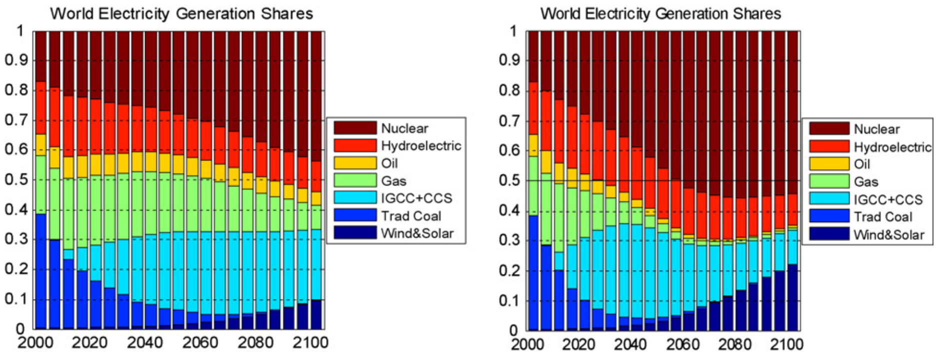

**Fig. 4.** Power generation shares for the 550 (left) and 450 (right) scenarios.

to meet the strong emissions cuts needed in the traditional non-electric sector. Such a radical change is achieved through three already operational technologies:[5] nuclear energy, renewable sources (wind and solar) and carbon capture and sequestration (CCS) (see Fig. 4 that shows the power generation shares for the 550 (left) and 450 (right) scenarios).

Nuclear power becomes extremely competitive given the range of carbon prices implicit in the adoption of climate policy, especially for the 450 case, where it eventually guarantees about 50% of total electricity generation. This remarkable expansion requires a 10-fold increase in present generation capacity. Twenty or more 1 GigaWatt (GW) nuclear plants would need to be built each year in the next half-century, bringing the nuclear industry back to the construction rates of the 1980s. Clearly, this gigantic capacity deployment for such a contentious technology would raise significant social and environmental concerns, to the point that the feasibility of a nuclear-based scenario would ultimately rest on the capacity to radically innovate the technology itself, as well as on the institutions controlling its global use. Alternatively, a scenario where nuclear power is constrained by political and environmental concerns would imply an enhanced deployment of wind and solar power plants and a minor increase in costs.

Renewable energies, especially wind power, have developed at an impressive rate in recent years (up to 10 GW per year), but the limited annual operating hours and costs bind their potential electricity contribution, at least in the short run. Only later in time would capacity additions reach 30 GW per year – especially via solar power – and be able to significantly contribute to the decarbonization of the power sector.

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[5] Although for carbon capture and sequestration only pilot projects are in place at the present moment, the technology has been operating on a smaller scale for enhanced oil recovery for a long time now.

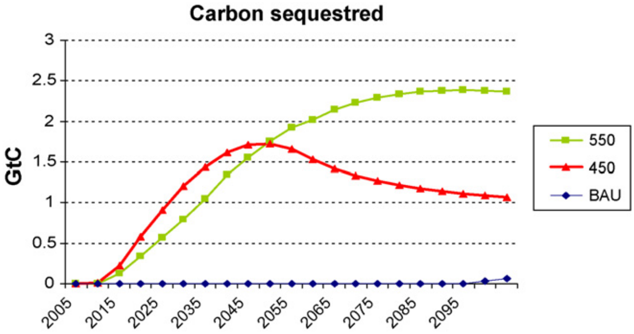

**Fig. 5.** Carbon capture and sequestration

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Carbon capture and sequestration makes it possible to burn coal in power plants while massively reducing carbon emissions. The decoupling of coal use and carbon emissions is particularly important for regions with a large endowment of coal reserves and because coal-fired power plants are very attractive for energy security reasons. However, the necessary investments are very large. To achieve the 550 ppm target, between 30 and 40 1 GW coal-with-CCS power plants would need to be built each year from 2015 onwards, a value in line with the historical capacity building of traditional coal plants (roughly 50% of electricity generated in the world). A number of large-scale pilot plants should thus be put into place in the next 10 years to ensure the feasibility of such a massive deployment.

Fig. 5 further elaborates on the role of CCS. The optimal amount of injected carbon is shown to be significant: about 2 GtC/yr (about 1/4 of today's emissions) are stored underground by mid-century. Over the whole century, about 150 GtC are injected in underground deposits (a figure in line also with the IPCC Fourth Assessment Report Working Group III). However, in the 450 scenario, the use of this technology decreases after 2050. The reason is that a more stringent target calls for a relatively greater deployment of very low carbon technologies; renewable energies and nuclear power are thus progressively preferred to CCS, because they have lower emission factors.[6] Advances in the capacity to capture $CO_2$ at the plant (assumed at 90%) would increase CCS competitiveness; though this could be counterbalanced by potential leakage from reservoirs (our simulations show that leakage rates of 0.5% per year would jeopardize the deployment of this technology).

Summing up, an equilibrium investment strategy in the energy sector that can achieve the two stabilization targets at reasonable economic costs exists (the cost would be about 2.1% of global GDP in the 450 ppm case, using a 5% discount rate, see Section 5). This energy investment strategy is based on the massive deployment of existing technologies (nuclear, solar and coal + CCS). It requires huge investments and urgent decisions. In the next section, we will explore how the potential availability of new energy technologies, developed through adequate R&D expenditures, can modify the investment scenario in the energy sector.

## 4. Innovation strategies for energy efficiency and technology breakthroughs

The previous section has outlined the need for a profound transformation of the energy sector, particularly if an ambitious climate target is to be achieved. Massive deployment of technologies that are controversial, such as nuclear power, or whose reliability and affordability is still to be proved, such as CCS, indicate that currently known technologies alone might not suffice, especially in the mid- to long-term, and that the simultaneous achievement of global economic and environmental wellbeing is likely to ultimately rest on our ability to produce innovation. This is especially important

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[6] A coal + CCS power plant emits roughly 1/3 of a natural gas one. Constraining the potential deployment of nuclear and renewables would offset this effect, since the power sector would have fewer options. A similar effect would result from the deployment of very low carbon options in the non-electric sector, since it would alleviate the mitigation effort required from the power sector, as shown in Section 4.

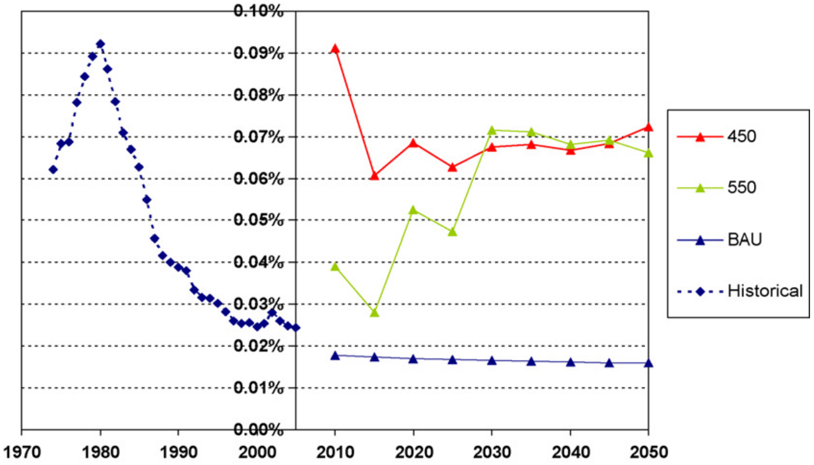

**Fig. 6.** Public energy R&D investments across scenarios to 2050.

for sectors that, at present, have a restricted portfolio of abatement options, such as transport. It is also important in case some of the mitigation alternatives described in the previous section do not deliver their expected abatement potential.

In order to address these issues, in this section we use a richer model specification in which it is possible to invest in R&D to develop technologies that still do not exist. In WITCH, R&D investments in these breakthrough technologies, both in the electric and the non-electric sector, are primarily meant to decrease the carbon intensity of energy by providing new sources with energy at zero or low carbon emissions. We refer to these technologies as "backstops". They substitute nuclear power for power generation and oil in the non-electric sector. For a complete description, see Appendix A. Technology advancement needed for achieving higher energy efficiency are still possible, but not the unique choice when it comes to invest in technological development, as it was in the scenario evaluated in the previous section. We can therefore compute the equilibrium R&D investments that countries need to implement to achieve the required improvements in energy efficiency *and* timely market penetration for new carbon free energy technologies.

Fig. 6 shows global public energy R&D expenditures. In the left-hand panel, we plot historical investment in R&D as share of Gross World Product (GWP); in the right-hand panel we plot optimal R&D investment in the three scenarios being examined. Historic data shows the well-known decline in public expenditure for energy related R&D after the 1980 peak caused by the oil crises. Very low oil prices in the 1990s led to cuts in public expenditure, which have yet to regain momentum despite the oil price surge of the past few years. A very different picture of future R&D investments emerges from the two scenarios considered here. While the baseline scenario foresees low and stable investments in R&D, both climate policy scenarios require a significant innovation effort.

For the 450 ppm case, energy expenditures ramp up to roughly 0.07% of GDP, the same share that prevailed in the 1980s. The public sector would thus be required to invest roughly 40–50 billion USD per year, globally, in the years to come; given the long time lags that separate research from commercialization, the innovation effort must be carried out immediately to allow for innovative technologies to become competitive in the medium term.[7] It should be pointed out that such investment inflow, although sizeable, is two to three orders of magnitude smaller than the investments needed to de-carbonize the energy sector using already existing technologies. The strategy based on R&D investments can thus be thought of as a hedging policy.

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[7] We assume that a 10-year lag time is necessary for R&D investments to bring cost reductions in backstops. See Appendix A for more details.

**Table 2**
Destination of R&D expenditure in a 450 scenario.

| | 2010 | 2030 | 2050 |
|---|---|---|---|
| Energy efficiency | 25% | 40% | 48% |
| Low carbon innovation in non-electric sector | 64% | 48% | 42% |
| Low carbon innovation in power generation | 11% | 12% | 12% |

**Table 3**
Total costs of stabilization 2005–100: net present value, percent of GWP losses at 5% (3% declining) discount rate.

| | 550 ppm | 450 ppm |
|---|---|---|
| Reference case | 0.27% (0.22%) | 2.1% (3.4%) |
| Limited power technologies | 1.08% (1.3%) | 3.6% (8.7%) |
| Breakthrough innovation | 0.22% (−0.11%) | 1.1% (1.3%) |

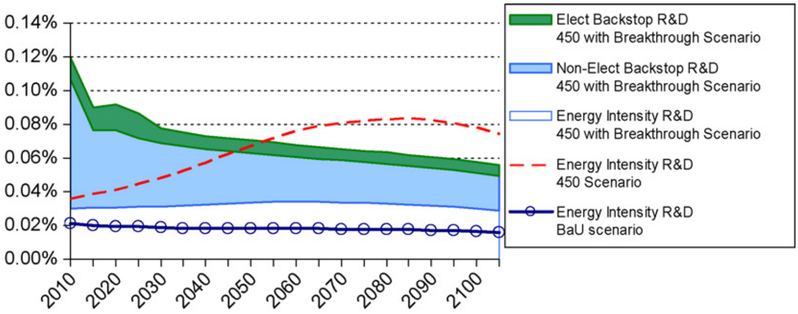

**Fig. 7.** Energy R&D investments/GDP for BaU and 450 scenarios with and without the possibility of breakthrough innovation.

The less stringent 550 ppm scenario shows a more gradual innovation pathway, with expenditure rising over time to eventually reach figures similar to those in the 450 ppm scenario, only with a 20-year delay.

A key policy question is where such public R&D investments should be directed to. Table 2 shows the optimal allocation of R&D investment between energy efficiency and de-carbonization programs, in both the electric and non-electric sectors, for the 450 scenario.

It shows that the non-electric sector, particularly to substitute the transport-led non-electric oil demand, should receive most of the innovation funding initially, though over time energy efficiency innovation expenditure increases its relevance and eventually takes the lead (in 2050). The power sector is allocated a smaller but constant share. This shift in the timing is due to the very nature of investment in breakthrough technologies: a flow of investments in specific R&D is needed to continue improving energy efficiency, which exhibits decreasing marginal returns. On the other hand, investing in backstop R&D builds a stock which decreases the costs of the technology with very high returns at the beginning. Once the technology becomes available and economically competitive, then investing in backstop R&D becomes less important as a channel to decrease the price of the backstop technology. In other words, R&D in energy efficiency does not have a permanent effect, while R&D in backstop does.

Note also that R&D investment in backstops substitute part of the energy efficiency R&D when the 450 ppm stabilization target is to be achieved without the aid of the backstop technologies, though investments in the backstop technologies remain higher than in the BaU (see Fig. 7).

The possibility of technology breakthroughs in the electricity sector also has an effect on the optimal investments in already known technologies. For example, investments in CCS are crucially affected by the presence of backstop technologies. In the 450 scenario, CCS investment no longer

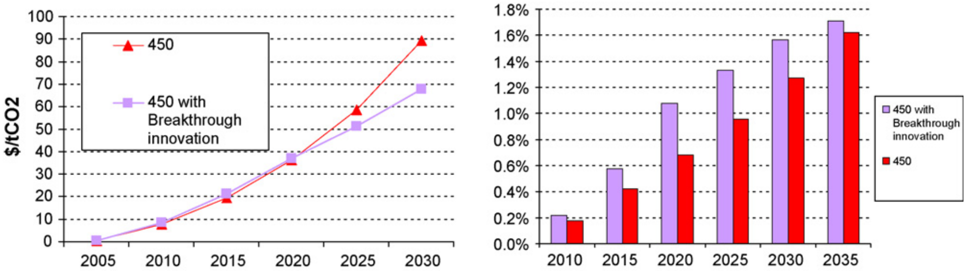

**Fig. 8.** Carbon price (left) and GWP loss (right) for a 450 scenario with and without the possibility of breakthrough innovation.

displays the peak effect observed in Fig. 5. The reason for this is the presence of a carbon free backstop in the non-electric sector: it relieves the electricity sector from an excessive mitigation burden, which jeopardized CCS in the long run due to the non-perfect capture rate of carbon.

## 5. Economic impacts of different technological scenarios

The previous sections have illustrated the need for drastic changes in the way we consume and produce energy. They highlighted the need to mobilize substantial investment resources towards carbon free technologies. This is likely to have important implications for the economic system. In this section, we summarize the economic impact of both 550 and 450 ppm stabilization scenarios, with a particular focus on the role played by energy technologies.

Table 3 shows net present value losses of GWP for both climate policy scenarios and different technology settings.[8] The reference case shows how, in the 550 ppm scenario, costs are almost negligible, whereas they are significant in the 450 ppm case. The cost difference between the two mitigation policies is a direct consequence of the different magnitudes of energy sector modifications required. It also stems from the non-linearity of endogenous marginal abatement curves in the model. The 450 ppm policy requires drastic cuts in emissions, especially in the second half of the century, when emissions are stabilized at around 3 GtC/yr. With growing economies and population, this entails a significant increase in energy costs, particularly as mitigation gets more and more stringent. The effect of temporal discounting is partially compensated by the growing dimension of economic activity.

The economic effect of limiting the power sector technologies described in Section 3 is shown in the second row. Indeed, if we assume a world in which the expansion of wind and solar technologies is bound by limits to large-scale deployment, the options to expand nuclear energy are limited (possibly because of political or environmental reasons) and Integrated Gasification Combined Cycle (IGCC) with CCS technologies do not become competitive,[9] then achieving a stabilization target is much more costly, with an increase in the order of 1.5–3 times. On the other hand, allowing for R&D investments in new low carbon technologies, that would enable breakthrough innovation, is shown to be able to substantially reduce the economic policy costs.[10] These differences are particularly important for the stringent 450 ppm target, which requires a fundamental restructuring of the energy sector.[11]

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[8] The numbers shown include the avoided climate damages induced by the policies. However, the NPV calculations put most of the weight on early periods for which almost no temperature decrease is achieved, so that gross economic losses are only 10–20% above the ones indicated here.

[9] The specific constraints used are nuclear energy cannot expand above current generation levels, CCS is not allowed; W&S can provide at most 35% of total electricity.

[10] Costs become slightly negative in the 550 ppm scenario with breakthrough technological innovation and low discount rate (3% declining). This result depends on the game-theoretic structure of the model that enables us to account for inefficiencies and free riding behavior in technological innovation. In the case of a mild climate policy and low discount rate, the future benefits in terms of lower inefficiencies produced by a mild climate signal are larger than the cost of controlling emissions.

[11] See Bosetti et al. (2009a) for a comparison of these results with those on the policy cost increases induced by delayed developing countries' participation in the global effort to control GHG emissions.

However different these scenarios may be, it should be noted that, in the short term, a strong carbon price signal would be needed to bring about what could be called a technology revolution. As shown in Fig. 8, left panel,[12] the carbon signal of a reference 450 scenario is very similar to that of the most optimistic case of breakthrough inventions.

Higher GWP losses will be experienced initially in the breakthrough technologies case (right panel) in order to make R&D resources available, but this would pay off in the future allowing for the substantial cost reductions shown in Table 3.

## 6. Conclusions

This paper has investigated optimal investment strategies in the energy sector for two climate policy scenarios. Our results show that the stabilization of $CO_2$ concentrations at 550 and 450 ppm (650 and 550 $CO_2$ equivalent) is feasible at reasonable economic costs, but that it requires radical changes in the energy sector and large investments in R&D.

Both energy efficiency and the de-carbonization of energy should be pursued. Currently known technologies in the power sector such as nuclear, renewable energy sources and CCS will be essential, but very large investments – greater than the energy sector has ever experienced – will be needed. At the same time, R&D investments for the development of new technologies, especially in the transport sector, will be required. Public R&D expenditures should increase considerably, over the peak levels of the 1980s for at least three decades. Given the long time lags inherent to the innovation process, such investments should be made starting today.

Our results thus support the call for R&D policies that complement climate stabilization policies and reduce the costs of limiting dangerous climate change (on this issue, see also Bosetti et al., 2009b). They also indicate that a strong price signal will nonetheless be needed if the climate change challenge is to be met, regardless of whether we expect low carbon breakthrough technologies to be available in the future, because of the inertia in the accumulation of GHG in the atmosphere and low decay rates.

Let us conclude by stressing that our results differ from previous analyses of GHG stabilization policies, where a single global economy is usually assumed (Nordhaus' RICE model and its applications by Nordhaus himself and by Eyckmans, Yang, Finus, Tulkens and others are notable exceptions). The game-theoretic framework used to compute the equilibrium outcomes allows us to capture the non-cooperative dynamic strategic interactions among the 12 regions in which the world is divided in WITCH. Regions compete on natural resources use (fuels and the global climate public good) and interact strategically on knowledge development and diffusion, as explained in Appendix A. The implications of this richer modeling environment are complex and cannot be appropriately addressed in this article. However, it is worth mentioning that while in our set-up climate policy performs, at least partly, as a coordination mechanism which brings the extraction path of natural resources closer to the global social optimum (the social optimum indeed for the climate global public good), thus driving stabilization costs down with respect to a traditional single economy global model, the non-cooperative representation of knowledge creation and diffusion processes works in the opposite direction, and yields a sub-optimal allocation of resources to technological advancements. This latter effect – as well as the well-known free-riding incentives on the climate global public good – tends to increase stabilization costs. This explains why our estimates of stabilization costs are higher than those reported by IPCC (2007), despite the presence of endogenous technical change and forward looking decision-makers. Further work on the implications of adopting a non-cooperative game-theoretic framework is still necessary.

## Appendix A. Description of WITCH

Full details on the WITCH model can be found in Bosetti et al. (2006b). The description below focuses on the overall model structure, and on the specification of endogenous technical change (ETC) processes.

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[12] The carbon prices displayed assume full country participation to an international carbon market. In case of fragmented or partial agreements, they would rise very significantly (see Bosetti et al., 2008b).

### A.1. Overall model structure

WITCH is a dynamic optimal growth general equilibrium model with a detailed ("bottom-up") representation of the energy sector, thus belonging to a new class of hybrid (both "top-down" and "bottom-up") models. It is a global model, divided into 12 macro-regions. A reduced form climate module (MAGICC) provides the climate feedback on the economic system. The model covers $CO_2$ emissions but does not incorporate other GHGs, whose concentration is typically added exogenously to $CO_2$ concentration in order to obtain overall GHG concentration—a 450 ppm $CO_2$ concentration scenario is roughly assumed to correspond to a 550 ppm overall GHG concentration scenario in the simulations below. In addition to the full integration of a detailed representation of the energy sector into a macro-model of the world economy, distinguishing features of the model are:

- *Endogenous technical change*. Advancements in carbon mitigation technologies are described by both diffusion and innovation processes. Learning by Doing and Learning by Researching (R&D) processes are explicitly modeled and enable to identify the "optimal"[13] public investment strategies in technologies and R&D in response to given climate policies. Some international technology spillovers are also modeled.
- *Game-theoretic set-up*. The model can produce two different solutions, a cooperative one that is globally optimal (global central planner) and a decentralized, non-cooperative one that is strategically optimal for each given region (Nash equilibrium). As a result, externalities due to global public goods ($CO_2$, international knowledge spillovers, exhaustible resources, etc.) and the related free-riding incentives can both be accounted for, and the optimal policy response (world $CO_2$ emission reduction policy, world R&D policy) be explored. A typical output of the model is an equilibrium carbon price path and the associated portfolio of investments in energy technologies and R&D under a given environmental target.[14]

### A.2. Endogenous technical change in the WITCH model

In the basic version of WITCH, technical change is endogenous and is driven both by learning-by-doing (LbD) and by public energy R&D investments.[15] These two drivers of technological improvements display their effects through two different channels: LbD is specific to the power generation industry, while energy R&D affects overall energy efficiency in the economy.

The effect of technology diffusion is incorporated based on experience curves that reproduce the observed negative empirical relationship between the investment cost of a given technology and cumulative installed capacity. Specifically, the cumulative installed world capacity is used as a proxy for the accrual of knowledge that affects the investment cost of a given technology:

$$\mathrm{SC}(t+1) = A \cdot \sum\nolimits_n K(n,t)^{-\log_2 \mathrm{PR}} \tag{1}$$

where SC is the investment cost of technology $j$, PR is the so-called progress ratio that defines the speed of learning, $A$ is a scale factor and $K$ is the cumulative installed capacity for region $n$ at time $t$. With every doubling of cumulative capacity the ratio of the new investment cost to its original value is constant and equal to $1/PR$. With several electricity production technologies, the model is flexible enough to change the power production mix and modify investment strategies towards the most appropriate technology for each given policy measure, thus creating the conditions to foster the LbD effects associated with emission-reducing but initially expensive electricity production techniques.

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[13] Insofar as the solution concept adopted in the model is the Nash equilibrium (see below), "optimality" should not be interpreted as a first-best outcome but simply as a second-best outcome resulting from strategic optimization by each individual world region.

[14] A stochastic programming version of the model also exists to analyze optimal decisions under uncertainty and learning. However, it was not used within the context of this paper.

[15] Due to data availability constraints, only public R&D is modeled in the current version of WITCH. However, private R&D would be expected to respond in a qualitatively similar way to climate change mitigation policies.

Experience is assumed to fully spill over across countries, thus implying an innovation market failure associated with the non-appropriability of learning processes.

R&D investments in energy increase energy efficiency and thereby foster endogenous technical change. Following Popp (2004), technological advances are captured by a stock of knowledge combined with energy in a constant elasticity of substitution (CES) function, thus stimulating energy efficiency improvements:

$$\mathrm{ES}(n,t) = [\alpha_{\mathrm{H}}(n)\mathrm{HE}(n,t)^{\rho} + \alpha_{\mathrm{EN}}(n)\mathrm{EN}(n,t)^{\rho}]^{1/\rho} \tag{2}$$

where EN($n$,$t$) denotes the energy input, HE($n$,$t$) is the stock of knowledge and ES($n$,$t$) is the amount of energy services produced by combining energy and knowledge. The stock of knowledge HE($n$,$t$) derives from energy R&D investments in each region through an innovation possibility frontier characterized by diminishing returns to research, a formulation proposed by Jones (1995) and empirically supported by Popp (2002) for energy-efficient innovations in the United States:

$$\mathrm{HE}(n,t+1) = aI_{\mathrm{R\&D}}(n,t)^{b}\mathrm{HE}(n,t)^{c} + \mathrm{HE}(n,t)(1-\delta_{\mathrm{R\&D}}) \tag{3}$$

where $\delta_{\mathrm{R\&D}}$ is the depreciation rate of knowledge, and b and c are both between 0 and 1 so that there are diminishing returns to R&D both at any given time and across time periods. Reflecting the high social returns from energy R&D, it is assumed that the return on energy R&D investment is 4 times higher than that on physical capital. At the same time, the opportunity cost of crowding out other forms of R&D is obtained by subtracting four dollars of private investment from the physical capital stock for each dollar of R&D crowded out by energy R&D, $\psi_{\mathrm{R\&D}}$, so that the net capital stock for final good production becomes:

$$K_{\mathrm{C}}(n,t+1) = K_{\mathrm{C}}(n,t)(1-\delta_{\mathrm{C}}) + (I_{\mathrm{C}}(n,t) - 4\psi_{\mathrm{R\&D}}I_{\mathrm{R\&D}}(n,t)) \tag{4}$$

where $\delta_{\mathrm{C}}$ is the depreciation rate of the physical capital stock. New energy R&D is assumed to crowd out 50% of other R&D, as in Popp (2004).

The WITCH model has been extended to carry out the analysis presented in this paper to include additional channels for technological improvements, namely learning through research or "learning-by-searching" (LbS) in existing low carbon technologies (wind and solar electricity, electricity from integrated gasifier combined cycle (IGCC) plants with carbon capture and storage (CCS)), and the possibility of developing breakthrough, zero-carbon technologies for both the electricity and non-electricity sectors.

### *A.3. Breakthrough technologies*

In the enhanced version of the model used for this paper, backstop technologies in both the electricity and non-electricity sectors are developed and diffused in a two-stage process, through investments in R&D first and installed capacity in a second stage. A backstop technology can be better thought of as a compact representation of a portfolio of advanced technologies. These would ease the mitigation burden away from currently commercial options, but they would become commercially available only provided sufficient R&D investments are undertaken, and not before a few decades. This simplified representation maintains simplicity in the model by limiting the array of future energy technologies and thus the dimensionality of techno-economic parameters for which reliable estimates and meaningful modeling characterization exist.

Concretely, the backstop technologies are modeled using historical and current expenditures and installed capacity for technologies which are already researched but are not yet viable (*e.g.* fuel cells, advanced biofuels, advanced nuclear technologies, etc.), without specifying the type of technology that will enter into the market. In line with the most recent literature, the emergence of these backstop technologies is modeled through so-called "two-factor learning curves", in which the cost of a given backstop technology declines both with investment in dedicated R&D and with technology diffusion (see *e.g.* Kouvaritakis et al., 2000). This formulation is meant to overcome the limitations of single factor experience curves, in which the cost of a technology declines only through "pure" LbD effects from technology diffusion, without the need for R&D investment (Nemet, 2006). Nonetheless, modeling long term and uncertain phenomena such as technological evolution is inherently difficult, which calls for caution in interpreting the exact quantitative results and for sensitivity analysis (see below).[16]

Bearing this caveat in mind, the investment cost in a technology tec is assumed to be driven both by LbS (main driving force before adoption) and LbD (main driving force after adoption), with $P_{\mathrm{tec},t}$, the unit cost of technology tec at time $t$, being a function of the dedicated R&D stock $\mathrm{R\&D}_{\mathrm{tec},t}$ and deployment $\mathrm{CC}_{\mathrm{tec},t}$:

$$\frac{P_{\mathrm{tec},T}}{P_{\mathrm{tec},0}} = \left(\frac{\mathrm{R\&D}_{\mathrm{tec},T-2}}{\mathrm{R\&D}_{\mathrm{tec},0}}\right)^{-e} \times \left(\frac{\mathrm{CC}_{\mathrm{tec},T}}{\mathrm{CC}_{\mathrm{tec},0}}\right)^{-d} \tag{5}$$

where the *R&D stock* accumulates with the perpetual inventory method and CC is the cumulative installed capacity (or consumption) of the technology. A two-period (10 years) lag is assumed between R&D capital accumulation and its effect on the price of the backstop technologies, capturing in a crude way existing time lags between research and commercialization. The two exponents are the LbD index ($-d$) and the learning by researching index ($-e$). They define the speed of learning and are derived from the learning ratios. The learning ratio lr is the rate at which the generating cost declines each time the cumulative capacity doubles, while lrS is the rate at which the cost declines each time the knowledge stock doubles. The relation between $d$, $e$, lr and lrS can be expressed as follows:

$$1 - \mathrm{lr} = 2^{-d} \quad \text{and} \quad 1 - \mathrm{lrS} = 2^{-e} \tag{6}$$

The initial prices of the backstop technologies are set at roughly 10 times the 2002 price of commercial equivalents. The cumulative deployment of the technology is initiated at 1000 TWh, an arbitrarily low value (Kypreos, 2007). The backstop technologies are assumed to be renewable in the sense that the fuel cost component is negligible. For power generation, it is assumed to operate at load factors (defined as the ratio of actual to maximum potential output of a power plant) comparable with those of baseload power generation.

This formulation has received significant attention from the empirical and modeling literature in the recent past (see, for instance, Criqui et al., 2000; Barreto and Kypreos, 2004; Klassen et al., 2005; Kypreos, 2007; Jamasab, 2007; Söderholm and Klassen, 2007). However, estimates of parameters controlling the learning processes vary significantly across available studies. Here, averages of existing values are used, as reported in Table 1. The value chosen for the LbD parameter is lower than those typically estimated in single factor experience curves, since here technological progress results in part from dedicated R&D investment. This more conservative approach reduces the role of “autonomous” learning, which has been seen as overly optimistic and leading to excessively low costs of transition towards low carbon economies.[17]

Backstop technologies substitute linearly for nuclear power in the electricity sector, and for oil in the non-electricity sector. Once backstop technologies become competitive thanks to dedicated R&D investment and pilot deployments, their uptake is assumed to be gradual rather than immediate and complete. These penetration limits are a reflection of inertia in the system, as presumably the large deployment of backstops would require investment in infrastructures and wide re-organization of economic activity. The upper limit on penetration is set equivalent to 5% of the total consumption in the previous period by technologies other than the backstop, plus the electricity produced by the backstop in the electricity sector, and 7% in the non-electricity sector.

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[16] This is especially true when looking at the projected carbon prices and economic costs at long horizons—typically beyond 2030, while the short-run implications of long-run technological developments are comparatively more robust across a range of alternative technological scenarios (see below).

[17] Problems involved in estimating learning effects include: (i) selection bias, *i.e.* technologies that experience smaller cost reductions drop out of the market and therefore of the estimation sample; (ii) risks of reverse causation, *i.e.* cost reductions may induce greater deployment, so that attempts to force the reverse may lead to disappointing learning rates *a posteriori*; (iii) the difficulty to discriminate between “pure” learning effects and the impact of accompanying R&D as captured through two-factor learning curves; (iv) the fact that past cost declines may not provide a reliable indication of future cost reductions, as factors driving both may differ; (v) the use of price – as opposed to cost – data, so that observed price reductions may reflect not only learning effects but also other factors such as strategic firm behavior under imperfect competition.

### *A.4. Spillovers in knowledge and experience*

In addition to the international LbD spillovers mentioned above, WITCH also features international spillovers in knowledge for energy efficiency improvements. The amount of spillovers entering each world region is assumed to depend both on a pool of freely available world knowledge and on the ability of each country to benefit from it. In turn, this absorption capacity depends on the domestic knowledge stock, which is built up through domestic R&D according to a standard perpetual capital accumulation rule. The region then combines knowledge acquired from abroad with the domestic knowledge stock to produce new technologies at home. For details, see Bosetti et al. (2007b).

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