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Optimal Energy Investment and R&D Strategies to Stabilise Greenhouse Gas Atmospheric Concentrations

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Summary

The stabilisation of GHG atmospheric concentrations at levels expected to prevent dangerous climate change has become an important, global, long-term 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 some cost-effective strategies that stabilise CO_2 concentrations at 550 or 450 ppm. In particular, this paper analyses the energy investment and R&D policies that optimally achieve these two GHG stabilisation targets (i.e. the future optimal energy mix consistent with the stabilisation of GHG atmospheric concentrations at 550 and 450 ppm). Given that the model accounts for interdependencies and spillovers across 12 regions of the world, optimal strategies are the outcome of a dynamic game through which inefficiency costs induced by global strategic interactions can be assessed. Therefore, our results are somehow different from previous analyses of GHG stabilisation policies, where a central planner or a single global economy are usually assumed. In particular, the effects of free-riding incentives in reducing emissions and in investing in R&D are taken into account. Technical change being endogenous in WITCH, this paper also provides an assessment of the implications of technological evolution in the energy sector of different stabilisation scenarios. Finally, this paper quantifies the *net* costs of stabilising GHG concentrations at different levels, for different allocations of permits and for different technological scenarios. In each case, the optimal long-term investment strategies for all available energy technologies are determined. The case of an unknown backstop energy technology is also analysed.

Keywords: Climate Policy, Energy R&D, Investments, Stabilisation Costs

JEL Classification: H0, H2, H3

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1. Introduction

Climate change may dramatically damage future generations. If anthropogenic GHG emissions are among the main causes of climate change, whatever their exact relevance in the overall climatic process, it becomes necessary to identify when, where and how these emissions ought to be controlled.

Policymakers in almost all world countries are indeed discussing how to tackle the climate change problem. In the 2007 G8 summit in Heiligendamm, the leading industrialised nations agreed on the objective of at least halving global CO_2 emissions by 2050[1]. Such an agreement follows earlier resolutions of other countries, such as the EU, Canada and Japan.[2] Therefore, a primary research effort is to provide information on the optimal strategy – in particular in terms of energy R&D and investments in the energy sector – that different regions of the world should adopt in order to minimise the costs of achieving their own emission reduction target.

How is optimality of energy strategies defined in this context? The long-term stabilisation target is clearly a political decision. There is indeed a lot of uncertainty on the threshold temperature level and its relationship with GHG concentrations (as made clear in the last IPCC Fourth Assessment Report). Therefore, for analytical purposes, this paper considers two long term targets, both expressed in terms of carbon atmospheric concentrations. The first target is a 550 ppm (CO_2 only) concentration target. The second one stabilises emissions at 450 ppm (CO_2 only). These two reference targets roughly coincide with IPCC Post-TAR stabilisation scenarios C and B respectively. Although the IPCC considers even more stringent emissions pathways, we resort to focus on the two that we consider more politically realistic. The first target is often advocated in the US (see for example Newell and Hall, 2007), whereas the second one is close to the EU objective of keeping future temperature changes below 2 degrees Celsius. Optimality is then defined as the welfare maximising path of energy R&D expenditures, investments in energy technologies and direct consumption of fossil fuels consistent with the proposed stabilisation targets.

The optimal R&D and investment strategies in a given world region depend upon many factors: for example, upon the discount rate, or the investment decisions taken in other regions or countries, or the effectiveness of R&D in increasing energy efficiency, or in providing new, low carbon, energy technologies. Optimal R&D and investment strategies also depend on the expected

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[1] http://www.g-8.de/nn_94646/Content/EN/Artikel/__g8-summit/2007-06-07-g8-klimaschutz__en.html

climate damages, on the economic growth in various regions of the world, and on other economic and demographic variables. In this paper, all these interdependencies are taken into account.

A new, hybrid, climate-energy-economy model has been developed to analyse the complex geographical and intertemporal interactions of the main socio-economic, technological and climatic variables. This is WITCH (Bosetti, Carraro, Galeotti, Massetti and Tavoni, 2006), a climate-energy-economy model in which a bottom-up specification of the energy sector is fully integrated into a top-down intertemporal optimisation model of the world economy. The model accounts for interdependencies and spillovers across 12 regions of the world. Therefore, optimal 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 stabilisation scenarios on induced technical change. Feedbacks from economic variables into climatic ones, and vice versa, are also accounted for in the model dynamic system.

These features enable WITCH to address many questions that naturally arise when analysing carbon mitigation policies. Among those to which this paper aims to respond are the following: what are the implications of the proposed stabilisation targets for investments and consumption of traditional – fossil-fuel-based – energy sources? In order to achieve a given stabilisation target, when and how should countries move to a different energy-mix in which renewables and/or nuclear energy become the main energy sources? What is the cost of maintaining CO_2 concentrations below 450 ppm? Is this target feasible from an economic and technological viewpoint? How is the cost distributed among different world regions? If some degree of innovation is necessary to achieve the 450 ppm target, what is the estimated R&D expenditure necessary to induce the required innovation? When should this expenditure be made?

This paper addresses the above questions from an economic viewpoint by using a model in which future technological scenarios are carefully modelled. The objective of this paper is therefore twofold. On the one hand, it will present the main features of the WITCH model. On the other hand, thanks to the new features of WITCH, it will provide some novel insights into the costs of climate change control and into the optimal strategies to achieve it.

The structure of the paper is as follows. Section 2 provides a concise description of the WITCH Model. For a thorough presentation of the model, the interested reader is referred to Bosetti, Massetti and Tavoni (2007). Section 3 presents our main results on the costs of stabilising GHG

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[2] The European Union, for example, has identified both its long term target (a temperature increase below 2 degrees Celsius) and the 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 all countries jointly reduce their emissions in the same manner).

atmospheric concentrations and on the related energy R&D and investment strategies. Section 4 analyses the implications of these optimal strategies for the price of emission permits in a global permit market. Section 5 provides a deeper analysis of some specific issues: the role of R&D expenditure, the effects of a backstop technology and the economic implications of carbon capture and sequestration. A concluding section summarises our main results.

2. The WITCH model

WITCH is a regional integrated assessment model designed to provide normative information on the optimal responses of world economies to climate damages and to model the channels of transmission of climate policy into the economic system (see Bosetti, Carraro, Galeotti, Massetti and Tavoni, 2006). It is a hybrid model because it combines features of both top-down and bottom-up modelling: the top-down component consists of an intertemporal optimal growth model, in which the energy input of the aggregate production function has been expanded to yield a bottom-up description of the energy sector. World countries are grouped in 12 regions whose strategic interactions have been modelled using a game-theoretic approach. A climate module and a damage function provide the feedback on the economy of carbon dioxide emissions into the atmosphere.

Several features of the model allow us to investigate a number of issues in greater detail than is usually done in the existing literature. First, although rather rich in energy detail and close in spirit to bottom-up energy models, WITCH is based on a top-down framework that guarantees a coherent, forward-looking, fully intertemporal allocation of investments in physical capital and in R&D. Second, the model accounts for most actions that have an impact on the level of GHG mitigation – e.g. R&D expenditures, investment in carbon-free technologies, purchases of emissions permits or expenditure for carbon taxes – and can thus be used to evaluate optimal economic and technological responses to different policy measures. This yields a transparent evaluation of abatement costs and a clear quantification of the uncertainties affecting them. Finally, the regional specification of the model and the presence of strategic interaction among regions – as for example through learning spillovers in wind & solar technologies, R&D spillovers or climate damages – allows us to account for the incentives to free-ride in the choice of optimal investments.

Optimal growth models are normally limited in terms of technological detail. This severely constrains the analyses of climate change issues, which are closely related to the evolution of energy sector technologies. In WITCH, this sector is more detailed than in standard optimal growth models and thus grants a reasonable characterisation of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilising greenhouse gases concentrations. Also, by endogenously modelling fuel prices, as well as the cost of storing the CO_2 captured, the model can be used to evaluate the implication of mitigation policies on the energy system in all its components.

A key feature of WITCH is that it explicitly models the interdependency of all countries' climate, energy and technology policies. The investment strategies are thus optimised by taking into account both economic and environmental externalities (e.g. CO_2, exhaustible resources, international R&D spillovers, etc). The investment profile for each technology is the solution of an inter-temporal game among the 12 regions. More specifically, these 12 regions behave strategically with respect to all decision variables by playing an open-loop Nash game. From a top-down perspective, this enables us to analyse both the geographical dimension (e.g. rich vs. poor regions) and the time dimension (e.g. present vs. future generations) of climate policy.

In comparison to other optimal growth models, WITCH shares a game set-up similar to that in RICE (Nordhaus and Boyer, 2000), but departs from that stylised representation of the energy sector by featuring a greater technological detail, the endogenisation of technical change, natural resource depletion, etc. Also MERGE (Manne, Mendelsohn and Richels, 1995) links a simple top-down model to a bottom-up model. However, WITCH is not a linked model, but a single, fully integrated model that represents the energy sector within the economy, and therefore identifies the optimal energy technology investment paths coherently with the optimal growth path.

Technical change in WITCH is endogenous and can be induced by climate policy, international spillovers and other economic effects. The hybrid nature of WITCH allows to portray endogenous technological change both in its bottom-up and top-down dimensions. It is driven both by Learning-by-Doing (LbD) and by energy R&D investments. These two factors of technological improvements act through two different channels: LbD is specific to the power generation costs, while R&D affects the non-electric sector and the overall energy efficiency of the system. Following Popp (2004), technological advances are captured by a stock of knowledge combined with energy in a constant elasticity of substitution (CES) function. Positive changes of this stock of knowledge improve energy efficiency. The stock of knowledge $HE(n,t)$ derives from energy R&D investments in each region through an innovation possibility frontier characterised by diminishing returns to research, a formulation proposed by Jones (1995) and empirically supported by Popp (2002) for energy-efficient innovations. As social returns of R&D are found to be higher than private returns in the case of R&D, the positive externality of knowledge creation is accounted for by assuming that the return on energy R&D investment is four times higher than the one in physical capital (Nordhaus, 2003). 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. We assume new energy R&D crowds out half of the other R&D investments, as in Popp (2004).

For a thorough discussion of model calibration the interested reader is referred to Bosetti, Massetti and Tavoni (2006).

3. The Cost of Stabilising GHG Atmospheric Concentrations

Two stabilisation targets have been considered in our analysis of stabilisation strategies and of the related costs. In the first one, optimal investments and R&D strategies are targeted to stabilise CO_2 atmospheric concentrations at 550 ppm by the end of the century. This is roughly equivalent to a 650 ppm target if all GHGs are included. The second target is more ambitious. The optimal investment and R&D strategies have been designed to stabilise CO_2 concentrations at 450 ppm (550 ppm all gases included). The optimal emission time profiles are shown in Figure 1. Among the different sets of emission profiles that are consistent with the aforementioned stabilisation targets, the ones shown here are the solution of the fully cooperative version of the WITCH model given the concentration constraint. Therefore, we can call them the *optimal* emission time profiles.

Current annual CO_2 emissions are about 7 GtC/yr. Without any stabilisation policy (the Business as Usual scenario), and according to the endogenous dynamics of the WITCH model, CO_2 emissions would reach about 21 GtC by the end of the century, a value in line with IPCC B2 SRES scenarios. Notice that this value takes into account feedbacks from climate damage on the production of economic goods[3]. In the case of the 550 ppm stabilisation target, annual emissions slowly increase until 2060 (when they reach 10 GtC per year) and then decrease to 8 GtC by the end of the century. If the target is 450 ppm, emissions start decreasing immediately and reach 3GtC by the end of the century. That is, the optimal profile does not allow for overshooting of emissions that would trade off current and future abatement. Such a reduction of emissions is particularly significant given the expected growth rate of world population and GDP; average emissions per capita in the second part of this century would have to change from about 2 to about 0.3 tC per year[4].

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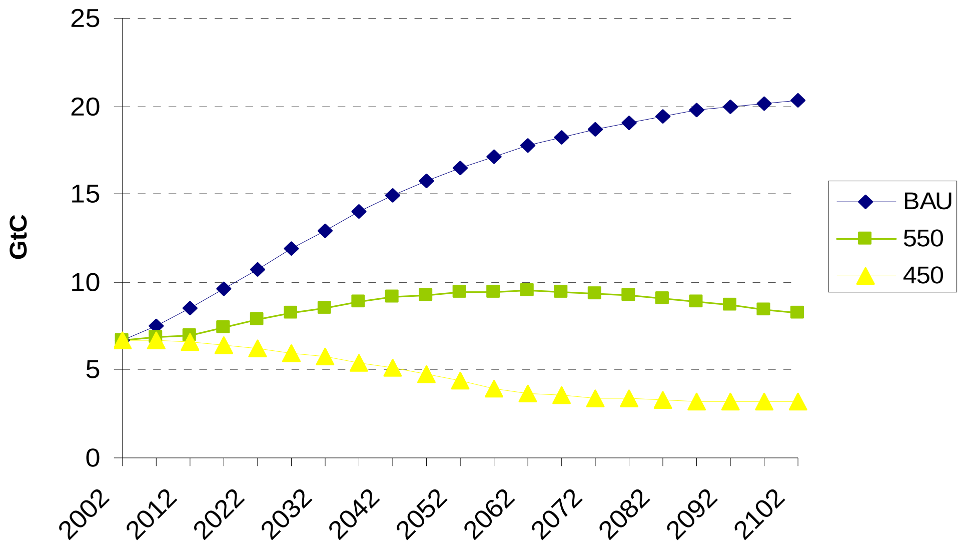
[3] We adopt the same damage function as in Nordhaus and Boyer (2000).

[4] 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.

Figure 1. World industrial emissions in the three scenarios (2002-2102).



A further understanding of the difference between the two concentration targets can be obtained by comparing the dynamics of the main economic variables under the three scenarios (business as usual, 550 and 450 ppm target). Let us focus on the variables belonging to the well-known Kaya identity (emissions, per capita GDP, energy intensity, carbon intensity of energy and population). Table 1 shows the changes in these variables for two periods: 1972-2002 (historical values) and 2002-2032 (projections from WITCH).

In the BAU scenario, future values of all economic variables are close to those observed in the past thirty years. Baseline emissions almost double in 30 yrs time, due to increasing population and improving lifestyles; this increase is partially compensated by a looser economy-energy interdependence, but not by an energy-carbon decoupling. The definition of the baseline has important implications in terms of efforts required to stabilise the climate (and therefore in terms of stabilisation costs). In this respect, the reproduction of history – at least over short time horizons – provides a useful benchmark.

In the 550 ppm scenario, the reduced emissions growth mainly stems from energy efficiency improvements as testified by the further decrease of energy intensity (Δ EN/GDP column), although some decarbonisation of energy is also needed. A more fundamental change of picture 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. Notice that in both the 450 and 550 ppm stabilisation scenarios, the GDP loss arising from the effort of stabilising GHG concentrations is fairly small. This issue will be discussed at length below.

Table 1. Ratio of future over past values of the Kaya' s variables in the three scenarios (1972-2032)

WORLD

2032 vs 2002	Δ EMI	Δ GDP/POP	Δ EN/GDP	Δ EMI/EN	Δ POP
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	Δ EMI	Δ GDP/POP	Δ EN/GDP	Δ EMI/EN	Δ POP
Historical	1,96	1,64	0,76	0,97	1,63

OECD

2032 vs 2002	Δ EMI	Δ GDP/POP	Δ EN/GDP	Δ EMI/EN	Δ POP
BAU	1,44	1,76	0,77	0,99	1,07
550	0,94	1,75	0,67	0,75	1,07
450	0,69	1,72	0,57	0,65	1,07

2002 vs 1972	Δ EMI	Δ GDP/POP	Δ EN/GDP	Δ EMI/EN	Δ POP
Historical	1,46	1,94	0,57	1,03	1,28

NON-OECD

2032 vs 2002	Δ EMI	Δ GDP/POP	Δ EN/GDP	Δ EMI/EN	Δ POP
BAU	2,51	3,76	0,45	1,09	1,35
550	1,68	3,76	0,36	0,92	1,35
450	1,05	3,75	0,28	0,75	1,35

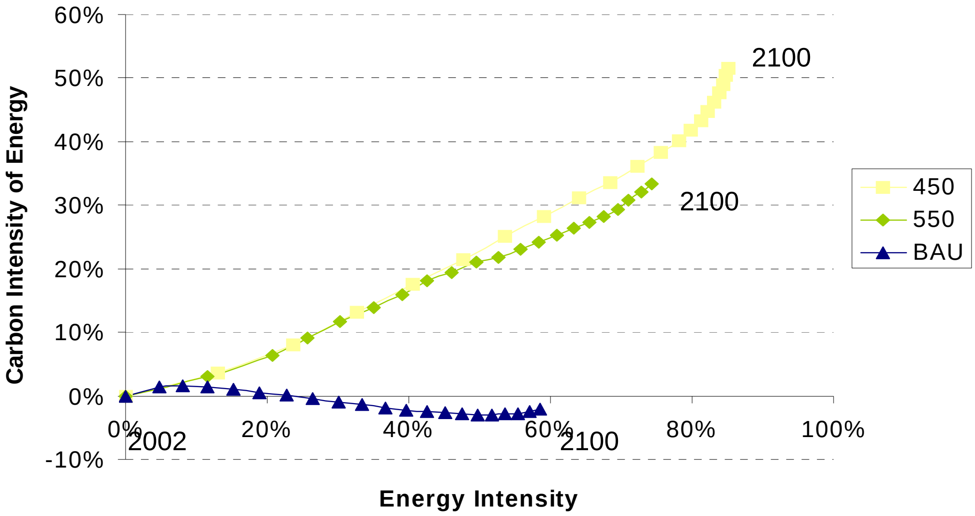
2002 vs 1972	Δ EMI	Δ GDP/POP	Δ EN/GDP	Δ EMI/EN	Δ POP
Historical	3,25	2,18	0,90	0,94	1,77

As for the distribution of effort between the OECD and Non-OECD countries, this depends on the allocation scheme considered. Even if we assume a burden-sharing agreement on the basis of evenly balanced emissions per person – the so-called equal per capita scheme – we can see from Table 1 that improvements of energy efficiency are larger in Non-OECD than in OECD countries.

Developing countries reduce the energy intensity of their economies by roughly 70% in order to keep emissions at present levels. This shows the increasing relevance of the developing world in contributing to control global carbon emissions. On the other hand, OECD countries improve their performance in terms of energy decarbonisation, given the higher energy efficiency standards and capacity to invest in capital intensive technologies with low carbon emission factors.

Figure 2 provides some additional interesting information on the temporal modifications of the energy sector, as it plots the evolution of energy intensity and carbon content of energy throughout the 21st century. The BAU scenario is characterised by a further improvement of energy intensity, which continues a phenomenon observed in the past decades. However, it envisages a slight carbonisation of energy over the century: although small, this effect reflects the increasing share of coal in the energy mix in the absence of an effective climate policy (this is also consistent with the Energy Information Administration’s medium term projections; see EIA, 2007). This increase is mostly driven by the growing energy consumption of developing countries. As for the stabilisation scenarios, the 550 ppm scenario calls for an improvement in energy intensity beyond the no-climate policy one, and eventually for energy decarbonisation. The 450 ppm scenario requires further advancements in both directions, and especially towards a production of carbon-free energy.

Figure 2. Reductions of energy and carbon intensity (changes w.r.t 2002 values)



One might wonder what changes in the energy sector are consistent with the dynamic paths shown above. For example, what energy sources are behind the necessary decarbonisation of the economics systems? For a first dive into this issue, Figures 3 and 4 show the dynamics of the shares of different energy sources in the electricity sector for the two scenarios. In both the 450 and 550 ppm scenarios there is a strong reduction of fossil fuel electricity production. In particular, in the 450 ppm scenario all the generated electricity is virtually carbon-free by the mid century (similarly to what found in the U.S. CCSP 2007 scenarios) – a result that stresses the centrality of the power generation sector in achieving stringent mitigation targets. Fossil fuels are phased-out, with the only exception of coal that maintains a significant share thanks to the introduction of carbon capture and sequestration. Fossil fuels are replaced by a significant increase of renewables (solar energy, in particular) and by the expansion of nuclear power plants.

Figure 3. Power generation shares in the 550ppmv scenario

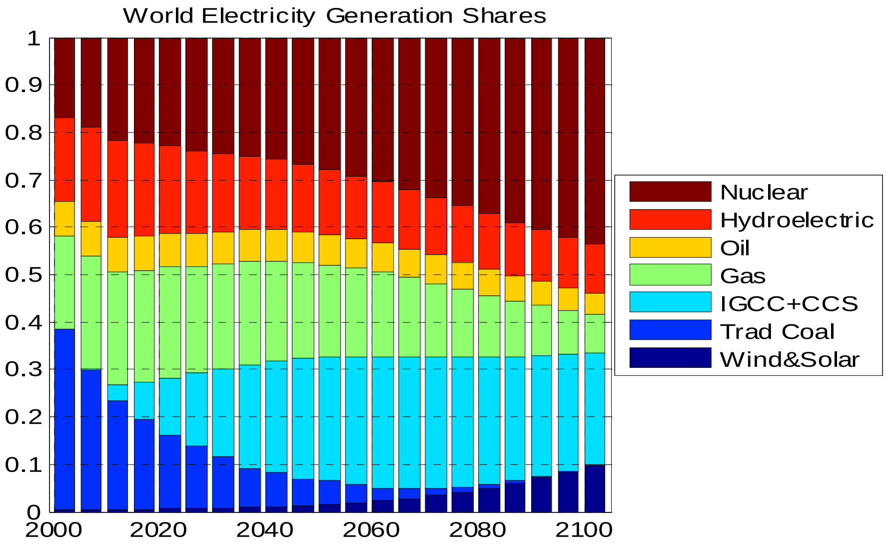
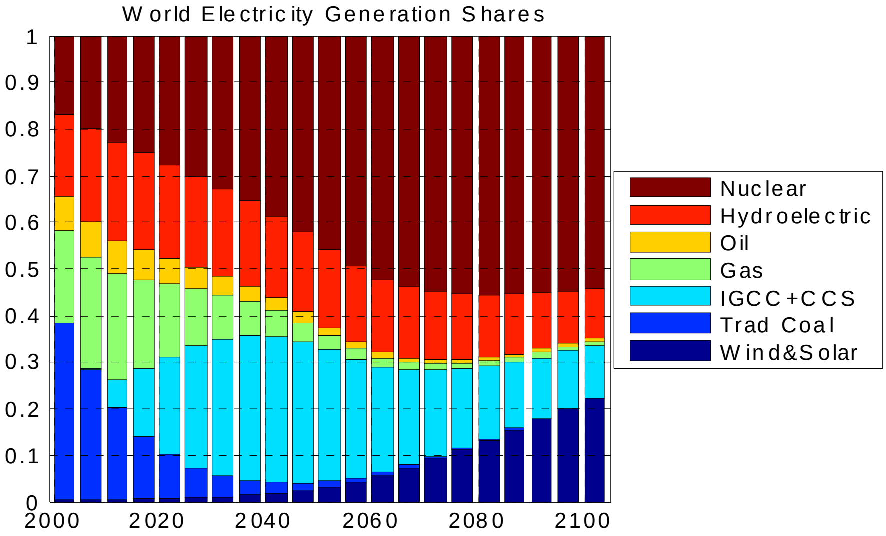


Figure 4. Power generation shares in the 450ppmv scenario



The expansion of nuclear energy is particularly relevant in the 450 ppm scenario. Nuclear energy would eventually guarantee about 50% of total electricity production, a 10 fold increase in the quantities of electricity generated. Let us stress that this result is not a prediction, but rather a normative conclusion. It is achieved on the basis of cost minimising strategies in all regions of the world and does not reflect concerns about nuclear weapons proliferation. External costs induced by nuclear plants – e.g. the cost of waste disposal – are instead accounted for.

Clearly the capacity deployment of such a contentious technology to the levels suggested by our optimisation exercises would raise additional questions, 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 the institutions controlling its global use. For these reasons, we have also explored a scenario in which the use of nuclear energy is limited by environmental and political concerns and where a carbon-free "backstop" technology – that can be made economical via targeted R&D investments – may displace nuclear plants. Such a currently unavailable technology can be thought of as a bunch of innovative green power generation devices or as a new nuclear technology based on nuclear fission (see Figure 14 below and Section 5 of this paper, for a discussion of the economic implications of this scenario).

In any case, the relevant changes in the energy sector induced by the adoption of a stabilisation target are likely to come at a cost. The shift towards nuclear and solar energy and the use of carbon capture and sequestration are likely to induce non negligible economic costs. Assumptions on the potential penetration of nuclear or of alternative backstop technologies are also key in defining the total cost of stabilising GHG concentrations. Additional costs come from the R&D expenditure which is necessary to achieve the aforementioned improvement in energy efficiency. By contrast, positive effects on world economies may be induced by lower climate damages and by the revenues arising from the sale of permits (for regions that are permit sellers). The distribution of these costs strictly depends on how the overall burden is allocated across regions. If permits are allocated according to the equal per capita criterion, OECD countries bear a larger cost than Non-OECD countries. The opposite holds if permits are allocated according to the sovereignty criterion. In this latter case, Non-OECD countries would pay for most of the stabilisation cost. A feasible compensation policy is analysed in Bosetti, Carraro, Massetti and Tavoni (2007).

Total net present value costs, and their disaggregation for OECD and Non-OECD countries, are shown in Table 2. Policy cost figures are provided for the two allocation strategies and for the two stabilisation targets. The last row of each table shows total stabilisation costs in the case in which nuclear energy is constrained to present levels, and a backstop technology is available. Notice how, in the 550 ppm scenario, costs are almost negligible, whereas they become significant in the 450 ppm case. Discount rates used to actualize future costs in present terms have a major effect: for example 450ppm policy cost drop almost by half when passing from a 3% declining discount (the same used for intertemporal discounting of the utility in the model) to a 5% constant (the standard NPV practice for model comparison such as in IPCC 4ar).

Table 2. Total costs of stabilisation (Net present value percent GDP losses, at 3% declining and 5% constant discount rates)

Equal per capita	WORLD		OECD		nonOECD	
	DR=3% decl.	DR=5% const.	DR=3% decl.	DR=5% const.	DR=3% decl.	DR=5% const.
550ppmv CO2	0.2%	0.3%	0.6%	0.5%	-0.3%	-0.2%
450ppmv CO2	3.6%	2.1%	4.1%	2.3%	2.9%	1.6%
“ with backstop, nuclear constrained@2002	3.8%	2.3%	4.3%	2.5%	3.1%	1.8%

Sovereignty	WORLD		OECD		nonOECD	
	DR=3% decl.	DR=5% const.	DR=3% decl.	DR=5% const.	DR=3% decl.	DR=5% const.
550ppmv CO2	0.3%	0.3%	-0.2%	-0.1%	0.9%	0.9%
450ppmv CO2	3.7%	2.2%	1.0%	0.8%	7.2%	4.5%

“ with backstop, nuclear constrained@2002	4.0%	2.4%	0.9%	0.7%	8.0%	5.4%

The cost difference between the two mitigation policies is a direct consequence of the different magnitude of the energy sector modifications in the 550 ppm as opposed to the 450 ppm case. It also stems from the acknowledged non-linearity of marginal abatement curves. The 450 policy requires drastic cuts in emissions, especially in the second half of the century, when emissions are stabilized at around 3GtC/yr. With growing economies and population, this entails a significant increase in energy costs, particularly as the mitigation gets more and more stringent. The effect of temporal discounting is partially compensated by the growing size of the economic activity. The benefits of avoided climate damages are visible but not very significant given the relatively conservative assumptions of Nordhaus’ damage function; costs gross of climate change increase to 0.6% and 4.2% for the 550 and 450 ppm respectively.

Constraining nuclear at present levels is shown to increase stabilisation costs to a limited extent if we expect that a backstop technology will enter the market during the next decades; costs are very large otherwise. Therefore, there is a trade-off between nuclear external costs (e.g. waste management) and the R&D investments needed to induce technological change in the power sector. For a detailed analysis of backstop technology and innovation uncertainty in the context of GHG stabilisation, see Bosetti and Tavoni (2007).

Let us look at how the burden of stabilising GHG concentrations is shared among different regions of the world. Our results confirm the contrasting implications of equal per capita and sovereignty allocation schemes, with the former imposing a higher relative contribution on OECD countries, whereas the latter more on Non-OECD countries, and also more unequally. As expected, except for some small income effects, aggregated stabilisation costs are very similar for the two allocation schemes, as the international permit market equalises marginal abatement costs globally.

Table 3. Total direct costs of stabilisation (undiscounted percent GDP losses in 2030) in WITCH and in the IPCC 4AR WGIII

Target	IPCC WG III	WITCH
550ppmv CO_2	median: 0.2 % (range -0.6÷1.2)	0.4 %

450ppmv CO_2	median: 0.6 % (range 0.2÷2.5)	EPC[5]: 1.2 % SOVRG: 1.4%
450ppmv CO_2 with backstop, nuclear constrained@2002 levels	-	EPC: 1.5% SOVRG: 1.7%

If compared with other cost estimates proposed in the literature, the undiscounted stabilisation costs in 2030 obtained using the WITCH model stand in the middle of the latest IPCC ranges (See Table 3). However, the IPCC median value is lower than our cost estimate, especially for the 450 ppm scenario, even though in WITCH technical change is endogenous and stabilisation induced effects on technological progress are accounted for. This gap somewhat widens over time: for example, in 2050, WITCH cost estimates for the 450 scenario are about 3 times higher than the IPCC median and the value suggested by Stern (2007). They are however lower than MIT IGSM, but 50% higher than those provided by MERGE and MINICAM (U.S. CCSP 2007).

One of the main reasons behind our result is that WITCH explicitly takes into account global externalities and the resulting inefficiencies. That is, contrary to most climate-economy models, our baseline is a second-best solution generated by a dynamic game that captures all regions' free-riding incentives on global externalities such as CO_2, exhaustible resources, knowledge spillovers, etc.. Indeed, when we compute the total stabilisation cost by maximising the world welfare – a first best solution as opposed to the Nash equilibrium – the gap between our policy costs estimates and the IPCC median is halved. It is therefore clear that free-riding incentives arising from public goods externalities impose extra costs that are especially important for ambitious targets (the 450 ppm scenario) where the mitigation effort is much larger and the required changes in the energy sector with respect to the BAU scenario are more relevant.

4. The Carbon Permit Market

In our scenarios, the main economic policy instrument that is used by the governments of all regions to stabilise GHG emissions is a global market for emission permits. Even though this may not be realistic in the short term, it may be a good approximation of future policy scenarios. In this

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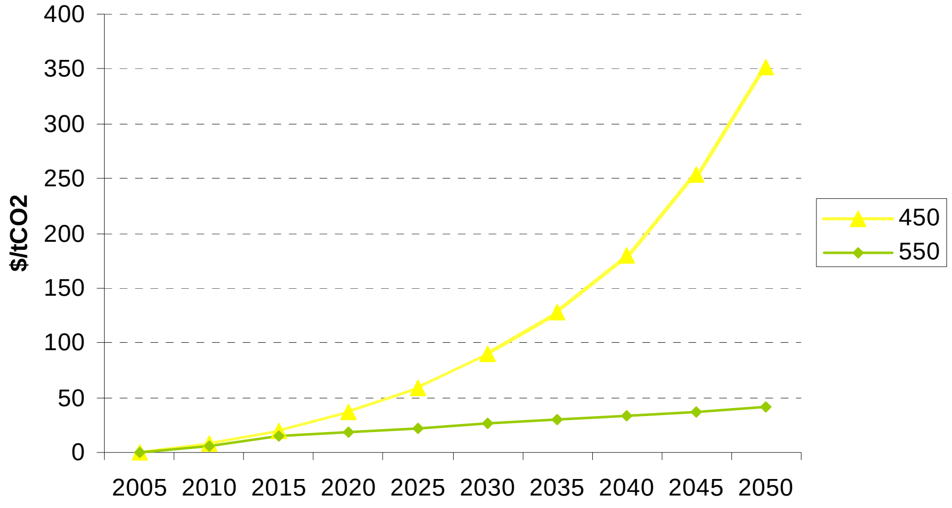
[5] EPC=Equal per Capita, SOVRG=Sovereignty

section, we also assume an equal per capita allocation of initial allowances and global participation from the first stage of the dynamic game.[6]

Figure 6 shows the dynamics of the permit price in the two stabilisation scenarios. The sharp difference between the 550 and the 450 ppm scenarios emerges again. The 450 ppm target is more costly and this is reflected in the equilibrium permit price (an indicator of the stringency of the target). In 2030, a ton of CO_2 is priced about 25$ and 100$ in the two scenarios[7]: such a fourfold ratio is needed to achieve a mitigation effort of 30% and 50% respectively, thus confirming the non-linear relation between costs and abatement. These figures are in line with those estimated using top-down models in the IPCC-4AR-WGIII (Table SPM.2). The price of carbon, however, keeps growing at a constant pace, thus increasing considerably over time, although this is partially compensated by the continued world economic growth. This path is aligned with high range estimates in the U.S. CCSP 2007, and reflects the increasing abatement cost in the absence of a technological breakthrough. As noted in the previous section, the extra-costs of overcoming countries' free-riding behaviour is an additional obstacle to cost reductions.

Figure 6. The price of carbon permits to 2050 in the two stabilisation scenarios



The price of carbon equalises the world marginal abatement cost, and thus ultimately depends on the assumptions on carbon mitigation options. Accounting for additional emissions reductions measures, for example in the agriculture and forestry sector, would decrease the costs of

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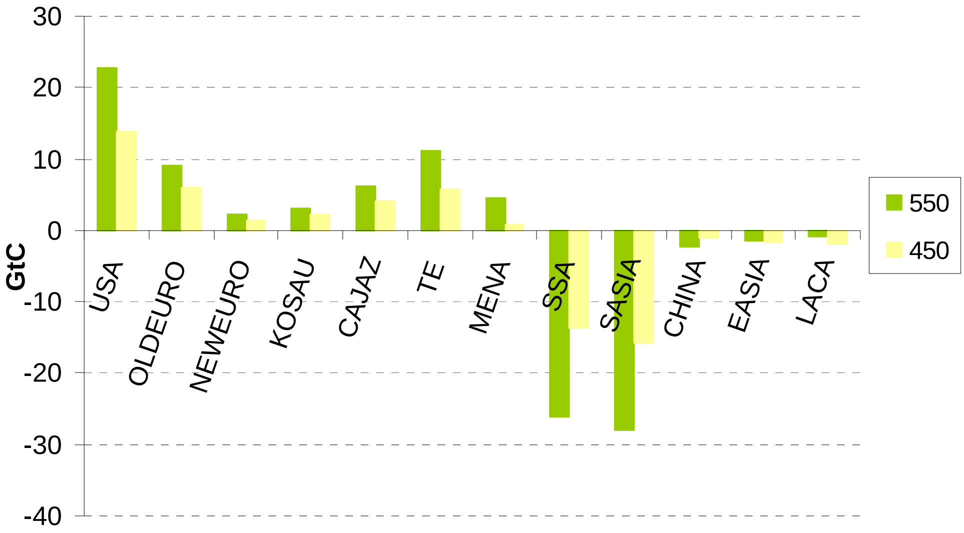
[6] In a companion paper we analyse the implications of different allocations of allowances and of different participation strategies of developing countries. In particular, different time profiles of participation decisions are investigated.
[7] Throughout the paper we refer to constant 1995 USD.

complying with the two targets. For instance, Tavoni, Songhen and Bosetti (2007) show that total abatement costs computed by WITCH are halved when including abatement options in the forestry sector.

The volumes traded in the carbon market are shown in Figure 7 (positive values indicate buying, negative values show selling). In a 550 stabilisation scenario, almost 60 GtC (an average of 0.6 GtC/yr, 10% of current emissions) are traded over the next century, a figure that goes down to 35 GtC in a 450ppm scenario, where the more stringent target requires more domestic action to abate GHG emissions. Therefore, there would be more emission trading in the less ambitious abatement scenario.

Figure 7. Trade of carbon permits (cumulatively to 2100) in the two stabilisation scenarios[8]



The equal per capita allocation makes OECD countries – especially the US, penalised by the high rate of per-capita emissions – short and Non-OECD long of permits. This partly holds also in the 450 ppm stabilisation scenario, at least in the initial time periods. Afterwards, China and East Asia also become buyers of permits: the only big sellers remain Sub-Saharan Africa (SSA) and South Asia (SASIA).

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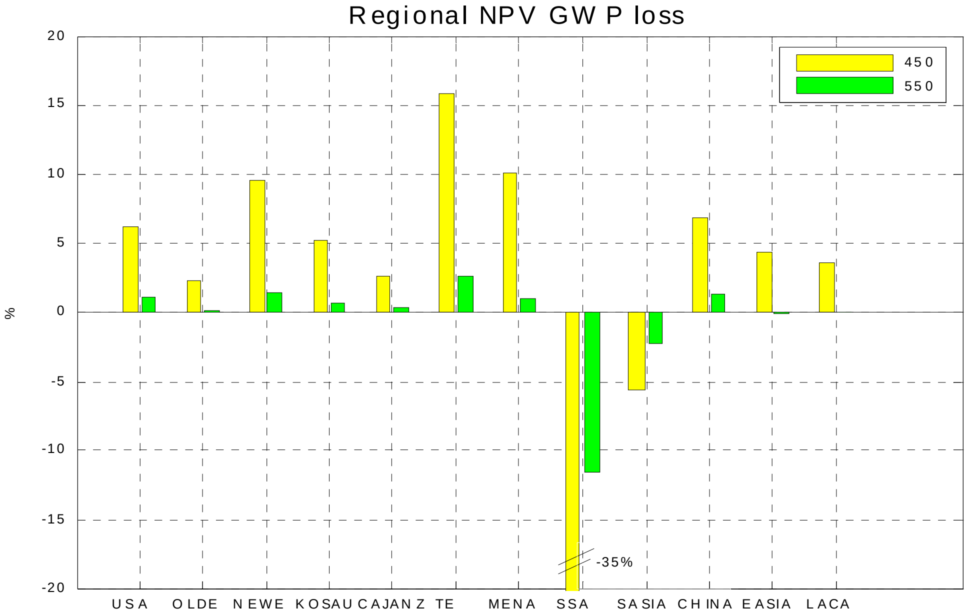
[8] Country legend: USA=Usa, OLDEURO=West Europe, NEWEURO=East Europe, KOSAU=Korea, South Africa and Australia, CAJANZ= Canada, Japan and New Zealand, TE=Transition Economies, MENA=Middle East and North Africa, SSA=Sub Saharan Africa, SASIA= South Asia, CHINA=China, EASIA= South East Asia, LACA=Latin and Central America

This has a clear implication for the geographical distribution of the costs of stabilising GHG concentrations (see Figure 8). In the 550 ppm scenario, all regions but Sub-Saharan Africa and South Asia bear some costs, albeit small. Sub-Saharan Africa and South Asia gain from selling permits. In the 450 ppm scenario, costs are much larger and concentrated in the Transition Economies, in the new EU countries and in the Middle East/North Africa. Sub-Saharan Africa and South Asia get some benefits, though much smaller than in the previous scenario. Notice that the 450 ppm concentration target is quite costly also for China.

Figure 8. Regional policy costs (net present value. Discount rate: 3% declining)



5. Carbon Leakage, Backstops and R&D

The role of technical progress is crucial in stabilising carbon concentrations. In order to increase energy efficiency and to de-carbonise the energy sector, large investments are necessary and new energy efficient technologies must become available. These large increases in energy efficiency require the deployment of relevant investments in R&D. The WITCH model provides some information on the size and the time profile of these investments (see Figures 9 and 10).

Whereas today R&D investments are about 10 billion USD, they should double in 2020 in the 450 ppm scenario (in 2035 in the 550 ppm scenario). Notice that in the 550 ppm scenario the time profile of optimal R&D investments is close to the one in the BAU scenario. By contrast, in the 450 ppm scenario, energy R&D investments increase very quickly after 2020 and become four times the BAU investments from 2050 onwards.[9]

R&D investments must be concentrated in the first half of the century: Figure 10 shows energy R&D investments as a share of GDP and emphasises how their most significant increase must be concentrated from 2020 to 2050. The share stabilises and even declines after 2080, when some energy efficient and/or carbon-free technologies will eventually become available.

Figure 9. The time profile of optimal R&D investments in the energy sector

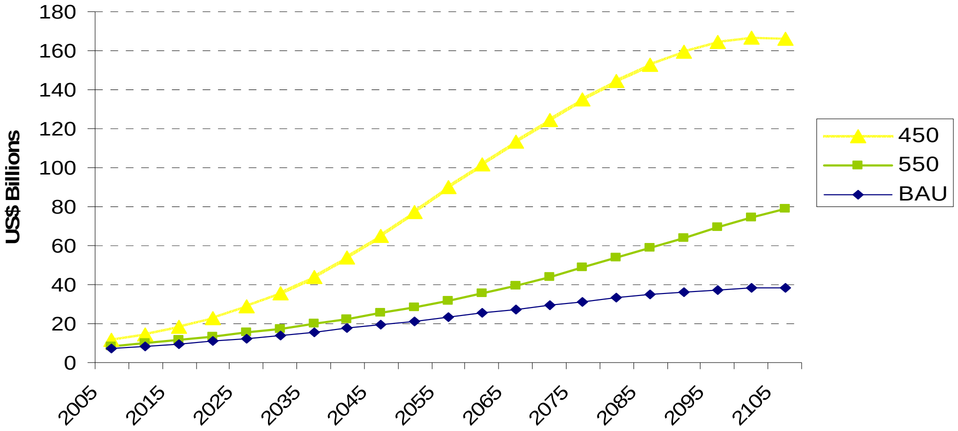


Figure 10. Optimal energy R&D investments as a share of GDP

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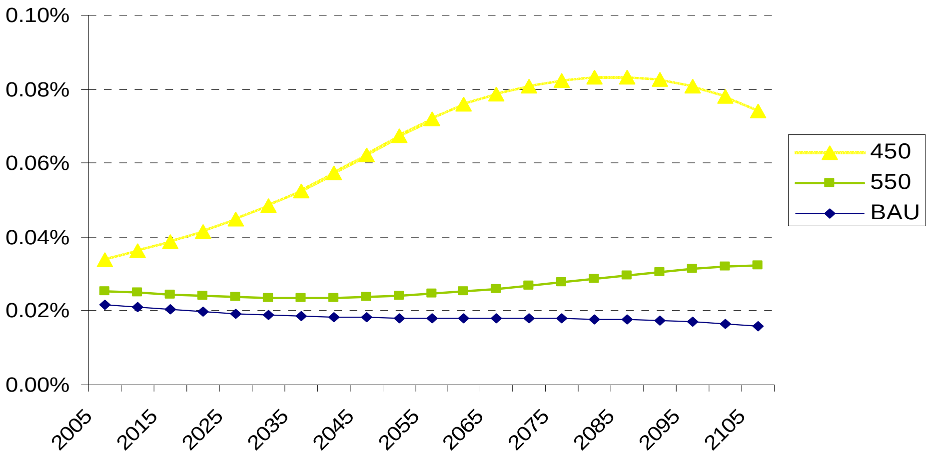
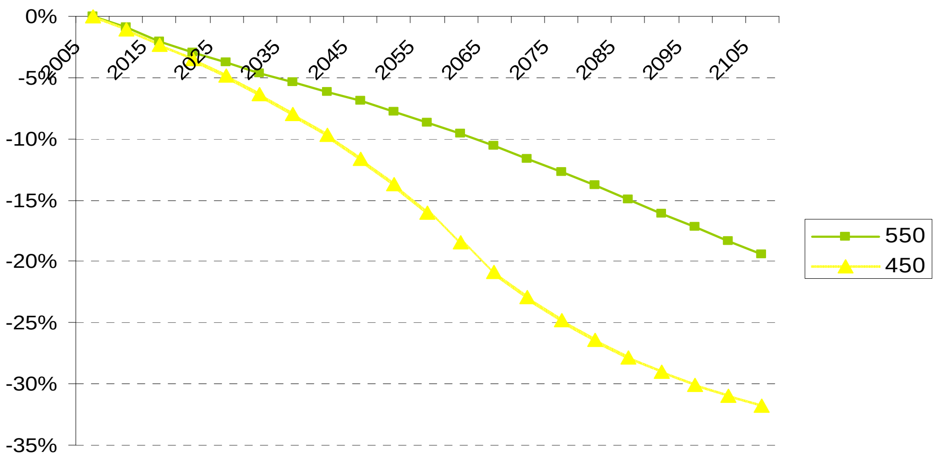
[9] Popp (2004) estimated energy R&D investments for a policy aimed at restricting emissions at 1995 levels. He found figures in the order of 30 and 50 Billions in 2050 and 2100 respectively. According to our model, a 450 stabilisation target requires a much larger R&D investment (at least three times the value estimated by Popp for the 1995 stabilisation target).



Similar remarks concern the learning-by-doing effects characterising renewable energy and in particular solar and wind energy (see Figure 11). Again, the 450 ppm target can be achieved only in the presence of important reductions in the unit cost of energy produced using solar or wind power plants. These cost reductions can be achieved only if technical improvements associated with an increase of the installed capacity are sufficiently large.

Figure 11. Investment cost of wind and solar power plants: variation w.r.t. BAU



One of the most promising abatement options in the power sector – that would allow a continued use of widely available fossil fuels such as coal – is the capturing and sequestering

(CCS) of the resulting CO_2 to prevent its accumulation in the atmosphere. The dynamics of investments in IGCC-CCS plants (not including the costs of transporting and injecting the CO_2) are reported in Figure 12: this figure shows how these investments should be very high from 2020 to 2050 and subsequently stabilise (decline as a share of GDP). For the 450 stabilisation scenario, CCS investments are actually shown to stabilise at a lower than peak level.

Figure 13 elaborates more on this. The optimal amount of injected carbon is shown to be significant: about 2 GtC/yr (1/4 of today emissions) are stored underground starting from mid century (a figure in line with U.S. CCSP 2007 estimates). Cumulatively to 2100, about 150GtC should be injected (in accordance with the IPCC 4AR WGIII). However, the use of this technology should decrease over time in the 450 scenario relatively to the 550 one. The reason is that a more stringent target calls for a relatively greater deployment of very low carbon technologies; renewables and nuclear are thus progressively preferred to CCS, because this latter technology is characterised by a higher emitting factor[10]. 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.

Figure 12. Investments in coal electricity generation with carbon capture and storage

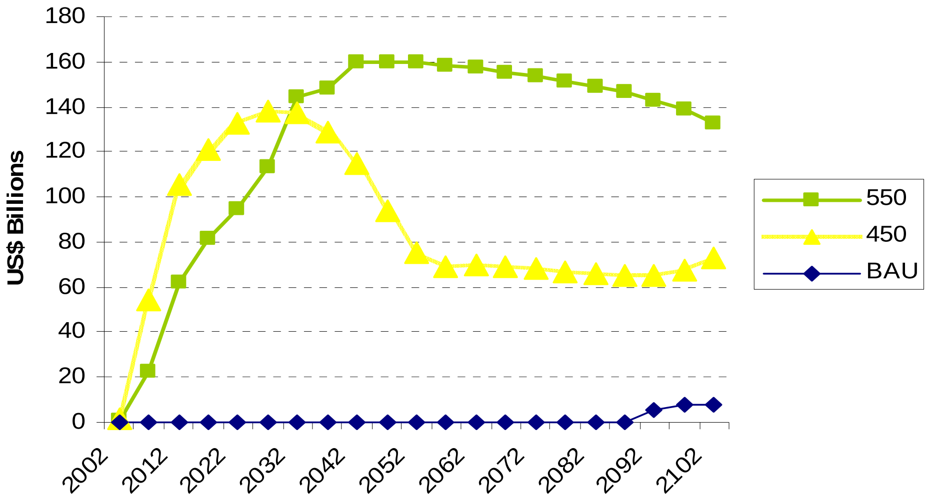


Figure 13. Optimal amount of sequestered carbon over time

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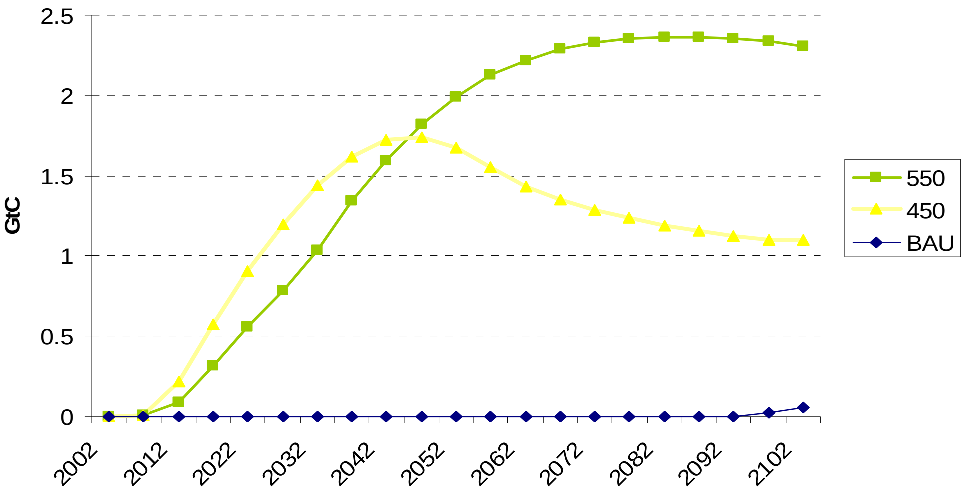
[10] Constraining the potential deployment of nuclear and renewables would offset this effect.

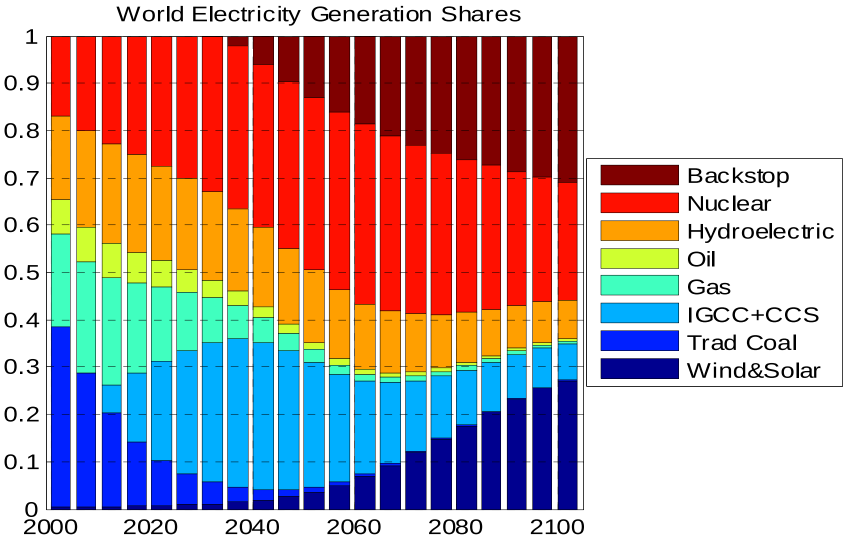


It may be argued that our results are conditional on one crucial assumption: the optimal intertemporal investment decisions are taken with respect to the existing energy technologies (and their improved efficiency), but no breakthrough technological change is considered for the energy sector. This is why we checked the robustness of our conclusions with respect to the possible emergence of a new technology in the electricity sector (e.g. a new solar or a new nuclear technology). The basic assumption is that there exists a carbon-free power generation technology, at present uneconomical, whose unit price can be diminished by investing in dedicated R&D. More specifically, the investment cost of building a unit of power capacity ($/kW) depends on cumulated R&D via a power formulation governed by the learning parameter. Starting from a present high investment cost (6000$/kW), we analyse whether there is the incentive to undertake these investments (in R&D but also in installed capacity to enhance the learning-by-doing effect).

New power generation shares are shown in Figure 14, which suggests that the backstop technology replaces mostly “old” nuclear energy (i.e. produced with existing technologies) as the main energy source. Most importantly, it shows that the 450 ppm target provides the incentives to invest in R&D and to develop an economically efficient backstop technology.

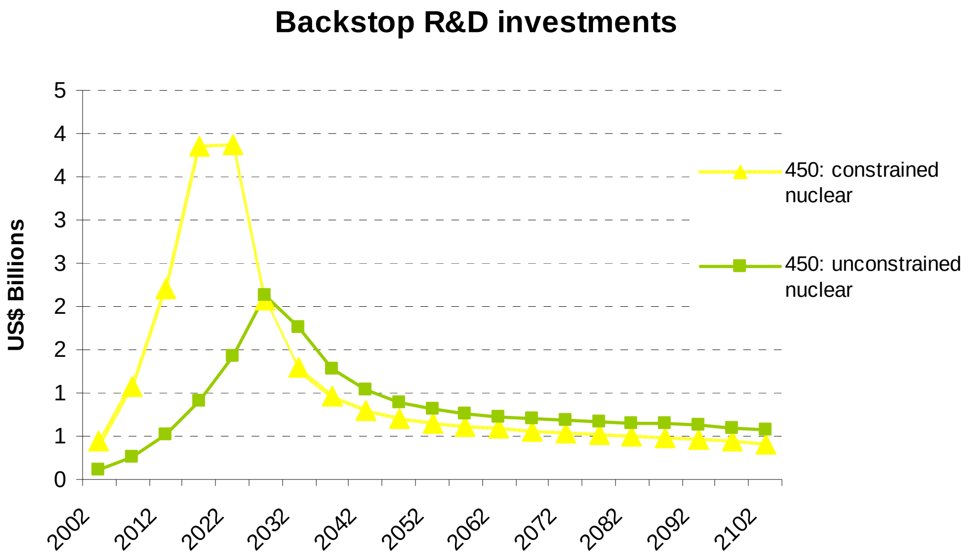
By comparing Figures 4 and 14, it can be noticed that renewables are not crowded out by the backstop technology, whereas fossil fuels are completely phased out by the end of the century.

Figure 14. Power generation shares in the 450ppmv scenario in the presence of a backstop energy technology.



Finally, Figure 15 shows the optimal amount of R&D investments that are necessary for the backstop technology to penetrate the market. Again most investments must be undertaken soon, before 2030. The size of the R&D investments is obviously larger and the decision more urgent if future nuclear power developments are constrained by the fear of nuclear weapon proliferation. Also notice that the final impact on stabilisation costs of this extra R&D effort is partly compensated by decreased variable costs (fuel and external) so that, as shown above in Section 4, global stabilisation costs increase moderately. This also emphasises the importance of developing mitigation options in the non-electric sector as a way to curb the costs of stabilising GHG emissions.

Figure 15. Optimal R&D investments to develop a backstop technology in 450 ppm scenario.



6. Conclusions

This paper has investigated the economic implications of stabilising GHG concentrations over the next century. Climate change is widely perceived as one of the most pressing environmental issues, and many countries are moving towards the implementation of carbon mitigation targets and agreements. As a consequence, the analysis of economically optimal strategies that stabilise GHG concentrations at non-dangerous levels has become an important research objective, as testified by the large number of studies and the research efforts evaluated by the IPCC WG III.

The previous sections of this paper have presented our quantitative assessment of GHG stabilisation policy. This has been performed using WITCH, an energy-economy-climate optimisation model based on a game-theoretical set up. The model is designed to carry out normative analysis of climate policy, i.e. to identify the optimal investment profiles in the energy sector and in R&D that achieve a pre-determined carbon concentration target. In this analysis, the role of both global externalities and of induced technological change has been accounted for.

Our results show that the stabilisation of CO_2 concentrations at 550 and 450 ppm is feasible, but requires radical changes in the energy sector and large investments in R&D. Both energy efficiency and decarbonisation of energy production should improve.

The required changes in energy investment profiles and R&D efforts imply some costs. According to our estimates, global GDP losses in 2030 would be equal to 0.4% if the 550 ppm target is to be attained, and to 1.2 % in the case of the 450 ppm stabilisation target. Total discounted costs over the next century would be 0.3% and 2.1 % of global GDP respectively. While well within the range identified by the IPCC, the higher median stabilisation cost estimated by WITCH, compared with IPCC, largely depends on the free-riding incentives that arise from the global public nature of the carbon and R&D externalities and on the consequent inefficiencies.

In our scenario, the stabilisation of GHG concentrations is achieved by implementing a global permit market. Therefore, we have been able to provide some information on the dynamics of this market and on how the mitigation burden is shared among different countries. As expected, burden-sharing depends on how the global target is allocated among the different world regions. An equal emission per capita criterion favours developing countries and can thus be used as a tool to enhance participation incentives.

Finally, our analysis sheds some lights on the large investments that are necessary in the energy sector to achieve the improvements in energy and carbon intensity required by GHG stabilisation. We have shown how fossils fuels will be gradually phased out and how other energy sources may emerge in the next decades. We have also been able to quantify the role of carbon capture and storage and the expected dynamics of renewable energy sources. Special attention has been devoted to the role of R&D. If ambitious abatement targets have to be achieved, large investments in R&D (four times the current levels) would be necessary to improve existing energy technologies and/or to foster the development of new ones.

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