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ALTERNATIVE PATHS TOWARD A LOW CARBON WORLD

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SUMMARY This paper analyzes the economic and investment implications of a series of climate mitigation scenarios, characterized by different levels of ambition in terms of long term stabilization goals and the transition to attain them. In particular, the implications of fairly ambitious scenarios are investigated for the first time by means of the model WITCH. Although milder climate objectives can be achieved at moderate costs, our results show that stringent stabilization paths, compatible with the target of the European Union and the G8, might have important economic repercussions. The timing of mitigation action influences the cost of meeting a target as well the stringency of the targets we can aspire to. To contain costs it is crucial to rely on a wide mitigation portfolio. Strong reductions in energy consumption through enhanced energy efficiency and life style changes are needed to achieve stringent climate policies. The analysis carried out in the present paper contains several idealistic assumptions that could be violated in the real world where some technologies may not be fully available, technology transfers and diffusion are imperfect, some world regions may not accept to reduce their GHG emissions, trading might be limited to some sectors or to a fraction of the total abatement effort, etc. This would increase the challenge of climate protection and the costs of reducing GHG emissions.

Keywords: Climate Policy, Stabilization Costs

JEL: C72, H23, Q25, Q28

1. Introduction

Although no clear consensus on a road map to reach the target has been reached yet, temperature stabilization at no more than 2° C above pre-industrial levels by the end of this century still represents the objective of most nations represented at the UNFCCC, and it has been recognized as a fundamental signpost in the Copenhagen Accord. To make it likely that this challenge will be met, greenhouse gas concentrations have to be limited to at least 450 ppm CO₂ equivalent (with a 50 % likelihood) or below. This objective can be met following different emission pathways; these can be characterized by a greater or shorter delay in action that, as a consequence, entails a more or less rapid reduction of emissions in later periods. The present paper aims at analyzing a set of scenarios aiming at different levels of ambition in terms of long term climate objectives, timing of initial commitment, and pace of decarbonization, by means of a hybrid integrated assessment model, the WITCH model.

A series of robust findings has emerged:

- a. **Potentially significant costs.** Although milder climate objectives can be achieved at low costs, stringent stabilization compatible with the 2° Celsius targets might have important economic repercussions (costs measured as discounted GWP losses range between 4 and 7 percent, depending on the choice of the discount rate). The costs of such policies depend crucially on when the transition to a lower carbon society starts, but also on the range of mitigation options and the pace of technological innovation
- b. **Early action.** When we act influences the cost of meeting a target as well the stringency of targets we can aspire to. Especially for ambitious targets, early action is crucial. Delayed action implies a higher post peak reduction rate, which in turn results in a replacement of capital that is more costly as it is more abrupt. Delaying the emissions peak period to 2030 makes the most stringent set of targets unattainable.
- c. **Wide mitigation portfolio.** Renewables, CCS, nuclear, REDD, and innovation (R&D) are all indispensable to minimize stabilization costs. Renewable

technologies and carbon free innovation should be incentivized through appropriate policies.

- d. **Energy Consumption.** Strong reductions in energy consumption through enhanced energy efficiency and life style changes are needed to achieve a low carbon economy.
- e. **Second best.** The analysis carried out here, as well as in all other quantitative assessments of the cost of climate policies, contains several idealistic assumptions that could be violated in a second-best world where some technologies may not be fully available, technology transfers and diffusion are imperfect, some world regions may not accept to reduce their own GHG emissions, trading might be limited to some sectors or to a fraction of the total abatement effort, etc. This would increase the challenge of climate protection and the costs of reducing GHG emissions.

2. The WITCH model

WITCH (Bosetti et al, 2006) is a climate-energy-economy model designed to assist in the study of the socio-economic dimensions of climate change. It is structured to provide information on the optimal responses of world economies to climate damages and to identify impacts of climate policy on global and regional economic systems. A thorough description and a list of related papers and applications are available at www.witchmodel.org.

It should be underlined that WITCH does not reflect the current financial crisis. Being a long term projection tool, WITCH is not suited to match short term disruptions, which are smoothed on the century time scale.

Four features deserve to be highlighted here, foresightedness of decision makers, the mitigation options, the specification of technological change in the energy sector, and reduced emissions from deforestation and forest degradation (REDD).

A key attribute of the WITCH model for our analysis is that it assumes governments to be **forward-looking**. If a policy is to be enforced, then each region's policy maker anticipates its arrival. Investments in the energy sector and in innovation are made in order to avoid a lock-in effect. Policy makers take into account the

prospective target, even if they do not face it in the immediate future, and choose investments keeping in mind the time needed for polluting capital to wear off and the penetration limits of carbon free technologies. Such features of the model only partially reproduce reality, where policy makers generally have a more myopic perspective. Hence, the perfect foresight feature might play a role in underestimating the costs of climate policy (see Bosetti et. al. 2009b and Blanford et. al 2009 or a detailed discussion of this issue).The WITCH model features a series of **mitigation options** in both the power generation sector and in the other energy carriers, e.g. in the non-electric sector. Mitigation options in the power sector include nuclear, hydroelectric, IGCC-CCS, renewables and a backstop option that can substitute nuclear. In the non-electricity sector, mitigation options include advanced biofuel and a backstop option that can substitute oil. Two other important mitigation options are the endogenous improvement of overall energy efficiency with dedicated energy R&D and reducing emissions from deforestation and degradation (REDD).

Energy saving is believed to be one of the most convenient mitigation options. In the model, **investment in energy saving**

knowledge is modeled to cumulate in a knowledge stock which substitutes energy inputs to produce energy services. Hence, instead of being modeled as an autonomous process, improvement in energy efficiency is the product of specific investments.

In the longer term, however, one could envisage the possible development of innovative technologies with low or zero carbon emissions. These technologies, which are currently far from being commercial, are usually referred to in the literature as **backstop technologies**, and are characterized as being available in large supplies. For the purpose of modeling, a backstop technology can be better thought of as a compact representation of a portfolio of advanced technologies that would ease the mitigation burden away from currently commercial options, though it would only be available in a few decades. Given that these technologies are not explicitly specified, we do not need to pick a winner but simply assume that through R&D investments one or the other potential alternative will become available at a competitive cost in the future. This representation has the advantage of maintaining 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 do not exist. WITCH includes two backstop technologies, one in the electric and one in the non-electric sector, that necessitate dedicated innovation investments to become economically competitive, even in a scenario with a climate policy. We have followed the most recent characterization in the technology and climate change literature, modeling the costs of the backstop technologies with a two-factor learning curve in which their price declines both with investments in dedicated R&D and with technology diffusion. **Forestry** is an important contributor of CO₂ emissions and it might provide relatively convenient abatement opportunities. WITCH is enhanced with baseline emissions and supply mitigation curves for reduced deforestation. Abatement curves for world tropical forests are based on the IIASA cluster model (Eliasch 2008). Bosetti et al. (2009a) describe the results of this analysis in depth.

3. Scenario Design

The scenarios designed for this modeling exercise have been chosen to test a range of assertions. These scenarios are described in detail in Table 1 and Figure 1 but they can broadly be placed into three main categories:

Scenarios 1-4: These achieve a 2° C stabilization target with a probability close to 50% (except scenario 4) and assess the sensitivity of global mitigation costs to early action.

Scenarios 5-7: These achieve a stabilization target of more than 2° C and propose to show that even when aiming for a higher stabilization target, early action is still worthwhile:

Scenarios 7-9: These are a range of scenarios that peak in 2020 with different post peak reduction rates, and aim to assess the impact of more aggressive post peak reduction rates on the global mitigation costs.

Scenario	Peak emissions year	Post peak emissions reductions	Post 2050 emissions floor GtCO ₂ e	Probability				Median temperature rise in 2100 °C	Cumulative emissions 2000-2050 GtCO ₂ e	Cumulative emissions 2000-2100 GtCO ₂ e
				of < 2 °C	of < 2.5 °C	of < 2.75 °C	of < 3 °C			
1	2014	3%	6	45%	78%	86%	91%	2.05	1849	2508
2	2016	4%	6	48%	78%	87%	91%	2.02	1875	2434
3	2020	5%	6	44%	76%	85%	90%	2.08	2000	2519
4	2030	5%	6	24%	58%	70%	81%	2.36	2447	3138
5	2020	2%	11	21%	56%	70%	81%	2.41	2263	3333
6	2020	1%	11	7%	34%	50%	64%	2.74	2392	4006
7	2030	1%	11	3%	20%	34%	49%	3.00	2622	4540
8	2020	3%	11	31%	64%	78%	85%	2.25	2172	2967
9	2020	5%	11	40%	73%	83%	90%	2.12	2063	2694

Table 1. Features characterizing the Scenarios 1 to 9.

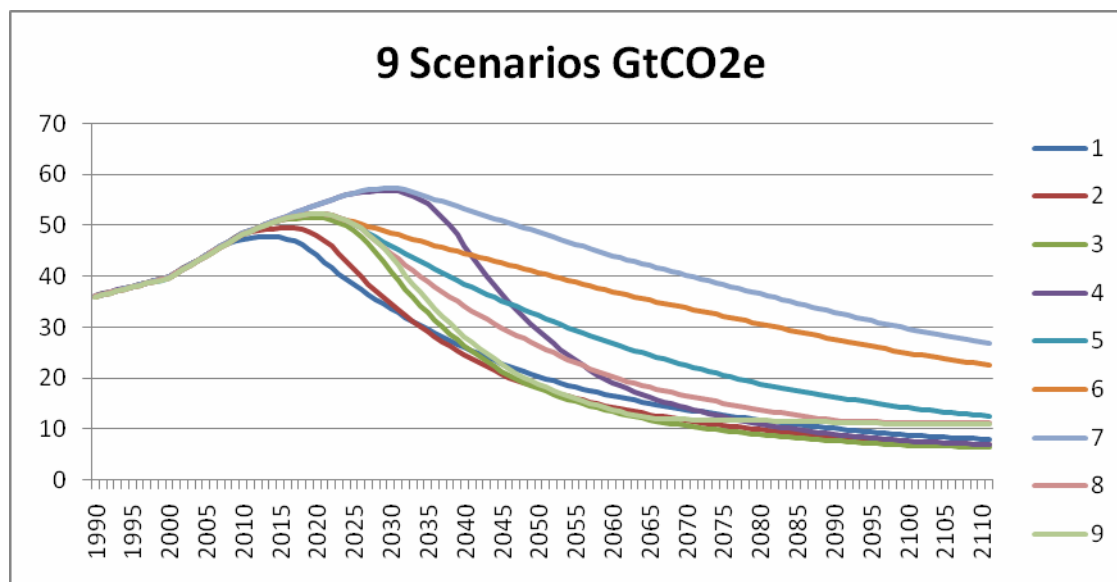


Figure 1. Emission pathways for scenarios 1 to 9.

The aim of the analysis is to pin down the different implications of global carbon emission trajectories, with different ambition levels in terms of long term climate objectives, timing of initial commitment and pace of decarbonization. Therefore, we do not model the “first-best” scenario for a given temperature target

(which would imply a single optimal path of emission reductions, where emission reductions are allocated optimally through time, i.e. minimizing the consumption loss required to meet the temperature target),

but rather we measure the costs of alternative sub-optimal pathways.¹

Scenarios are simulated under a subset of “first-best” assumptions. A perfect international carbon market is assumed to be in place with no limits on carbon transfers and no transaction costs. Marginal abatement costs are thus equalized globally, and maximum economic efficiency is attained, irrespective of the burden sharing scheme adopted. All countries are assumed to take part in the international climate agreement as soon as it is established.

Moreover, the model features perfect foresight, allowing for anticipatory mitigation actions in response to future targets. Economic agents prepare for the transition to low carbon scenarios by building up efficient capital stock in

advance, and thus mitigate the shocks of early capital retirement or sudden deployment of new technologies. The anticipation of a future policy target induces a smoother transition, leading to a change in the investment choices even before the policy is actually implemented (to avoid lock-in in long-lived carbon intensive capital). On the other hand, the assumption of a completely myopic behavior, before the starting date of the policy, would increase the costs of the policy. The anticipation effect has been shown to be important in determining the investment strategies and costs of climate policies (Bosetti et. al. 2009b, Blanford et. al 2009).

Emissions in the WITCH model (the baseline and the main emission drivers are described in greater detail in Appendix 1) are endogenous as well as the results of the investment decisions in the energy sectors. Fossil fuel CO₂ emissions grow from the current 30 GtCO₂, to 47 in 2030, in line with the B2 SRES scenarios. By 2030, WITCH emissions are 10% above the forecasts of the Energy Information Agency and the International Energy Agency. By 2100, fossil fuel emissions grow to 86 GtCO₂, slightly

¹ We decided not to look into the effect of banking as a way of smoothing emission reductions given the long term nature of the proposed policies. In addition, the chief scope of the present analysis is to look at the effects of alternative pathways thoroughly. We examined the effect of banking on policy costs in two previous studies (Bosetti, Carraro and Massetti (2008) and Bosetti et al 2009a) and found that full “when flexibility” results in a reduction of policy costs of 10-15%. The magnitude of the effect depends on the scenario (and whether there is a combined effect with REDD or not).

above the B2 SRES scenario group. The 2100 figure is within the average of more recent modeling comparisons (see Figure A2 for a comparison of the latest baseline emission pathways within the EMF 22 comparison exercise).

4. Presentation and discussion of main results

This section presents the main results of the analysis, by comparing 9 scenarios across two main variables of interests, namely the implications for the economy and those for energy investments.

Macro-economic implications

We begin by reporting the global economic implications of the various climate mitigation scenarios, focusing on the costs of meeting the different emission trajectories. Gross policy costs will be presented, without taking the benefits from avoided climate change into account.

Figure 2 shows the global GDP losses with respect to the baseline across the various scenarios. Several patterns are identifiable. Keeping the temperature increase at the end of the century between 2.5 and 3°

Celsius (S6 and S7) entails very contained costs that hardly exceed 1% of GWP and that decline in the second half of the century thanks to technological progress. Economic losses increase for the more stringent scenarios, but remain below 5% for a 2.4 °C objective. However, they rise very rapidly for temperatures close to (albeit always slightly higher than) the 2° C objective set forth by the European Union and the G8. In the latter class of scenarios, global GDP losses can greatly exceed 10% and begin accruing earlier in time. The only scenario of this kind that never exceeds the 10% value is S1, in which mitigation actions are supposed to start immediately.

Scenario S4, which entails postponing the peak in emissions till 2030, results unfeasible to run with the WITCH framework. The speed of decarbonization required to meet the 2° C target and, at the same time, to allow for such a late start is such that the model crosses the boundary of reasonable assumptions and no feasible solution can be found. Inertia and fossil fuel capital accumulation, on the one hand, and investments, infrastructure and capacity building needed to cope with the sudden

change, on the other, would not be in line with what we have seen in the past and what we can reasonably project in the future. Even assuming some radical innovation will be soon available, time is required for the necessary changes in

infrastructure and in order to allow for the new technology to penetrate. Given these constraints, S4 implies a pace of change in the energy sector that is too abrupt for the model to find a feasible solution.

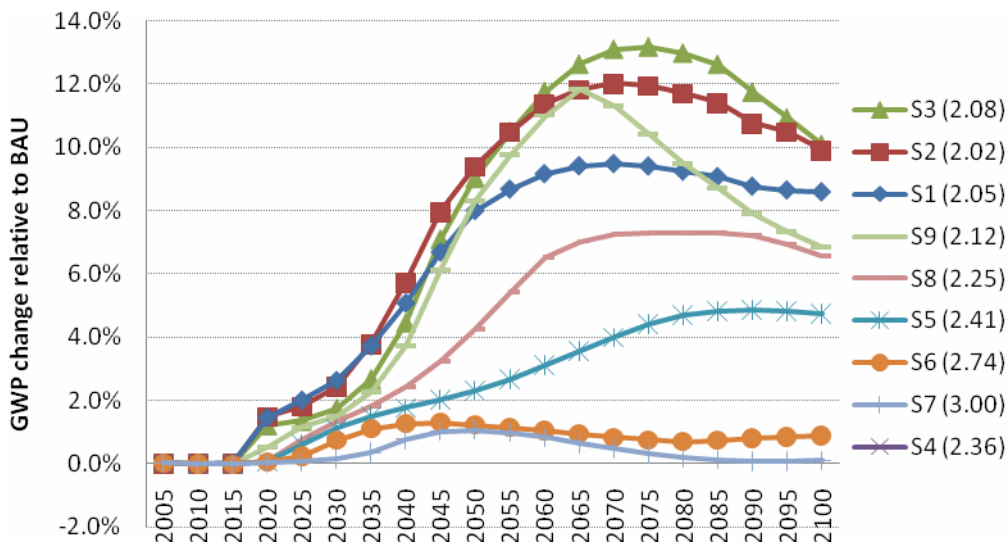


Figure 2: Gross World Product (GWP) losses over the century. The legend shows the scenario number and (in brackets) its median temperature change in 2100 in degree Celsius

Figure 3a reports a more compact measure of costs, in which losses are actualized in today's terms at 5% and 3% discount rates. As can be clearly seen from the above graph, approaching the 2 °C objective is

likely to have important economic repercussions, with present term GWP losses in the order of 4% to 7% over the period 2015-2100, depending on the discount rate.

Delaying action by only a few years is shown to have a negative effect on costs; for example S3, despite achieving a somewhat higher temperature than S1, entails costs that are 12% higher in discounted terms, because it postpones the peak year by 6 years (2020 as opposed to 2014). Stretching the delay further in time -as in S4- would make it impossible to comply with a stringent stabilization objective, since the

additional overshoot would require too sudden emission cuts.

The remaining scenarios show that relaxing the stabilization objective reduces the economic penalty considerably, especially when the temperature objective is reduced by 0.5 to 1 °C, on average. However, one should bear in mind the great uncertainties that surround the translation of concentrations into temperature changes.

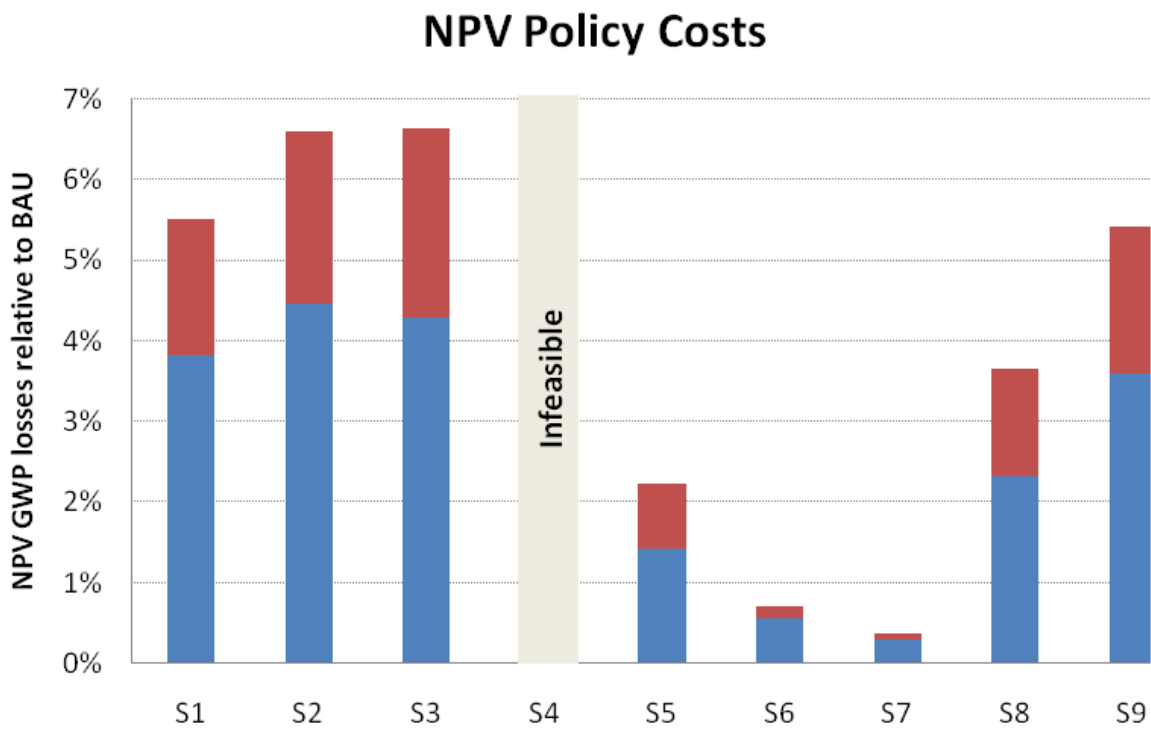


Figure 3a: Gross World Product (GWP) losses in net present value (NPV), with a discount rate of 5% (lower part of the bar) and 3% (whole bar).

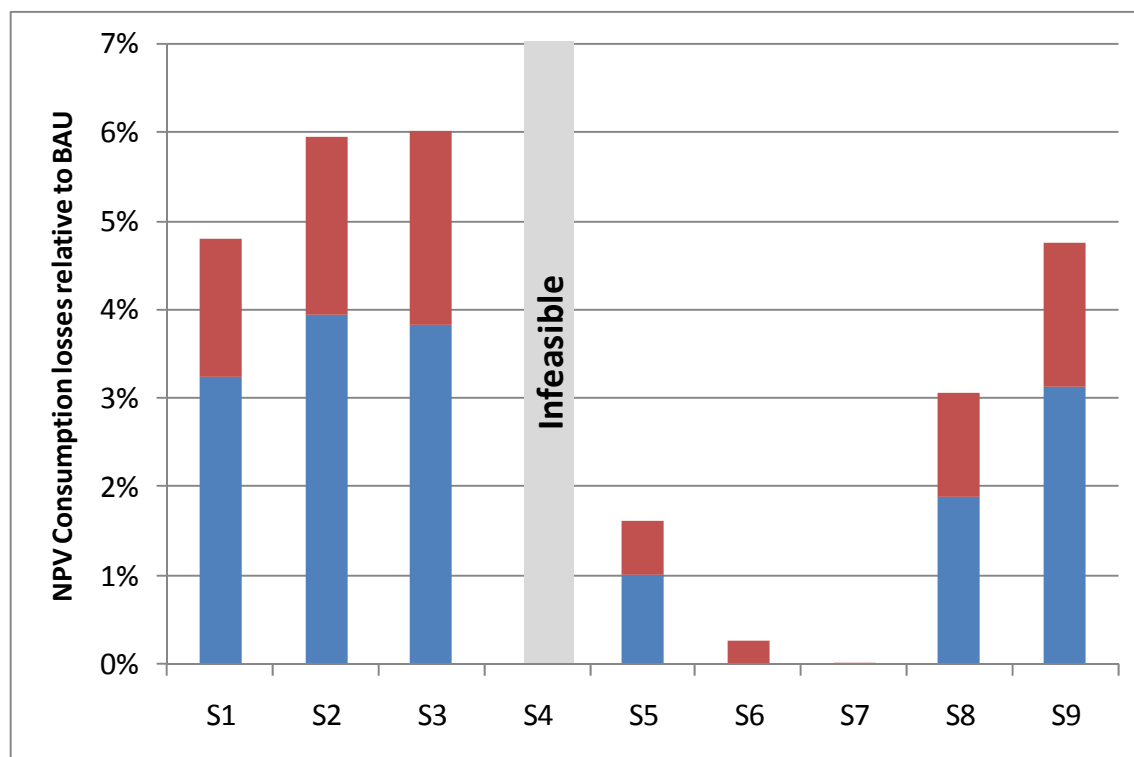


Figure 3b: Consumption losses in net present value (NPV), with a discount rate of 5% (lower part of the bar) and 3% (whole bar).

Figure 3b records policy costs expressed as consumption losses. The ranking of different policies is unchanged. However, since in the long run, foregone consumption is partially compensated by a lower investment rate, percentage figures are lower than in GWP terms.

Our modeling estimates suggest that attaining stringent stabilization objectives would imply relatively high costs, but that moderate objectives can be accomplished at a far smaller charge. Table 2 compares our

figures with those made for the IPCC 4th AR and the CCSP study². The most stringent scenarios were not reproduced in the CCSP study. For the less stringent categories the WITCH results lie within the cost range of published estimates. However, for more ambitious scenarios closer to the 2° Celsius objective, we report costs that are substantially higher and range more widely.

² CCSP is the US Climate Change Science Program, the most acknowledged modeling comparison exercise in the US. (Clarke, et al 2007)

One should bear in mind that, since only the most optimistic models have been able to simulate stringent climate policies so far, published estimates of the costs of stringent

stabilization scenarios are likely to be biased towards costs that are too low, as shown in Tavoni and Tol (2009).

Table 2: Policy Cost Comparison (measured as GDP losses in 2050).

	GDP reduction in 2050		
	IPCC 4 th AR Estimates	CCSP	WITCH AVOID Study
445-535 ppm CO ₂ e (S1, S2, S3,S8 and S9)	<5.5%	NA	4.2-9.4%
535-590 ppm CO ₂ e (S5 and S6)	Slightly negative- 4%	1.2-4.1%*	1.2-2.3%
590-710 ppm CO ₂ -e (S7)	-1-2%	0-1.2%	1.1%

** This figure refers to 2040, as 2050 is not reported in the CCSP study.*

Moreover, WITCH fully models the limited substitutability and the inertia characterizing the energy sector as well as the limited availability of carbon free alternatives for the transport sector. Overall, WITCH envisages low-carbon alternatives in the non-electricity sector to penetrate slowly, thus limiting the

decarbonization of the sector. Consequently, a significant decline of primary energy demand is required. This contraction of non-electric energy supply gives rise to a substantial decrease in macro-economic productivity. In addition, rather than being an autonomous process, in WITCH innovation is modeled as

depending on R&D expenditures. These factors contribute to the realism of the modeling experiment but result in higher costs.

For this transition to a low carbon society to take place, several policy instruments are likely to be needed, and one in particular will be indispensable. Carbon should be priced considerably high to foster the changes needed on both the supply and demand sides. Our calculations suggest that ambitious scenarios would require a price above 100\$/tCO₂-eq by 2025, even assuming a totally flexible international carbon market with no ex-ante constraints on offsets. Such prices are needed to foster substantial investments in the energy sector, in innovation, and in land conservation as shown in the next section. Figure 4 indicates carbon prices for the policy scenarios in the period 2015-2030. It shows that the more stringent scenarios require a strong price signal from earlier

periods, but that a growing carbon cost is needed across all scenarios. As already noted, one should keep in mind that higher carbon prices can be obtained if we relax the assumption of an unrestricted international carbon market equalizing marginal abatement costs.

Despite being a stringent scenario, S3 has an initial carbon price lower than S1 and S2 (though it is compensated for in subsequent periods) given the larger emission overshoot. Also, given the anticipation of very stringent emission reductions in the future, significant investment effort is put on improving energy and carbon efficiencies, which lowers the abatement costs and contains the price of carbon at the outset. Nonetheless, such investments have important economic consequences, as shown in Figure 2; this suggests, as can also be inferred from the literature, that carbon prices are only partial indicators of the macro-economic costs of policies.

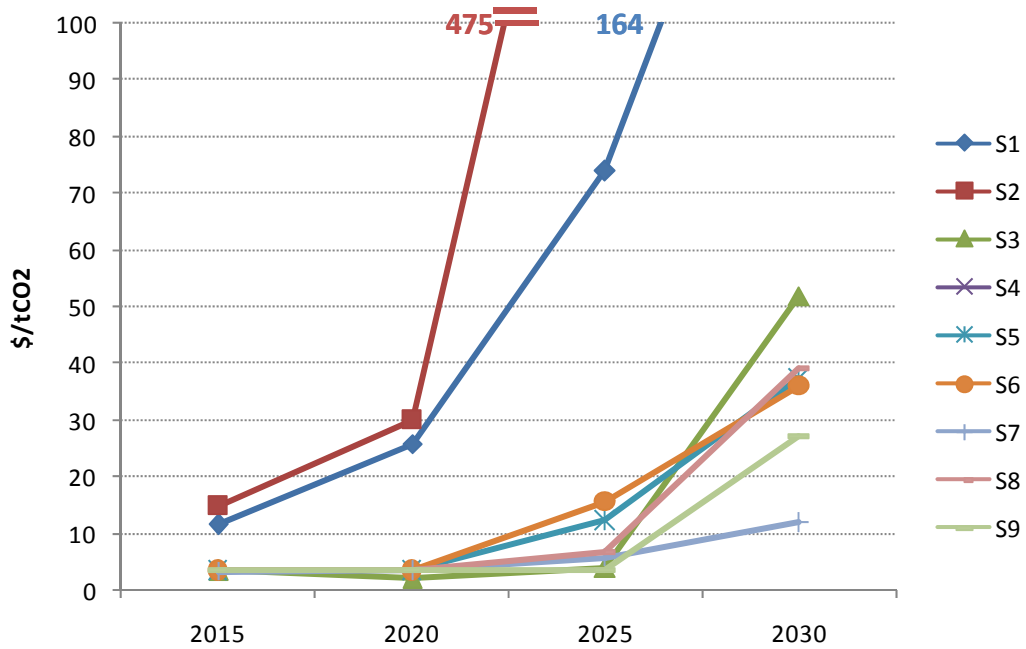
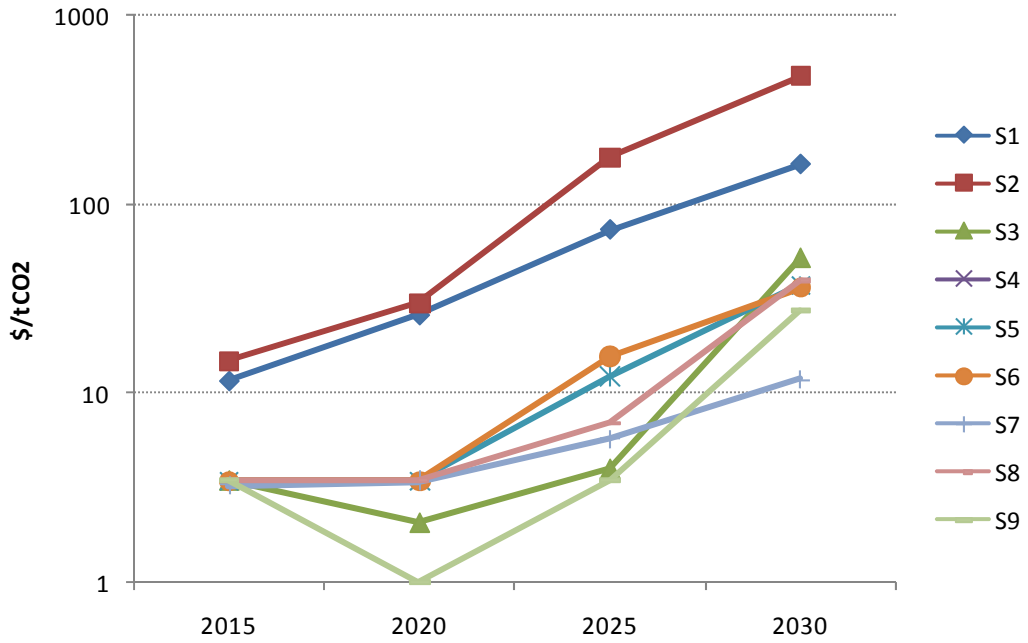


Figure 4: Carbon Permit Price in 2005 in USD per ton CO2 equivalent.

Mitigation requirements

To achieve climate mitigation, a vast portfolio of mitigation solutions is required, ranging from energy to agriculture. The actions required in the energy sector, the most important contributor of carbon emissions, can be seen in Figure 5. Indeed, it indicates that a range of options should be pursued concurrently. Renewables such

as wind, solar, biomass and advanced fuels such as bio-energy are expected to play an especially important role in meeting the world energy demand at a low carbon rate; but so will nuclear and coal with carbon capture and storage (CCS), which will ensure the stability of the load. Each of them will come with drawbacks, either in terms of land utilization, waste management and proliferation risks, or coal extraction.

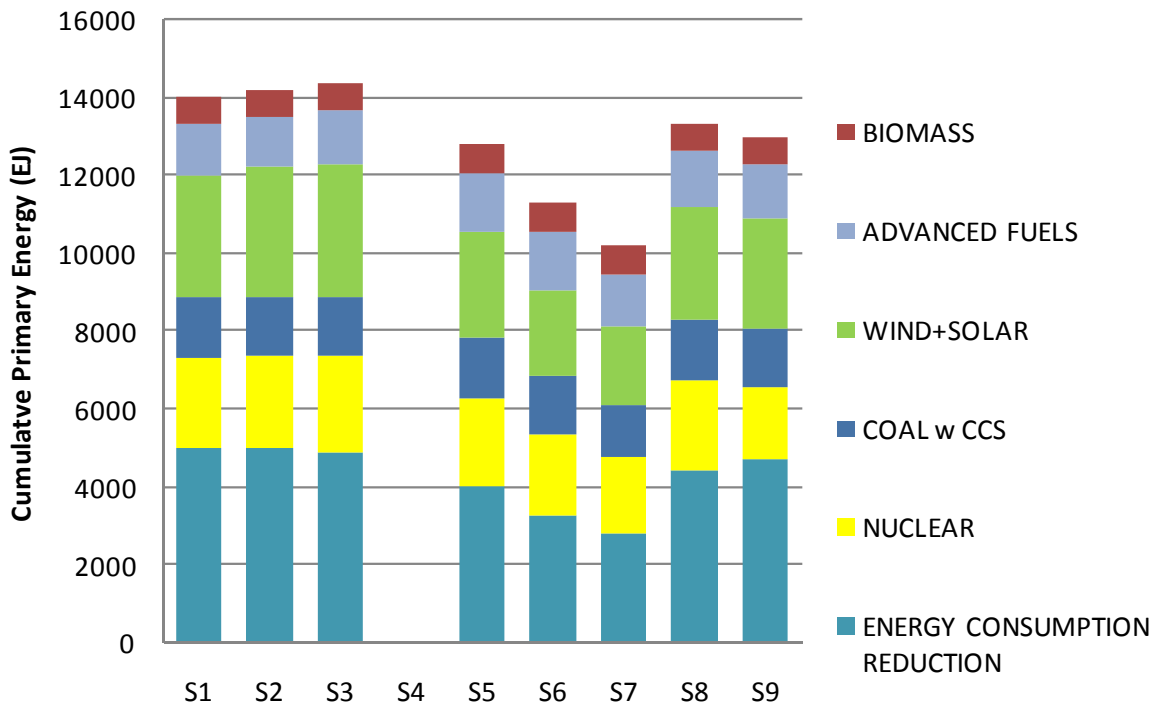


Figure 5: Savings and low carbon options in primary energy throughout the century

One striking feature of this chart is that all stabilization targets eventually require a somewhat similar reallocation of the supply to cleaner forms of energy; however, for serious climate protection, it is the demand that will need to play the biggest role. The demand cuts will be achieved by enhanced energy efficiency, and this indeed is a key mitigation option, especially in the early periods. Inevitably, however, lower consumption will be required, and this will happen only through changes in lifestyle.

In previous studies, (Bosetti et al 2009d and Edenhofer, Carraro et al. 2009) we have analyzed the relative values of single technologies in the portfolio of mitigation options. Carbon capture and storage (CCS) and renewables have the highest potential to act as low-cost mitigation options. Nuclear energy can contribute substantially to emission abatement, although it entails specific risks that can only be partially accounted for in the models. In the long-term, the higher the restrictions on technology availability, the larger the role that will be played by energy efficiency. Given major uncertainties in future

technology development, it is necessary to encourage diversification in order to have a broad portfolio of options.

An additional and important issue regards innovation. Technological advancement, especially for clean fuels, will be indispensable to mitigate GHG emissions. This calls for substantial investments in R&D, as shown in Figure 6. Roughly 200 billion USD per decade will need to be mobilized in the next 30 years to meet the technological change requirements of stringent stabilization targets, repartitioned roughly equally over time (and thus higher in earlier periods relative to GDP).

Although these figures are much larger than what has been invested in the recent past, they are small when compared to the investments needed in the installation of new low carbon capital, and thus represent an efficient hedging strategy (Bosetti et al, 2009c). Figure 6 also suggests that for less stringent targets, R&D investments will need to ramp up more gradually, but will nonetheless be eventually needed to ensure the decoupling of GHG emissions from economic growth.

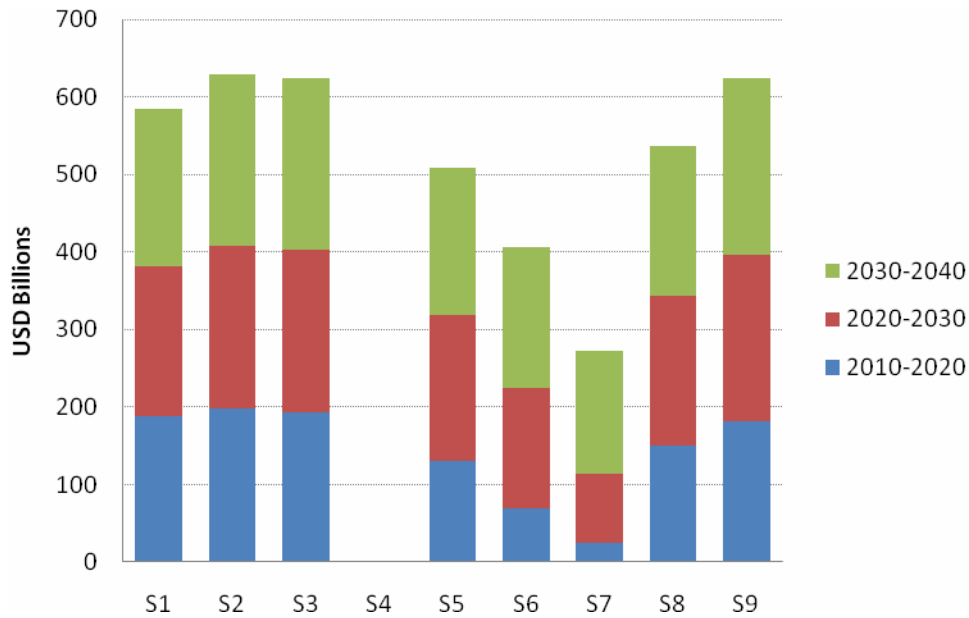


Figure 6: Investments in energy R&D.

Finally, emissions should be reduced in all sectors of the economy, not only in the energy one. Our analysis envisages substantial mitigation in CH₄, N₂O and CO₂ from land use change. The latter – especially through tropical deforestation - represents a particularly relevant source of emissions today, and its solution is deemed economical and has various additional co-benefits.

For the more stringent scenarios, we find reduced emissions from deforestation and land degradation (REDD) in order of 2.7 GtCO₂ in 2020, mostly in South America and South East Asia. For this to be viable, necessary institutions that monitor and verify emission reductions will need to be quickly established in major countries such as Brazil and Indonesia.

5. Policy implications

The analysis of our modeling results has highlighted a series of issues related to global climate mitigation, which have important policy repercussions.

We have shown that a **large portfolio of mitigation options** will be needed in all mitigation scenarios. This will include renewables and CCS as key technologies. Nuclear could also play an important role (though it entails specific risks that can only be partially accounted for in the model). Deployment of these options will require a **strong carbon price signal**, but specific policy instruments could also be envisaged, though they might increase the costs of technology.

Also, **innovation** has been shown to be fundamental, with a four-fold increase in requirements respect to current investment levels. In this respect, innovation could also be supported by specific policies aimed at internalizing innovation market failures such as international knowledge spillover.

Last but not least, **radical energy consumption lowering** is needed to achieve the 2° C objective. This will only be partially met through improved efficiency and policies aimed

at **changing habits and lifestyle** should be envisaged as additional instruments.

Establishing the institutions that can handle large **REDD** projects as early as 2015 would also be important for the transition to a low carbon world.

Our modeling results have highlighted that serious stabilization targets are likely to have important economic repercussions, with estimated global **GDP losses** above the ones reported by the Fourth Assessment Report of the IPCC, at least for very stringent stabilization targets. Several percentage points of GDP could be lost in such cases. Although the risks of abrupt climate changes might well justify this effort, policy makers should be aware that **efficient policies and international cooperation** should be designed to minimize these costs. A **major effort** will be required by current and next generations in order to achieve stringent GHG stabilization targets.

As shown in Figure 7, our simulations have shown a trade-off between climate protection and economic activity. The relation is highly non linear and statistically significant. Achieving additional temperature reductions will call for more than proportional losses of GDP. In addition, if stringent targets are

envisaged, **early action is important. An early start would allow the achievement of more ambitious targets at lower costs, or viceversa,**

as can be clearly seen comparing scenarios S1, S2, S3 and S9.

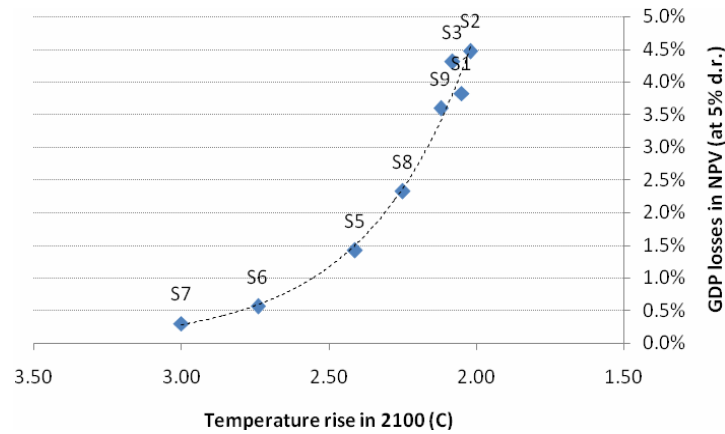


Figure 7: The temperature/economy trade off

The obvious intuition for this result is that the capital turnover for energy is particularly low, and thus the **transition to decarbonization needs to be gradual**, to avoid costly early capital retirement. Since post peak reduction rates have to increase in response to a delay in policy action, in order to maintain the environmental effectiveness unchanged by the end of the century, delayed action results in sharply increased policy costs. Also, as shown in previous sections, **innovation is key** to decoupling the economy and the environment, but it is known to be a gradual process which sometimes involves lengthy processes before new technologies achieve break even.

Adjustments on the demand side, which we have shown are equally important for meeting low stabilization objectives, can also be attained only in a gradual way. One parameter that synthesizes the costs of a hurried transition to decarbonization is the emission reduction rate after emissions reach their peak. A simple econometric investigation, limited by the small sample size, shows that two significant **predictors of the (log) climate policy costs are the policy stringency** (measured by temperature or cumulative emission reductions) **as well as the post peak emission reduction rate**, see Table 3.

Table 3. OLS analysis of scenario results

Source	SS	df	MS	Number of obs = 8		
-----+-----				F(2, 5) = 4655.87		
Model	7.2927422	2	3.6463711	Prob > F = 0.0000		
Residual	.008915883	5	.000783177	R-squared = 0.9995		
-----+-----				Adj R-squared = 0.9992		
Total	7.29665808	7	1.04237973	Root MSE = .02799		

logcost	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]	
-----+-----						
temp	-2.518964	.056906	-44.27	0.000	-2.665246	-2.372683
postpeakred	7.999511	1.28006	6.25	0.002	4.709011	11.29001
_cons	1.657636	.1671854	9.91	0.000	1.227872	2.0874

Finally, we would like to express a word of caution. Models are a partial representation of reality and rest on important assumptions. The analysis performed here is a **quasi-“first-best” world**, with full international participation, a perfect international carbon market, and foresight of future climate obligations. In reality, departures from all or many of these assumptions are likely to occur and would result in **potentially higher economic penalties**. First of all, it might well be that global participation is only reached after a set of partial agreements are first put in place. In

particular, it is very likely that developing countries will not take action until serious commitment to mitigation is not demonstrated by the developed world. The latest Energy Modeling Forum exercise (EMF 22, Clarke et al, 2009) showed that the penalty of such second-best scenarios can be substantial. More stringent stabilization scenarios can be eventually ruled out if developing countries delayed their participation.

If global participation is not to be given for granted, full availability and unconstrained potential of all carbon free technologies should also be questioned. Again several studies

(Edenhofer (ed), 2009, Richels et al, 2007 and Bosetti et al, 2009c) have shown that constraining assumptions on the availability of technologies might not only dramatically increase climate policy costs, but might also preclude more stringent climate targets.

Several other second-best elements could contribute to inflate policy costs as some sectors could be left out of regulation, the link of the regional carbon policy could be suboptimal, or the actual foresightedness of policy makers and firms might be very limited.

6. Future Avenues for Research

Given the conclusions and caveats described in the previous section, the first step towards achieving realistic estimates of policy costs would be to further explore the **second-best world**. This could be done by dropping some of the model assumptions; for example, limiting countries' participation, allowing for limitations in international carbon trade and where flexibility, considering limits on technology availability. Also, one could consider measuring net policy costs, thus including **avoided climate damage** (although uncertainty surrounding climate damage estimates makes it hard to produce reliable figures, rather than value

ranges). Finally, the report has dealt with the global costs of climate policy. However, within the negotiation debates the **distribution of costs** will matter as much, if not more. The initial allocation of permits could entail major transfers of funds through emission permit trades from developed to developing countries, or it could be designed to minimize these flows. Possible allocations range from grandfathering, under which emission rights are allocated on the basis of each country's share of global emissions in some base year, to a per capita rule, under which the same amount of allowances is granted to every human being, to an ability-to-pay rule that allocates allowances every year to each human being in inverse proportion to its GDP per capita ratio vis-à-vis the world average, to some application of the "historical responsibility" principle and many others. A thorough investigation of the regional implications of different allocations schemes across the scenarios would warrant further research.

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Appendix 1: WITCH Baseline Emissions

Figure A1 distinguishes the different drivers of GHG emissions in the WITCH baseline, following Kaya's decomposition of total emissions (EMI) into carbon intensity of energy (EMI/EN), energy intensity of the economy (EN/GDP), per capita GDP (GDP/POP) and population. The left part of the graph reproduces the historical components of GHG emissions observed over the past thirty years, whereas the right panel depicts the long-term trends produced by the model in the baseline up to 2100. Historically, per capita GDP and population have been the major determinants of emission growth, whereas improvements in carbon intensity have had the opposite effect of reducing emissions.

The long-term scenario is still characterized by the preponderant role of economic growth, whereas the role of population fades over time. Economic growth, measured in terms of per capita GDP, is the major driver of GHG emissions over the whole century whereas population growth contributes to the increase in GHG emissions up to 2075, when population starts to follow a slightly negative trend. A decrease in energy intensity has a positive effect on emission reduction, which, however, is not large enough to compensate for the pressure of economic and population growth. The carbon content of energy remains rather constant over time, with a slight carbonization of energy due to an increase in coal consumption in fast-growing countries like China and India.

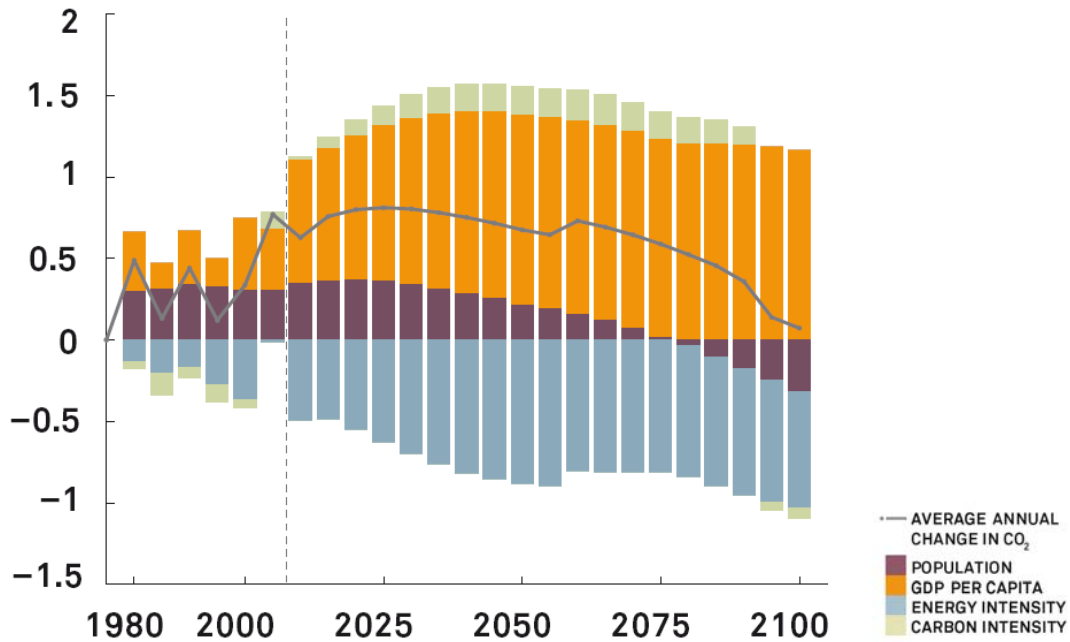


Figure A1: Components of CO2 emissions: historical data and future path

When compared to other integrated assessment models, WITCH positions itself in the middle range of baseline emissions. Figure A2 shows the energy-related CO2 emissions projected in a baseline scenario by the models that participated in the recent EMF22 comparison exercise (Clarke et. al., 2009)³. The chart shows that WITCH fossil fuel CO2 emissions grow from the current 30 GtCO₂, to 47 in 2030 and 86 in 2100, in line with the average of the various scenarios. In the shorter run of 2030, WITCH emissions are somewhat (roughly 10%) above the forecasts of the Energy Information Agency and the International Energy Agency.

³ Data is publicly available at the following website
http://emf.stanford.edu/events/emfbriefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures/

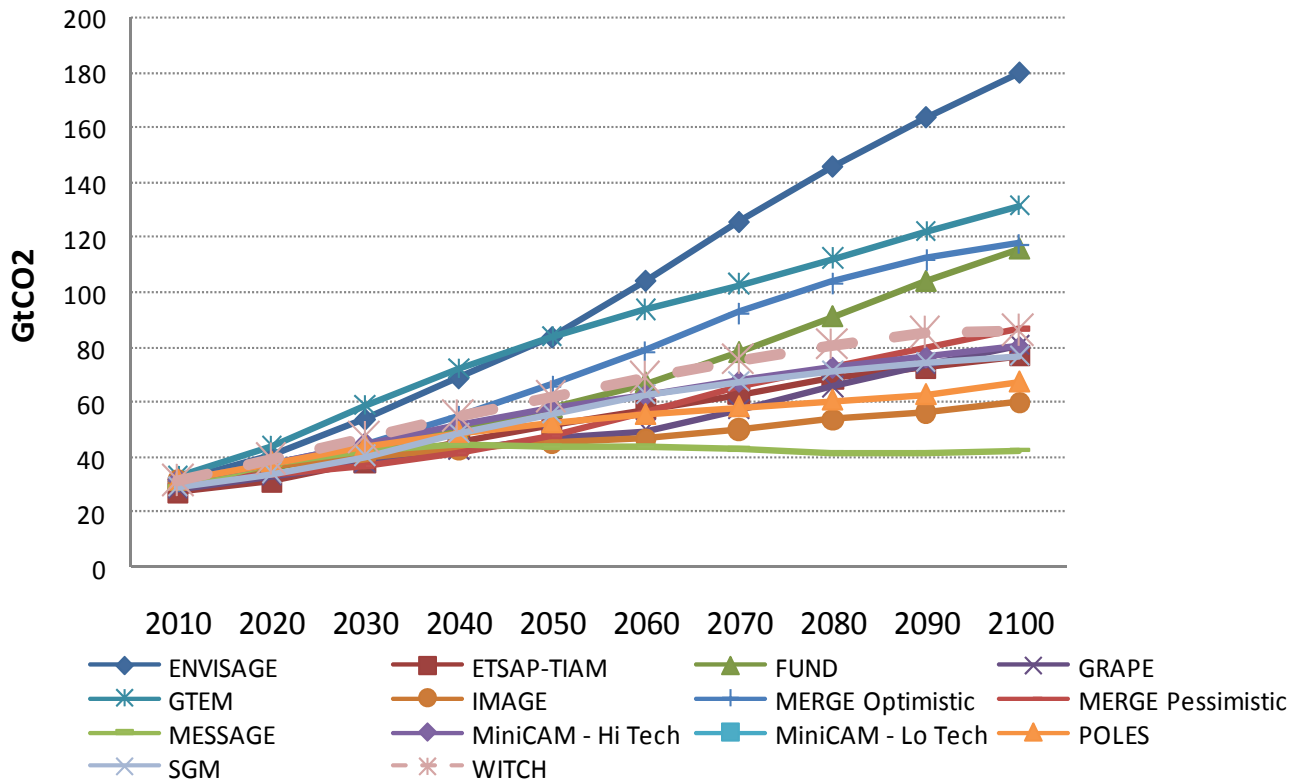


Figure A2. Energy-related CO2 emissions in the baseline for models participating in the EMF22 exercise (Clarke, L.E., J.A.Edmonds, V.Krey, R.G.Richels, S.Rose, and M.Tavoni (2009), 'International Climate Policy Architectures: Overview of the EMF22 International Scenarios', Energy Economics, 31 S64–S81)

The baseline emissions from land use of CO2 and non-CO2 greenhouse gases are exogenous inputs to the model, and have been taken from the literature.