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Timing of Mitigation and Technology Availability in Achieving a Low-Carbon World

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Abstract This paper analyzes the economic and investment implications of a series of climate mitigation scenarios, characterized by different levels of ambition for long-term stabilization goals and transitional pathways. Results indicate that although milder climate objectives can be achieved at moderate costs, stringent stabilization paths, compatible with the 2°C target, might require significant economic resources. Innovation and technology are shown to be able to mitigate, but not structurally alter, this trade-off. Technologies that allow capturing CO_2 from the atmosphere are shown to be important for expanding the feasibility space of stringent climate policies, though only if deployed at a scale which would represent a tremendous challenge. In general, the analysis indicates that the timing of mitigation is an important factor of cost containment, with early action being desirable. It also elaborates on the set of mitigation strategies and policies that would be required to achieve climate protection at maximum efficiency.

Keywords Climate policy · Stabilization costs

JEL Classification C72 · H23 · Q25 · Q28

1 Introduction

Although no clear consensus of 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

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century still represents the objective of most nations represented at the UNFCCC, and has been recognized as a fundamental signpost in the Copenhagen and Cancun agreements. To meet this challenge, greenhouse gas concentrations must be limited to at least 450 ppm CO_2 equivalent (with a 50% likelihood) or below. This objective can be met by following different emission pathways, which can be characterized by a greater or shorter delay in action. As a consequence, this entails a reasonably rapid reduction of emissions in later periods. This paper analyzes a set of scenarios aiming at different levels of ambition for long-term climate objectives, the timing of initial commitment, and the pace of decarbonization, by means of a hybrid integrated assessment model (the WITCH model). It also assesses the role of the available set of technologies, and two specific key technologies; carbon capture and sequestration, which are associated with coal power plants and bioenergy power plants. The latter allows absorbing CO_2 from the atmosphere, and thus potentially achieving negative emissions.

The main finding of this exercise can be summarized as follows:

(a) Potentially significant costs. Although milder climate objectives can be achieved at low costs, stringent stabilization compatible with the 2°C target might have important economic repercussions (costs measured as discounted GWP losses range between 4 and 7%, depending on the choice of the discount rate). The costs of such policies crucially depend on when the transition to a lower carbon society starts, as well as on the range of mitigation options, the pace of technological innovation and the feasibility of the large-scale removal of CO_2 from the atmosphere.

(b) Early action. Action timing influences the cost of meeting a target as well the stringency of the 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. Only under the optimistic assumption of large-scale CO_2 removal can the tradeoff between costs and timing of action be less severe.

(c) Wide mitigation portfolio. Renewables, CCS, nuclear, REDD, and innovation (R&D) are all crucial options to minimize stabilization costs. Renewable technologies and carbon-free innovation should be incentivized through appropriate policies. Moreover, negative emissions technologies are crucial for the attainability and costs of stringent policy cases.

(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 of the cost of climate policies carried out in many other quantitative assessments contains several idealistic assumptions. These assumptions could be violated in the real world where some technologies may not be fully available, technology transfers and diffusion may be imperfect, some world regions may not accept to reduce their own GHG emissions, trading may be limited to some sectors or to a fraction of the total abatement effort. This would increase the challenge of climate protection and the costs of reducing GHG emissions.

The paper is structured as follows. Section 2 briefly reviews the modeling tool used for analysis. Section 3 describes the main characteristics of the emission paths considered. Section 4 discusses the main results, while Sect. 5 investigates the technological dimensions of CCS and negative emissions mitigation options. Section 6 concludes presenting future avenues for research.

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 the 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.feem-web.it/witch.

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

The following four features of WITCH should be highlighted:

- Foresightedness of decision makers;
- Mitigation options;
- Specification of technological change in the energy sector;
- 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 enforced, then each region's policy maker anticipates its arrival. Investments in the energy sector and in innovation are made to avoid a lock-in effect. Policy makers consider 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, for instance, in the non-electric sector. Mitigation options in the power sector include nuclear, hydroelectric, IGCC-CCS, renewables, bioenergy burning with CCS, 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. Therefore, rather than being modeled as an autonomous process, improvement in energy efficiency is the product of specific investments.

In the longer-term, however, one could envision 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 available in large supplies. For the purpose of modeling, a backstop technology can be better thought of as a compact representation of an advanced technologies portfolio that would ease the mitigation burden away from currently commercial options, though it would be available in a few decades. Given that these technologies are not explicitly specified, we do not need to choose 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 require 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 with both investments in dedicated R&D and technology diffusion. Forestry is an important contributor of CO_2 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) described the results of this analysis in depth. The supply cost curves of biomass for bioenergy and CCShave been generated by the GLOBIOM land use model, developed at IIASA.[1]

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 Fig. 1 and can 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 test if, in case of somewhat even lower ambitious stabilization targets, 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.

Summary statistics for the nine scenarios are shown in Table 1. Emission and abatement paths over time are shown in Fig. 1.

The aim of the analysis is to determine the different implications of these global carbon emission trajectories, with different ambition levels for long-term climate objectives, as well as the timing of initial commitment and pace of decarbonization. Furthermore, in the second part of the paper we consider an additional dimension of analysis and evaluate the same nine scenarios under two opposite technological scenarios; a pessimistic one in which CCS is not viable and an optimistic one in which we allow for large-scale deployment of negative emissions technologies.

Scenarios assuming a slower pace of decarbonization in the early period can also be interpreted as scenarios in which only a subset of countries has accepted to curb emissions while the rest of the world's regions agree to keep their emissions at their business-as-usual levels and only start to accept binding targets at a later point. It is noticeable that the latter is the direction emerging from the latest rounds of negotiation within the UNFCCC. Indeed, the Copenhagen pledges for 2020 that were presented during the 2010 Cancun meeting of the parties imply business-as-usual non-binding targets for many emerging economies.

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, for instance minimizing the consumption loss required to

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[1] http://www.iiasa.ac.at/Research/FOR/globiom.html?sb=13.

Table 1 Features characterizing the 9 Scenarios

Scenario	Peak emissions year	Post peak emissions reductions (%)	Probability of <2°C (%)	Probability of <2.5°C (%)	Probability of <2.75°C (%)	Probability of <3°C (%)	Median temperature rise in 2100°C	Cumulative emissions 2000–2050 $GtCO_2e$	Cumulative emissions 2000–2100 $GtCO_2e$
2014 peak—2.05°C	2014	3	45	78	86	91	2.05	1849	2508
2016 peak—2.02°C	2016	4	48	78	87	91	2.02	1875	2434
2020 peak—2.08°C	2020	5	44	76	85	90	2.08	2000	2519
2030 peak—2.36°C	2030	5	24	58	70	81	2.36	2447	3138
2020 peak—2.41°C	2020	2	21	56	70	81	2.41	2263	3333
2020 peak—2.74°C	2020	1	7	34	50	64	2.74	2392	4006
2030 peak—3°C	2030	1	3	20	34	49	3.00	2622	4540
2020 peak—2.25°C	2020	3	31	64	78	85	2.25	2172	2967
2020 peak—2.12°C	2020	5	40	73	83	90	2.12	2063	2694

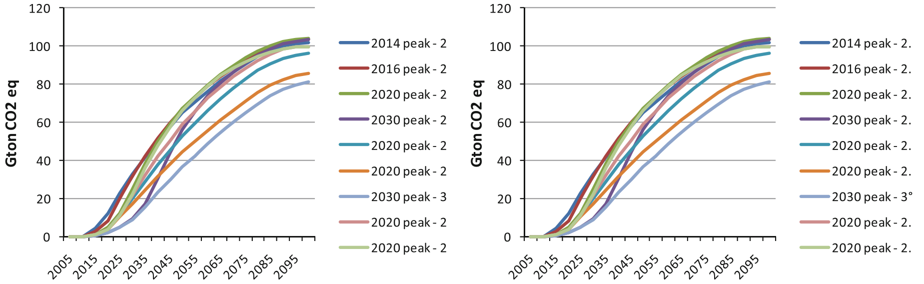

Fig. 1 *Left panel* Emission pathways for scenarios 1 to 9. *Right panel* Abatement effort for scenarios 1 to 9, according to the baseline emissions of the WITCH model

meet the temperature target), rather we measure the costs of alternative sub-optimal pathways.[2] Although scenarios mimic different levels of early commitments from different areas of the world we assume a perfect international carbon market is 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 (as the focus of the paper is on global costs we do not investigate regional issues). All countries are assumed to take part in the international climate agreement as soon as it is established, even though they might simply agree on emission allowances equal to their baseline level.

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") are endogenous as well as the results of the investment decisions in the energy sectors. Fossil fuel CO_2 emissions grow from the current 30 $GtCO_2$, 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 $GtCO_2$, slightly above the B2 SRES scenario group. More (less) optimistic assumptions on fossil fuel resources' availability or on economic growth would lead to higher (lower) emissions in the baseline; henceforth the climate constrained scenarios would imply larger (smaller) abatement efforts and costs. The 2100 figure is within the average of more recent modeling comparisons (see Fig. 11 for a comparison of the latest baseline emission pathways within the EMF 22 comparison exercise).

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[2] We decided not to look into the effect of banking as a way of smoothing out 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 et al. 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).

4 Presentation and Discussion of Main Results

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

4.1 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 considering the benefits from avoided climate change.

Figure 2 shows the global GDP losses regarding the baseline across the various scenarios and times. Several patterns are identifiable. Keeping the temperature increase at the end of the century between 2.5 and 3°C (scenarios "2020 peak—2.74°C" and "2030 peak—3°C") 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 EU and the G8. In the latter class of scenarios, global GDP losses can be as much as 10% and begin accruing earlier in time. Within this class of stringent mitigation policies, the scenario which shows lower costs is surprisingly not the one in which mitigation actions should start immediately (scenario "2014 peak—2.05°C").

The "2030 peak—2.36°C" scenario, which entails postponing the peak in emissions until 2030, is 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 if some radical innovation will soon be available, time is required for the necessary changes in infrastructure and to allow for the new technology to pervade. Given these constraints,

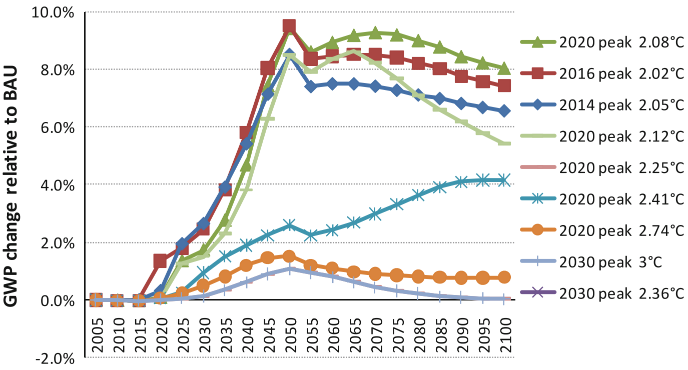

Fig. 2 Gross world product (GWP) losses over the century. The legend shows the scenario number and (*in brackets*) its median temperature change in 2100 in degree Celsius. Scenario 4 is not feasible

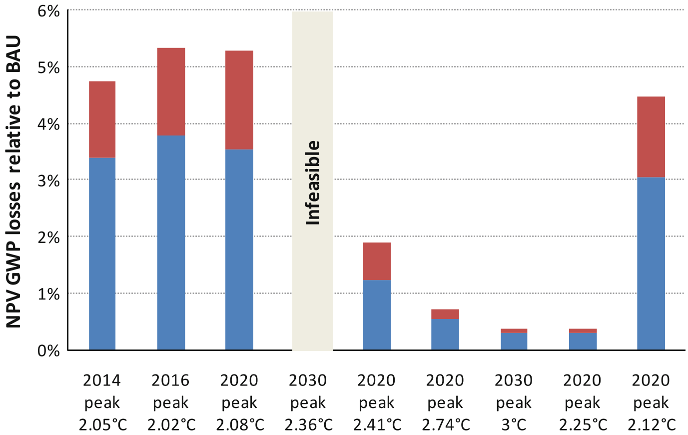

Fig. 3 Gross world product (GWP) losses in net present value (NPV), with a discount rate of 5% (*lower part of the bar*) and 3% (*whole bar*). Each series is defined by the scenario number and (*in brackets*) its median temperature change in 2100 in degree Celsius

the “2030 peak—2.36°C” scenario implies a pace of change in the energy sector that is too abrupt for the model to find a feasible solution.[3]

Figure 3 reports a more compact measure of costs, in which losses are actualized in today’s terms at 5 and 3% discount rates. The above graph clearly shows that approaching the 2°C objective will most likely have important economic repercussions, with present term GWP losses from 3.5 to 5.5% within the 2015–2100 period, depending on the discount rate.

Delaying action by only a few years is shown to negatively affect costs; for example the “2020 peak—2.08°C” scenario, despite achieving a somewhat higher temperature than the “2014 peak—2.05°C” scenario, entails costs that are 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 the “2030 peak—2.36°C” scenario, would make it impossible to comply with a stringent stabilization objective, since the additional overshoot would require emission cuts too sudden to be attained with the reference mitigation portfolio of the model.

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 recall the great uncertainties that surround the mapping of concentrations into temperature changes.

Our modeling estimates suggest that attaining stringent stabilization objectives would imply relatively high costs, but that moderate objectives can be accomplished at a much smaller charge. Table 2 compares our figures with those made for the IPCC 4th AR and the CCSP study.[4] 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°C target, we report costs that are substantially higher and range more widely. One should recall that, since only the most optimistic models have been able to simulate stringent climate policies until now, published

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[3] An important, though not the only one, assumption is that capital depreciates but cannot be scrapped earlier. Given this assumption, which is extremely realistic from a political view point, the scenario is unfeasible. We shall see later how, assuming negative emissions technologies are available makes this scenario feasible.

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

Table 2 Policy cost comparison (measured as GDP losses in 2050)

	GDP reduction in 2050		
	IPCC 4th AR estimates	CCSP	WITCH AVOID study
445–535 ppm CO_2e (2014 peak—2.05°C, 2016 peak—2.02°C, 2020 peak—2.08°C, 2020 peak—2.25°C, 2020 peak—2.12°C)	$<5.5\%$	NA	4.2–9.4%
535–590 ppm CO_2e (2020 peak—2.41°C 2020 peak—2.74°C)	Slightly negative to 4%	1.2–4.1%*	1.2–2.3%
590–710 ppm CO_2e (2030 peak—3°C)	-1 to 2%	0–1.2%	1.1%

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

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).

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 envisions 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 leads to a substantial decrease in macro-economic productivity. In addition, rather than being an autonomous process, innovation within WITCH is modeled as depending on R&D expenditures. These factors contribute to the realism of the modeling experiment but result in higher costs.

For the 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$/t$CO_2$-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 between 2015 and 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 recall 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, the “2020 peak—2.08°C” scenario has an initial carbon price lower than the “2014 peak—2.05°C” and ”2016 peak—2.02°C” scenarios (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 applied to improve 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 Fig. 2; this suggests that carbon prices are only partial indicators of the macro-economic costs of policies.

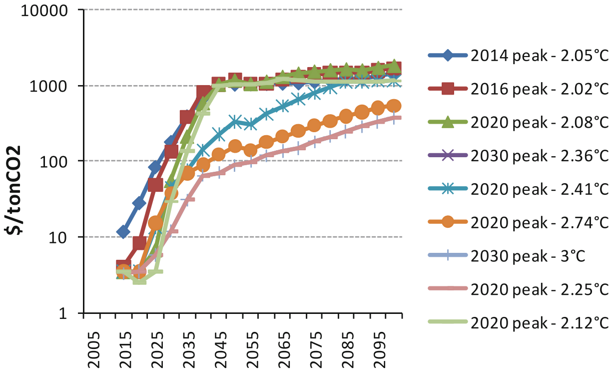


Fig. 4 Carbon permit price in 2005 in USD per ton CO_2 equivalent, log scale

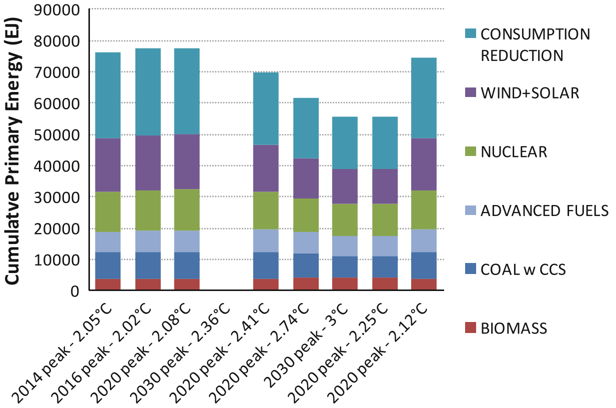


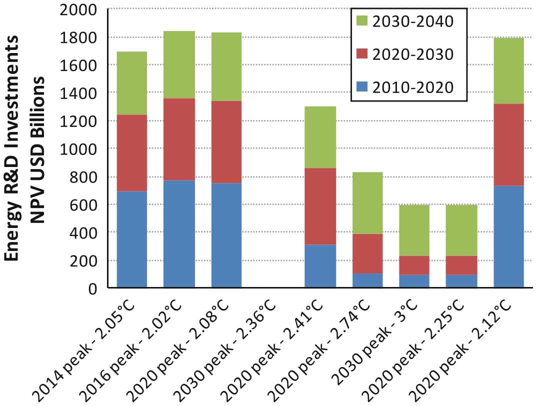
Fig. 5 Savings and low-carbon options in primary energy throughout the century

4.2 Mitigation Strategies

To achieve climate mitigation, a vast portfolio of mitigation solutions is required, encompassing several technologies and sectors. The actions required in the energy sector, the most important contributor of carbon emissions, are shown in Fig. 5. The graph 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. The same applies for nuclear and coal with carbon capture and storage (CCS), which will ensure the stability of the power generation base-load. Each of them will come with drawbacks, either with land utilization, waste management and proliferation risks, or coal extraction.

One striking feature of this chart is that, throughout the century, the various emission pathways require a rather similar reallocation of the supply towards a diversified portfolio of the above mentioned low-carbon energy options. What obviously changes across scenarios is the speed at which this transition is implemented. Changes on the demand side are shown to be equally, if not more, important than supply restructuring, especially for the case of ambitious climate scenarios. The demand cuts will need to be achieved by enhanced energy

Fig. 6 Investments in energy R&D. Each series is defined by the scenario number and (*in brackets*) its median temperature change in 2100 in degree Celsius



efficiency, and this indeed is a key mitigation option, especially in the early periods, but also through demand side management measures.

An additional and important issue regards innovation. Technological advancement, especially for clean fuels, will be indispensable to mitigate GHG emissions. To generate this change, substantial investments in clean energy R&D will be needed. The model logic allows the endogenous calculation of such resource needs, which are shown in Fig. 6. Roughly up to 600 billion USD per decade will need to be mobilized in the next 30 years to meet the technological change requirements of stringent stabilization targets, roughly repartitioned equally over time (in Fig. 6 numbers are given in present terms).

Although these figures are significantly larger (up to 10 times) than what has been invested in the recent past, they represent a share of GDP similar to that of the peak of energy R&D activities in 1980. These figures are small when compared to the investments needed in the installation of new low-carbon capital, thus representing an efficient hedging strategy (Bosetti et al. 2009c). Figure 6 also suggests that the size of R&D investments varies quite considerably across stringent and mild scenarios. The difference between the R&D programs of the emission pathways is especially evident for the investment needs in the next two decades. However, all the emissions pathways consistent with a temperature increase below 2.5 Celsius require a large and immediate research program, with important repercussions on the size and composition of short-term resources.

Finally, emissions should be reduced in all sectors of the economy, not only in the energy one. Our analysis envisions substantial mitigation in CH4, N2O and CO_2 from land use change. The latter, especially through tropical deforestation, represents a particularly relevant source of current emissions, 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 the order of 2.7 $GtCO_2$ 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 Exploring the Role of CCS and Negative Emissions Technologies

The analysis presented so far has highlighted an important tradeoff between climate effectiveness and economic costs of implementing climate mitigation pathways. The non linearity

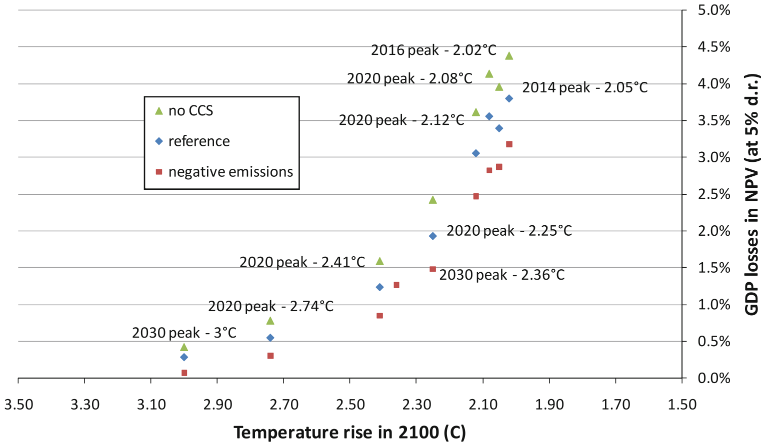


Fig. 7 The climate policy costs trade off

of the relation between these two variables depends upon the shape of the marginal abatement costs which are implicit in the model, and which depend upon the assumptions about competitiveness and evolution of the technological frontier. This also has important implications for the timing of mitigation, one of the key issues explored in this paper, since more (less) optimistic assumptions about technology could result in later (earlier) mitigation action.

We address these issues in this section by exploring two opposing technological views. The first case is labeled no CCS, in which carbon capture and storage (CCS) is assumed not to be viable, either for technological or social reasons. The second case is labeled negative emissions, in which CCS works and furthers technologies that allow capturing CO_2 from the atmosphere (such as burning biomass and storing CO_2 in the ground), are assumed deployable at large-scale. These two opposite cases, each of which we run for all the nine scenarios under examination, allow us to explore the sensitivity of the results presented so far in the role of technology. Negative emission technologies have been shown to play a major role on the feasibility of stringent climate policies (Azar et al. 2010; Clarke et al. 2009), but have also raised issues about the reliability of model comparison exercise results (Tavoni and Tol 2009).

Results are summarized in Fig. 7, which plots the costs of implementing the various emission scenarios under the three technological cases (reference, no CCS and negative emissions). The series is labeled only for the no CCS scenario, as the reference and negative emissions scenarios reproduce the same trend though shifted (the only noticeable difference is for the “2030 peak—2.36°C” scenario emission path which is only visible for the negative emission scenario, as it is unfeasible under the other two). The plot indicates a quite clear tradeoff between climate protection and economic activity. The relation is highly non-linear. Achieving additional temperature reductions will call for more than proportional losses of GDP. In addition, if stringent targets are envisioned, early action is important. An early start would allow the achievement of more ambitious targets at lower costs, or vice versa, which can be clearly seen by comparing the “2014 peak—2.05°C” and, ”2016 peak—2.02°C”, “2020 peak—2.08°C” and ” 2020 peak—2.12°C” scenarios.

The chart indicates that the role of technology availability has consequences on the level of total compliance costs, in the expected direction of increasing (lowering) the costs in case of less (more) technological availability. In the case of the optimistic scenario with large-scale negative emissions, the “2030 peak–2.36°C” scenario, which previously proved infeasible because it is characterized by the postponement of mitigation activity from early to later

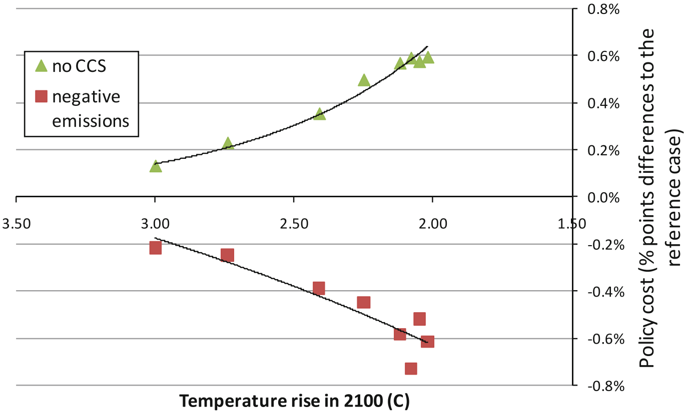


Fig. 8 The impact of technology on policy costs

periods, is now achievable thanks to the possibility of absorbing CO_2. Note though, that this scenario remains inefficient regarding the neighboring "2020 peak—2.41°C"and "2020 peak—2.25°C" scenarios. At the other end of the spectrum, the case without CCS shows that higher costs are needed for the same level of climate protection, but all scenarios feasible in the reference case remain so in this case, since the lost mitigation potential of CCS is made up by the greater share of renewables and nuclear power.

Technology, though, doesn't seem capable of breaking the climate-policy costs tradeoffs: policy costs remain clearly convex in the temperature increase goal. We further elaborate on the impact of technology on policy costs in Fig. 8, which plots the cost difference between the two opposite technological cases regarding the reference model. The chart shows that the value of technology increases with the ambition of the climate goal because each technological option gains in importance the tougher the climate objectives become, but also because the cost levels increase with the stringency of the climate target, precisely for the reasons outlined above.

Figure 7 shows the tradeoff between climate protection and economic activity, characterized by a non linear relation: achieving additional temperature reductions will require more than proportional losses of GDP. We summarize this relation by means of a simple econometric investigation of the 24 scenarios, whose results are reported in Table 3. The analysis indicates that the stringency of the climate objective (measured by the temperature increase) is a strong predictor of the policy costs (in logarithm). Technology is shown to be capable of lowering the policy bill, thanks to CCS and especially to negative emission technologies.

Finally, the analysis clears up the timing of mitigation issue. Results indicate that rapid decarbonization transitions (measured by the post-peak emission reduction rate) are costly, thus indicating that early action is important.

The 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. However, this result is reverted if we allow large-scale deployment of negative emission technologies: the interaction term of the speed of decarbonization and the availability of negative emission technologies has a sign which is opposite and larger in magnitude, suggesting that in the presence of these technological options it might be optimal to somewhat defer abatement to later periods, since CO_2 absorption from the atmosphere would allow us a much more rapid and profound shift to a low-carbon economy.

Table 3 OLS analysis of scenario results (dependent variable = log of NPV GDP loss, number of obs = 24, adj. R^2 = .97)

	Coef.	Std. Err. *t*	$P > t$	[95% Conf. Interval]
Temperature	−2.84	.203	0.000	−3.26978 to -2.415807
Negative emissions technology dummy	−1.05	.173	0.000	−1.422195 to −.6947898
CCS dummy	−.226	.086	0.017	−.40879 to −.0450831
Post peak reduction	16.89	5.65	0.008	5.008252 to 28.77745
Interaction term between post-peak red. and negative emis. tech	−20.97	4.99	0.001	−31.472 to −10.47316
Constant	2.87	.601	0.000	1.61049 to 4.136906

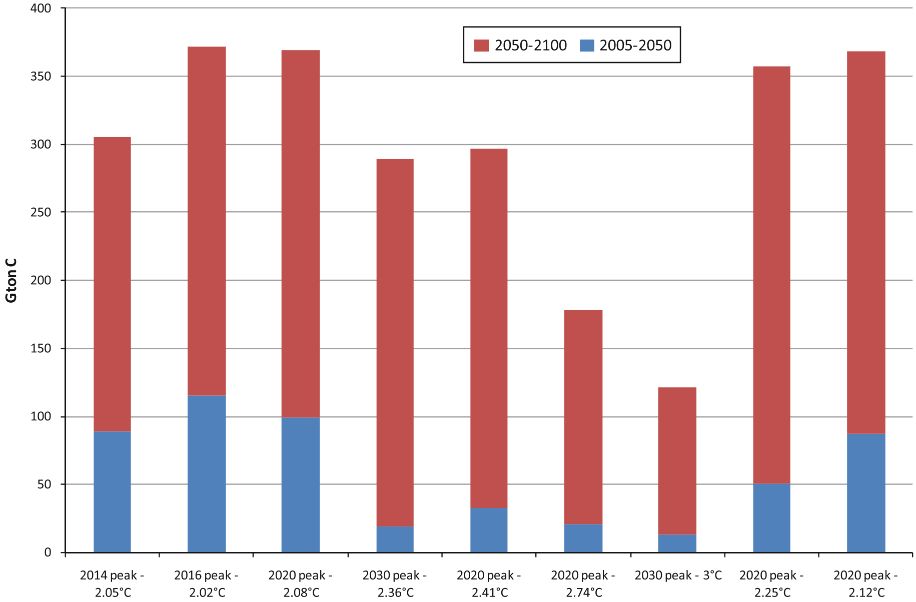


Fig. 9 Global, cumulative CO_2 captured from the atmosphere across scenarios

There is one important warning to keep in mind when considering the optimality of deferred emission reduction when negative emissions are available: The technological challenge of deploying negative emission technologies should not be underestimated.

It is important to note that the scale of implementation of negative emission technologies consistent with the technological optimistic (negative emissions) scenarios are considerable. Figure 9 shows the amount of CO_2 that would be captured from the atmosphere and stored underground with negative emission technologies.[5] Cumulatively throughout century, up to approximately 400 $GtCO_2$ would be captured. Even though most capturing activity would happen in the second half of the century, when innovation in agriculture could have substantially changed land productivity, the bioenergy feedstock requirement (up to 80 EJ/year)

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[5] Note that these are higher than the net negative emissions, since the model assumes positive lifecycle emissions associated with the growing and harvesting of biomass.

would still be considerable, with potential implications on land use, biodiversity and water resources, let alone availability of sites for CO_2 storage.

6 Conclusions

To conclude 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 almost a 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, it is likely that global participation is only reached after a set of partial agreements are put into place first. In particular, it is very likely that developing countries will not take action, not even based on non-binding targets. 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 delay their participation.

Regarding recommendations for future research, this paper has shown that the set of technologies that will be available, and the speed at which they will be deployed, significantly affect not only the costs of any climate policy, but also the time we can wait without entering an irreversible path. The stricter the climate objective or the later the mitigation effort starts, the more will we need to resort to technologies which have potential implications that we have not yet understood. This obviously requires a careful and realistic estimation of the costs and potentials of these technologies, the RD&D requirements to make them available with a reasonable level of certainty, and the potential barriers and external costs that might be linked to their deployment on a large-scale. From a political viewpoint, betting on the unconstrained availability of some negative emissions technologies in the second half of the century is appealing, hence it is important to keep track of the feasibility and of the costs of decarbonization paths with and without these technological solutions. A logical next step is to include the uncertain availability of these technologies in the analysis and perform a fully stochastic investigation on the RD&D needs, potential costs, and hedging strategies when innovation is not a given and deterministic process. Finally, the paper 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. A thorough investigation of the regional implications of different allocations schemes across the scenarios would warrant further research.

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Appendix: WITCH Baseline Emissions

Assumptions on baseline emissions are a crucial driver of climate policy costs as they influence the necessary effort to curb emissions. In the following we describe the drivers of emissions in the model baseline and how it stands regarding that of other models. One of the

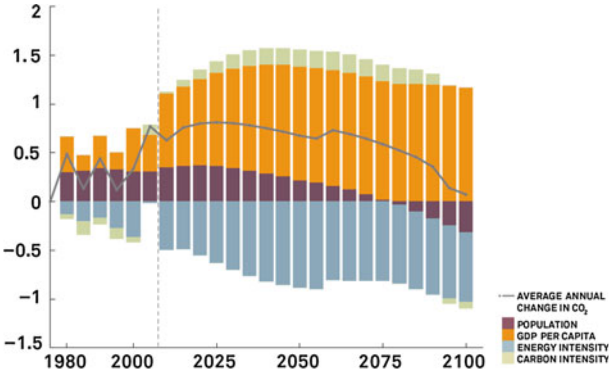

Fig. 10 Components of CO_2 emissions: historical data and future path

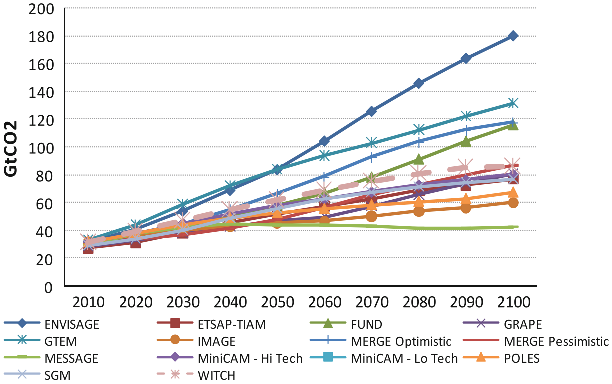

Fig. 11 Energy-related CO_2 emissions in the baseline for models participating in the EMF22 exercise (Clarke et al. 2009)

main drivers in the difference between baselines is the fossil fuel availability assumption, as more optimistic assumptions will lead to higher estimates of policy costs.

Figure 10 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 shows 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 predominant role of economic growth, whereas the role of population fades over time. Economic growth, measured for per capita GDP, is the major driver of GHG emissions throughout the entire 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.

When compared to other integrated assessment models, WITCH positions itself in the middle range of baseline emissions. Figure 11 shows the energy-related CO_2 emissions projected in a baseline scenario by the models that participated in the recent EMF22 comparison exercise (Clarke et al. 2009).[6] The chart shows that WITCH fossil fuel CO_2 emissions grow from the current 30 $GtCO_2$, 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.

The baseline emissions from land use of CO_2 and non-CO_2 greenhouse gases are exogenous inputs to the model, and have been taken from the literature.

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[6] Data is publicly available at the following website http://www.emf.stanford.edu/events/emfbriefing_on_climate_policy_scenarios_us_domestic_and_international_policy_architectures/.