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The clean energy R&D strategy for 2°C

By Giacomo Marangoni and Massimo Tavoni

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Giacomo Marangoni (1)*, Massimo Tavoni (1)

Affiliation:
(1): Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Corso Magenta 63, Milan, Italy

** Corresponding author: giacomo.marangoni@feem.it*

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The clean energy R&D strategy for 2°C

Abstract

This paper uses an integrated assessment model to quantify the climate R&D investment strategy for a variety of scenarios fully consistent with 2°C. We estimate the total climate R&D investment needs in approximately 1 USD Trillion[1] cumulatively in the period 2010-2030, and 1.6 USD Trillions in the period 2030-2050. Most of the R&D would be carried out in industrialized countries initially, but would be evenly split after 2030. We also assess a 'climate R&D deal' in which countries cooperate on innovation[2] in the short term, and find that an R&D agreement slightly underperforms a climate policy based on the extension of the Copenhagen pledges till 2030. Both policies are inferior to full cooperation on mitigation starting in 2020. A global agreement on clean energy innovation beyond 2030 without sufficiently stringent GHG emissions reduction policies is found to be incompatible with 2°C.

1. Introduction

The purpose of this paper is to assess the role of R&D investments in clean energy technologies under the objective of limiting the average global surface temperature increase of 2°C above the pre-industrial average by the end of this century with sufficient probability. 2°C is considered an important signpost for the scientific community as well as for the climate policy debate. The international community has recognized this threshold as the long term goal for the negotiation process which was initiated in Durban, and more recently moved forward in Doha, and which is supposed to lead to a global agreement after 2020. While governments started to acknowledge anthropogenic climate change and the need for action 20 years ago with the first Earth Summit conference, several obstacles have made implementing such a goal very challenging. One of the most important concerns for action is that mitigating emissions, especially at the deep levels required to meet the 2°C objective, could have serious economic repercussions, given that currently available low carbon technologies are costlier than fossil fuel alternatives. A successful climate policy will thus require significant improvement of existing technologies, and invention of new alternatives which can help to reduce energy consumption and emissions at contained costs. Although the innovation component of the climate agenda has been emphasized by many governments, especially in Europe, the literature that has assessed the clean energy R&D gap remains limited.

The objective of this paper is in line with the main purpose of the LIMITS special issue it belongs to: contributing to a better understanding of the implications of a 2°C stabilization. In order to provide quantitative answers to the problem

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[1] All monetary values in this paper are given in 2005 US dollars using market exchange rates.
[2] While innovation is a broad topic, in this paper we will be referring to its R&D component.

at hand, this and most of the other works of the special issue rely on so-called Integrated Assessment Models (IAMs). This family of models is increasingly common in the field of climate policy analysis, since they provide fairly complete descriptions of the problems that climate policy makers are called to decide upon, and present them with sets of possible least-cost solutions. Further information on the broader results obtained with the models involved in the LIMITS comparison exercise can be found in the overview papers of this same special issue (Kriegler et al., and Tavoni et al., this issue). For a focus on how investments related to clean energy technologies are expected to be allocated under a 2°C target, the reader is invited to refer to McCollum et al. in this special issue.

The literature based on multi-model ensembles has indicated that a huge transformation on the way we produce and demand energy, as well as we use and manage land resources, will be required if we want to meet the climatic constraint of 2°C (Calvin et al., 2012; Clarke et al., 2009; Kriegler et al., this issue). This transformation would require emission reductions rates which exceed by far what has been observed historically. Currently available technologies have the potential to initiate the road towards decarbonization (Pacala and Socolow, 2004). Yet, ultimately, groundbreaking technological innovation will be needed to avoid excessive economic losses. Integrated assessment models have indeed shown that technology availability plays a major role on the feasibility and costs of facing the challenge of 2°C (Krey and Clarke, 2011; Kriegler et al., Submitted). The literature thus confirms a deep link between the chances of achieving a low carbon world and the ability to improve the performance of currently known technologies, as well as to create new technologies altogether.

Several policies have been put into place in recent years as a way to promote the development of renewables, with the hope that this would have led to the creation of an industry and would have ultimately profited the manufacturing base they supported. However, incentivizing the installation of currently existing technologies does not necessarily provide the best economic answer (Borenstein, 2012); on the other hand, subsidizing research and development is justified by the innovation market failures arising from property rights protection and knowledge spillovers (Geroski, 1995). Thus, a fundamental research question in the field of climate economics is to what extent climate stabilization can be achieved by just focusing on setting the right carbon price, or by considering also policies aimed at fostering innovation (Jaffe et al., 2005, 2003).

A related question to setting the right levels of R&D subsidies is the assessment of the R&D investments gaps that we need to bridge to get to 2°C. Despite the policy relevance of this topic, only a handful of modeling studies have looked into this issue. This can be partly attributed to the complexity of the topic of technical change, an uncertain process which is difficult to model. Surprisingly, however, these studies (Blanford, 2009; Bosetti et al., 2011, 2008; IEA, 2010; Margolis and Kammen, 1999; Nemet and Kammen, 2007; Popp, 2006) tend to agree on a series of important results. First, R&D plays a fundamental role on the costs and feasibility of climate stabilization policies. Second, the gap in R&D investments between a Business as Usual and a climate policy scenario is substantial, in the order of 50 USD Billions per year.

A further research question pertains to the role of innovation policies in case of fragmented cooperation on climate. Given the difficulties in reaching an inclusive agreement on emissions reductions among the major emitters, it is natural to wonder whether focusing on a technology and innovation agreement could offer better prospects and a more efficient outcome than continuing with a set of uncoordinated efforts to reduce CO_2 emissions (De Coninck et al., 2008; Newell, 2008).

This paper aims at contributing on the latter two lines of research, and thus improving the understanding of the role of innovation and R&D in the clean energy sector. Our study relies on the integrated assessment model WITCH (see next section). The originality of this article is twofold. First, the clean energy R&D gap is quantified with specific reference to the 2°C objective. To this end, we use the set of scenarios developed in the LIMITS project which combines short term policy realism with two different probabilities of meeting 2°C in 2100. The climate outcome of all scenarios has been tested using the probabilistic version of a medium complexity climate model (MAGICC), ensuring that the exceedance probability remains within specified ranges (see Kriegler et al., this issue). Second, we work out the implications of an alternative climate policy agreement based on a concerted international R&D programme. We refer to this policy setting as the 'RD-deal'. This agreement is meant to replace the current fragmented emission reductions pledges in the near-term with near-term high R&D efforts. International technology innovation policies have been widely discussed as alternatives to binding emission reduction targets, but have been rarely assessed by the IAM community.

The paper is organized as follows. We briefly discuss the main features of the WITCH model, and then present the study design. We show the implications of 2°C policies on the transformation of the energy system, and quantify the size and the regional distribution of the R&D investments needed to comply with it. We then assess the R&D climate agreement in relation to the feasibility of the 2°C objective. Finally, we summarize our conclusions.

2. Technical change in WITCH

WITCH (World Induced Technical Change Hybrid Model) is an energy-economy-climate model developed within FEEM's Sustainable Development research programme (Bosetti et al. 2006, 2009). The model divides the worldwide economy into 13 regions, whose main macroeconomic variables are represented through a top-down inter-temporal optimal growth structure. This approach is complemented with a compact description of the energy sector, which details the energy production, and provides the energy input for the economic module and the resulting emissions input for the climate module. The endogenous representation of R&D diffusion and innovation processes constitute a distinguishing feature of WITCH, allowing to describe how R&D investments in energy efficiency and carbon free technologies integrate the currently available mitigation options. The different regions can either behave as forward-looking agents optimizing their welfare in a non-cooperative, simultaneous, open membership game with full information, or be subject to a global social welfare planner in order to find a cooperative first-best optimal solution. In this game-theoretic set-up, regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of oil and carbon permits, and technological R&D spillovers.

For this paper, two channels of endogenous technical change are accounted for in the model. Their characteristics are summarized and compared in Table 1. One type of formulation of technical change affects the investment costs of an alternative, carbon-free technology in the non-electric sector. This 'backstop' zero-emission fuel can be thought of as an advanced biofuel mitigation option whose costs are currently much higher (e.g. 10 times) than oil, due to lacking of sufficient knowledge for transforming cellulose into ethanol. With sufficient R&D and physical investments, the low carbon backstop can become a viable substitute to low carbon fossils. However, we also impose a global constraint on the resource base which can be used to produce the low carbon fuel, as a way to mimic the limitation of land use which can be devoted to growing the bio-feedstock. The global cap is fixed at 150 EJ/yr, in line with available estimates of bioenergy crop potential (see Calvin et. Al, this issue, for a detailed discussion of bioenergy). Thus, although at times we refer to this unnamed technology to as backstop in the paper, its implementation in the model provides a realistic representation of the technology as a bioenergy-based low carbon fuel. While the climate mitigation literature mentions also bioenergy-based systems capable of removing carbon from the atmosphere, by means of carbon capture devices, no negative emissions are envisaged through our backstop technology.

The externality nature of the backstop innovation process is modelled via international spillovers of *knowledge* and *experience* across countries and time. In each country, the productivity of this low carbon technology depend on the region's stock of energy R&D and on the global cumulative installed capacity, two proxies for knowledge and experience respectively. This is modelled via two factor learning curves. The regional R&D stock depends on domestic investments, previous domestic knowledge stock, and foreign knowledge stock through international spillovers. The spillover term for knowledge depends on the interaction between the countries' absorptive capacity, and the distance of each region from the technology frontier. On the other hand, there are complete spillovers of experience across countries.

The other main channel of technical change in WITCH is about energy savings. Following Popp (2006), energy efficiency is modelled through improvements in the productivity of the energy input in the production of the final good sector, via a constant elasticity of substitution (CES) production function. Differently from the previous case, innovation is now subject only to knowledge externalities through a single factor learning curve. The knowledge stock depends on domestic and foreign R&D investments in a similar way than the one used for the backstop, with the only difference that the new additions to the stock of knowledge depend also on the previous domestic stock of knowledge.

Further details for both innovation formulations can be found in (Bosetti et al., 2011) and at www.witchmodel.org. The most relevant equations are reported for convenience in the Appendix.

	Energy Efficiency	**Carbon-free Advanced Biofuels (Backstop)**
Technological implications of the innovation	Introducing new energy-saving equipment and devices in any of the energy end-use sectors (buildings, industry, and transport).	Introducing advanced carbon-free biofuels as a primary energy supply for non-electric energy end-use sectors (mainly transport).
Economic implications of the innovation	Increasing overall energy efficiency of output.	Reducing the costs of carbon-free non-electric energy supplies.
Integration in the model	As a substitute for energy supply in producing energy services.	As a substitute fuel for oil in meeting the non-electric energy demand.
Technical change drivers	1. Domestic & foreign investments in R&D.	1. Domestic & foreign investments in R&D. 2. Domestic & foreign experience (i.e. amount of advanced fuels already used).

Diffusion limitation	Implicit in the constant elasticity of substitution (CES) production function structure.	Explicit through expansion and total resource constraints.
Knowledge to actual technical change delay	None.	10 years lag.
References in the literature	Jones (1995) for the knowledge formulation, Popp (2002) for the empirical estimation of the parameters, and Popp (2004) for the integration as a CES.	Kouvaritakis et al. (2000) for the knowledge formulation, Bosetti et al. (2009) for further references on the empirical estimation and modeling, Calvin et al. (this issue) for cumulative deployment potential estimates.

Table 1: The two channels of innovation in WITCH.

When elaborating on regional results, we will be referring to the 13 native regions of WITCH, which are: USA, OLDEURO (Old Europe), NEWEURO (New Europe), CAJAZ (Canada, Japan, New Zealand), KOSAU (Korea, South Africa, Australia), CHINA (including Taiwan), INDIA, SASIA (South Asia), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa excl. South Africa) and TE (Transition Economies). For the sake of brevity, also the following aggregations will be used: EUROPE (OLDEURO + NEWEURO), OTHER-OECD (KOSAU+CAJAZ), OTHER-ASIA (SASIA+EASIA), and MEA (MENA+SSA).

A distinctive feature of WITCH is the ability to assess the optimal response to climate policies either in a competitive or in a cooperative setting. In the latter, a social planner chooses the optimal financial efforts to allocate in innovation and mitigation, in a way that welfare is maximized conjunctly with the achievement of a given climatic target. This type of optimization can be regarded as a useful benchmark for evaluating the consequences of internalizing the set of externalities which are taken into account in the WITCH model, namely: GHG emissions, dependence on exhaustible natural resources, and technological R&D spillovers. A particular advantage of this setting lies in the ability of estimating the economic benefits of a cooperative world, where classic climate policy instruments are replaced by sets of policy instruments that promote coordinated efforts in achieving the desired climatic targets.

As one could expect, full cooperation scenarios lead to lower consumption losses and higher accumulation of R&D backstop investments compared to the non-cooperative corresponding cases. The results obtained in the context of this paper with the cooperative settings are not reported here, as they are in line with previous studies with this same model (Bosetti et al., 2011), and with the aforementioned literature on R&D subsidies. For the sake of this paper, it is only worth mentioning that cooperation not only affects the global picture (with a general increase of investments), but also the regional contributions to innovation (with a more prominent role for developing countries).

3. Study design

To assess the role of energy innovation in decarbonizing the energy system, the 2° degrees target was translated into a set of significant scenarios implementable by the WITCH model. Most of the scenarios we consider here were defined in the context of LIMITS, whose purpose is to explore the implications on feasibility and costs of different policy assumptions, i.e. the probability of achieving the 2° degrees target, the timing and stringency of global and regional mitigation action, and the distribution of regional costs. Further details on the whole scenario framework adopted for this study, as well as on how the economy and the energy system of different IAMs respond to the different scenarios assumptions, can be found in the two overview papers by Kriegler et al. and Tavoni et al. in this issue.

Besides the standard LIMITS scenarios, we have run three additional scenarios to address the specific questions under investigation. Specifically, we have assessed 'second best' policy scenarios in which no agreement is achieved on emission reduction policies, but in which countries decide to cooperate on R&D by investing at the optimal levels consistent with their stabilization objective, either 450 ppm-eq or 500 ppm-eq.

Table 2 reports a brief description for all of the scenarios used in this study. The last row shows the ones which are additional to the LIMITS study protocol.

Scenario	Description
Base	No climate policy, either global or regional, is in place.
RefPol	Regions are subject to 2020 targets that represent the lower end (or lower if more plausible) of their (or of their neighboring regional leaders) Copenhagen pledges. The stringency level of 2020 regional targets is extended until the end of the century by using average GHG emissions intensity improvements per year as a proxy.
StrPol	Like RefPol, but the more stringent end of their (or of their neighboring regional leaders) Copenhagen pledges are taken into account, and extended until the end of the century.
RefPol-450	Regions apply the RefPol policy package up to 2020, then a globally-harmonized carbon tax is adopted so that the concentration of GHGs reaches 450ppm-eq in 2100, with overshoot allowed. This corresponds to a likely to very likely (>70%) chance of reaching the 2 °C target.
RefPol-500	Like RefPol-450, but with an as likely as not (~50%) chance of reaching the 2 °C target, and with the concentration of GHGs reaching 500ppm-eq in 2100.
RefPol2030-500	Like RefPol-500, but with global commitment delayed till 2030.
RD-deal-450 **RD-deal2030-500**	These scenarios correspond to those with the same names where RD-deal is replaced with RefPol. In the near-term, carbon emission mitigation pledges are removed from the corresponding RefPol policy packages, while energy R&D is fixed at the optimal level. Afterwards, a globally-harmonized carbon tax is adopted so that the concentration of GHGs reaches the levels of the corresponding scenarios.

Table 2: List of scenarios used in this study, along with their description.

In the next sections, after describing the challenge for the economy and the energy systems to stabilize the climate to non-dangerous levels, the R&D investment gap is quantified for what can be considered as first-best settings, where mitigation action, even if fragmented, starts immediately, and global cooperation starts in 2020 or in 2030. Then, R&D figures are analyzed in a class of second-best scenarios, in order to see if other sub-optimal policies, where the regional emission reduction efforts of the Copenhagen pledges are replaced by high energy R&D investments and global cooperation is delayed up to 2030, could constitute viable cost-effective alternatives.

4. Challenges of stabilization to 2° degrees

A world without any climate policy is expected by WITCH to be a world with a temperature in 2100 of 4° degrees above the pre-industrial levels, which is likely to imply serious ecological, social and economic consequences. More than 60% of yearly global GHG emissions are related to CO_2 emissions resulting from the burning of fossil fuels for energy related purposes, which are supposed to increase in the baseline on average by 1.3% per year. Population and global economy are also supposed to increase, at an average rate of 0.4% and 2.4% per year respectively, while global energy intensity levels are expected to decrease at an average rate of 1.4% per year. On one side, this implies an improvement of carbon intensity over the century, due to the expected diffusion of more efficient energy systems around the world. On the other side, countries are expected to show an increase in the average carbon emissions per capita, representing the worldwide claim for better living standards met by a fossil based energy system.

Looking at the regional emission contributions, the largest emitter is expected to be with wide margin China, with almost 30% of the total cumulated GHG emissions of the century. Following with 10.4%, 9.8% and 9.3% we find India, USA and LACA, respectively. Europe (6.7%) places itself in the middle of the list, after TE (8%) and MENA (7.6%). When considering emissions growth rates, India distinguishes itself with its average rate of 2.1%, followed by China and MENA, both at 1.5%, concurrent with double growth rate figures for GDP.

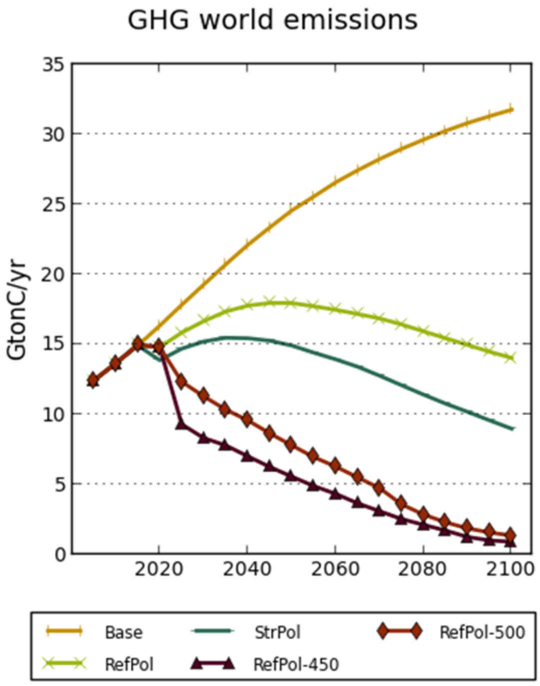

Figure 1: Emission profiles for a subset of LIMITS scenarios

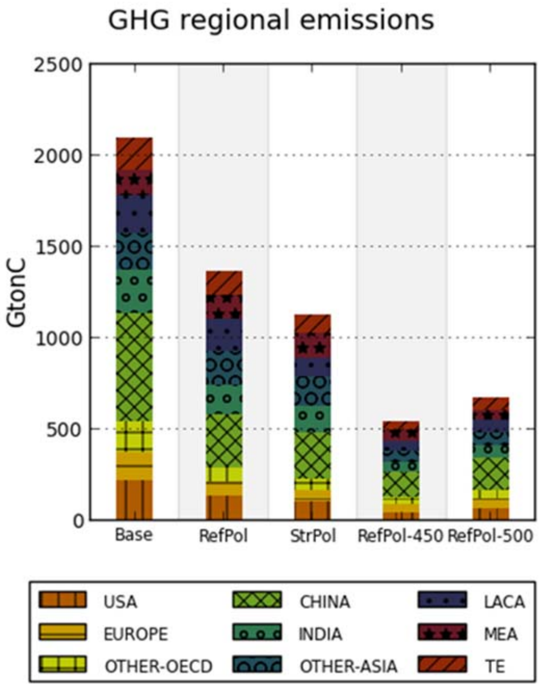

Figure 2: Cumulative emissions over the century decomposed by regions.

If regional economies were able to respect a weak fragmented commitment to climate mitigation, as foresighted in the RefPol scenario, cumulated GHG emissions over the century could be reduced by about one third. A further 10% could be abated with a more stringent fragmented commitment (as in StrPol). The rate of carbon intensity reduction varies across regions, according to explicit targets set after 2020. Focusing on the RefPol case, for some regions like MEA, OTHER-ASIA and LACA, the baseline carbon intensity profile already meets the assumed pledge. For other regions, this target involves a binding constraint on emissions, pushing the transformation towards a less carbon intensive energy system. This transition is further elicited by explicit targets on the amount of renewable energy over the total final or electrical energy production after 2020, and of wind and nuclear capacity installed by 2020. Again, China happens to be one of the most significant players, with huge reductions in emissions and a significant slowdown of GDP. Of the 780 GTonC reduced from baseline in the RefPol, 322 (~41%) are to be attributed to China, more than what OECD countries together are supposed to mitigate (269 GTonC). This impacts its GDP with a yearly 2.9% loss with respect to the baseline, on average over the century, a rate which is above the average of 1% that is globally experienced. The countries with the highest losses are CAJAZ, TE and KOSAU, with yearly average GDP losses of 3.3%, 3.2% and 2.2% respectively. The carbon intensity rate improvements these regions are asked to provide on average are between 1 to 3 times those of the Base scenario.

A substantial decarbonisation of the economy is required if more ambitious emissions targets are to be imposed, namely those where GHG concentrations reach 450ppm-eq and 500ppm-eq in 2100. This implies deep changes both in the electric and in the non-electric energy production sectors. Concerning the former, the reduction of carbon emissions is achieved in four ways: i) decreasing the power demand through efficiency improvements and economy contraction; ii) limiting the use of fossil fuels, partially switching to expensive technologies of carbon capture and storage (CCS); iii) increasing the diffusion of renewable energy sources; iv) enforcing the role of nuclear power, as a consequence of the reduction in the use of the base-load fossil technologies, and the limitations in the share of wind and solar power supply due to their intermittency issues[3].

Fossils cover around two thirds of the present world electric demand. In the Base scenario, this quota slightly increases over the century mostly at the expense of renewables, decreasing from 20% to 12%, while nuclear slightly decline from 14% to 12%. In the moderate Copenhagen scenarios, instead, fossil fuels are progressively substituted, especially in the second part of the century, mainly by nuclear and renewables: in 2100, nuclear settles around 20%, renewables take 25% of the power share, while fossils decrease accordingly. It is interesting to note that the role of CCS technologies grows considerably with the stringency of the climatic policy. Even if they only appear in the last decades of the century in the RefPol and StrPol cases, their share amounts to 13% and 22% in 2100. In the more stringent stabilization scenarios, finally, a complete decarbonisation of the power sector takes place over the century: fossil fuel power supplies constantly decline, and need to be fully combined with CCS technologies. The diffusion of renewables is extensive: biomass plants reach 20% of the share, almost all of them with CCS, while wind and solar plants rise to 20%, capped by the aforementioned intermittency-related system integration constraints. In absolute

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[3] The penetration of intermittent renewables in the electric system is limited by 1) penalty costs dependent on the share of intermittent renewables in the power mix 2) equations ensuring the presence of flexible generation options, like coal and gas plants, to adequately compensate for the intermittency of wind and solar supplies.

terms, 2100 electricity consumption decreases by 23%, 32%, 49% and 50% in the considered scenarios (RefPol, StrPol, RefPol-500 and RefPol-450) with respect to the corresponding Base value. These reductions complement the transition to a less carbon intensive power system in meeting the emissions targets.

A strong decarbonisation is recognizable also when looking at the overall energy sector. Again, energy efficiency improvements allow for equal levels of GDP given smaller final energy amounts. Jointly with a shrink of the economy forecasted by the model to meet the various targets, these effects determine a considerable decline in the absolute demand: in 2100, it is 12 ÷ 25% lower than the Base case in the Copenhagen scenarios, while it is more than halved in the stabilization. Besides demand reduction, significant impacts of the policies under study can be seen in the share of fossil fuels and renewables in global primary energy supply, demonstrating a progressive transfer of production quotas from the former to the latter. Nonetheless, one of the most important factor in assisting the regional mitigation actions remains the diffusion of the carbon-free backstop in the non-electric sector. While this technology doesn’t enter in the baseline, it turns out to be very reactive to the stringency of the climatic policy when one is imposed. At the end of the century, the 25%-32% of the non-electric demand is satisfied by the backstop in the fragmented cases, whereas the share rises to 72% in the stabilization ones. In the latter scenarios, a complete switch from oil to advanced carbon-free biofuels is envisioned by the model by 2090.

The diffusion of the backstop, along with the energy efficiency improvements, is an essential part of the optimal model response to the ambitious targets under investigation. The huge reductions in energy demand would not be economically reasonable without adequate investments in energy efficiency improvements. Furthermore, if the transportation energy demand and the decarbonization requirements are to be jointly met, replacing oil with carbon-free alternatives becomes essential for the levels of stringency under consideration. The deployment of these two mitigation strategies would not be possible without specific investments in R&D, which will be explored in detail in the following sections.

5. The R&D gap for 2°C

In this section we quantify the R&D investments which are optimal for the set of 2°C compatible scenarios outlined in the previous sections. As described above, the WITCH model features two types of R&D investments that can improve the economic efficiency of the energy system. The first aims at compensating the need for final energy by increasing the energy efficiency of the whole energy sector. A second type involves the deployment of a non-electric carbon-free technology.

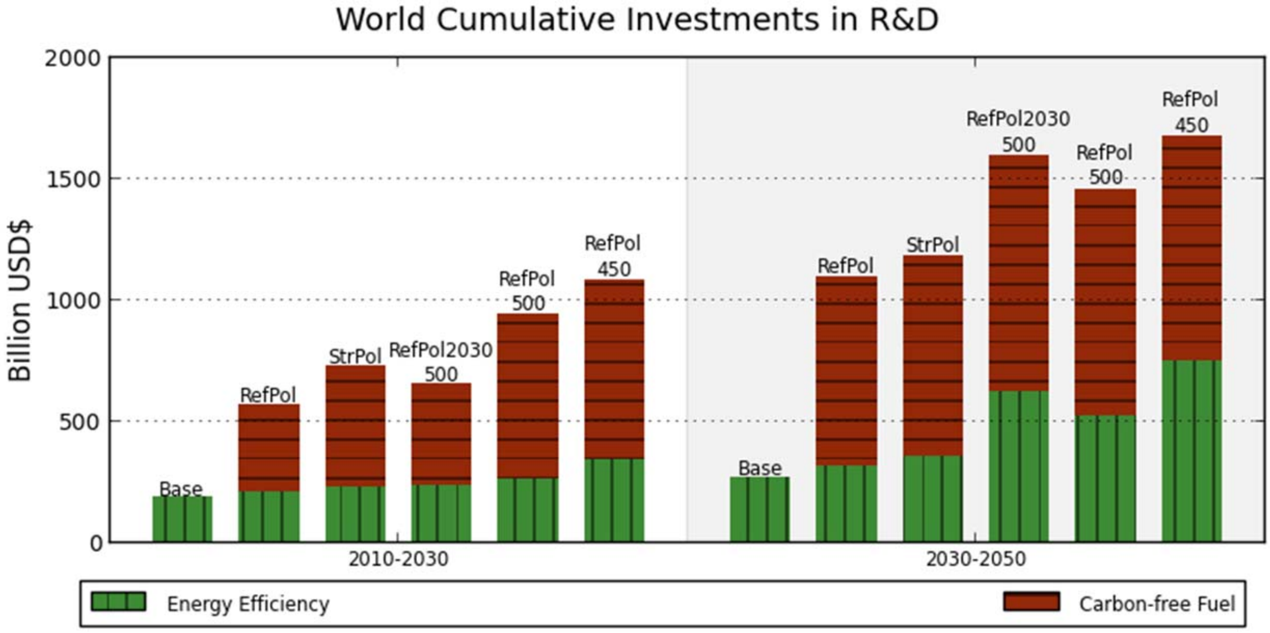

Figure 3: Optimal innovation investments in response to different climate policy scenarios

It is interesting to note that the model promotes a certain level of innovation effort already in the baseline case, where no particular climate policy is in place. This is related to the economic benefit of reducing the cost of the energy production by saving energy, but does not involve investing in carbon-free fuels given that no price is attached to CO_2, and that fossil fuels are assumed to be relatively available throughout the century. Regarding the impact of climate policies on R&D, as shown by Figure 3, investment cumulative levels increase both over time and in the stringency of the climate policy. RefPol2030-500 shows a lower effort in the near term, similar to RefPol[4]. In the medium term, the avoided initial investments are fully recovered, bringing the overall cumulative amount to a level comparable with the RefPol-500 scenario.

The increase in investments due to the stringency of the climatic policy is not equal in the two sectors, as the non-electric carbon free R&D appears to be much more sensitive to the climate policy stringency. This is due to the fact that energy efficiency R&D is carried out already in significant quantity in the Base case, because of the rising cost of the energy production factor. Further investments provide smaller benefits, due to the assumption of decreasing returns. On the other hand, carbon-free R&D is particularly valuable in the presence of the climate policies, since it provides a carbon free alternative in a sector which is notoriously difficult to decarbonizes, namely the transportation sector.

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[4] Even if one would expect that the 2010-2030 cumulative investments of RefPol2030-500 should be exactly the same of the RefPol, in period 2030 investments of the delayed scenario are let free to deviate from the RefPol, otherwise also the next period would be mostly fixed. This also applies to scenarios with a delay up to 2020, in which case investments are let free from period 2020.

Overall, Figure 3 indicates that the global R&D investment needs for attaining 2°C is approximately 1 USD Trillion in the period 2010-2030, and 1.6 USD Trillions in the period 2030-2050, if we consider RefPol-450 and RefPol-500 as our benchmark scenarios. Depending on the desired climatic target and on the near-term stringency of commitment, we can also quantify the gap between the optimal corresponding R&D investments efforts and the business-as-usual case. As no advancement is done in clean non-electric technologies, the global R&D gap to the no-policy baseline on average ranges from 30 (RefPol) to 58 (RefPol-450) USD Billions per year, up to 2050. These figures roughly double when considering the second half of the century in the same setting. The estimates reported above are consistent with previous studies with the same model (Bosetti et al., 2009), and more recent studies conducted by IEA (IEA, 2010), which establish the current annual public RD&D spending shortfall between 40 to 90 USD Billions. This projected additional effort asked to clean energy investors is 3 to 6 times the total annual amount of RD&D, averaged in the period 2005-2010, spent by IEA member states, which account for almost all of the OECD, and most of the global, R&D spending in that period (IEA, 2011). Cumulatively, between 1990 and 2010, the same countries invested about 220 USD Billions, less than half of the amount WITCH suggests to be optimally invested by OECD countries for the next 2 decades consistently with the 2°C target.

In relative terms, even if today R&D investments represent a small percentage of the world GDP (around 0.02%), it is clear from our results that most stringent scenarios will definitely benefit from increasing this share, and especially from doing so in the early near-term. This is what has been consistently found in the considered framework, where investments relative to GDP peak at around 2020 at 0.1%, and then gently decline to 0.05% towards the end of the century, as the return on investments decrease. For comparison, the level of investments in capital of wind and solar electric plants in 2020 is about 0.17%, and peaks before 2020 to 0.23% (RefPol) - 0.35% (StrPol) when imposing the constraints following from the Copenhagen pledges, and declines to 0.1% at the end of the century. Further characterization of the R&D dynamics can be gained by inspecting the regional distribution of the R&D investments. This is illustrated first for the efficiency case in Figure 4. The chart highlights a rather constant allocation of regional contributions across time and scenarios. While China among non-OECD regions is the one that increases its share the most over time, the coverage of efficiency R&D investments by OECD countries remains dominant, fluctuating around 80%. The reason for this dynamics depends on the fact that the current energy intensity is considerably lower in industrialized countries, which use more efficient technologies and have a less energy intensive economic production[5]. As a result, further improvement in energy saving technologies must be fostered by inventive activities (in this model dependent on R&D investments), whereas - in emerging economies - there are more opportunities for reducing energy intensity by adopting more efficient technologies and shifting the production structure towards a more capital intensive one.

More diversity in terms of regional R&D schedules is evident when focusing on the regional shares of backstop investments (Figure 5). The chart shows that the more stringent the climate target, the higher the share of investments in non-OECD countries. This is due to the fact that, for climate stabilization policies, the majority of the mitigation effort happens in the developing countries (see Tavoni et al., this issue). For the policy more compatible with 2°C (the 450ppm-eq case), R&D investments in low carbon fuels in the next 20 years are shown to be evenly balanced between industrialized and developing economies. This equal regional split consolidates in the medium term (2030 to 2050) for all scenarios.

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[5] In WITCH, GDP is measured in MER. Using the PPP metrics, instead, might weaken this effect, by reducing the energy intensity gap between industrialized and developing economies.

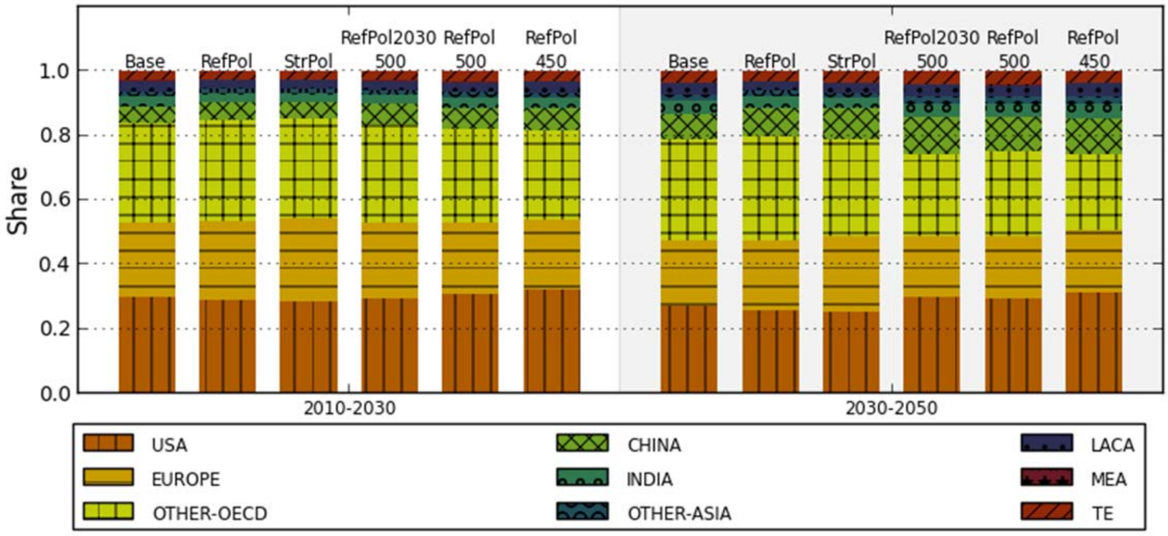

Figure 4: Regional shares of cumulative R&D investments in energy efficiency for the near and medium terms.

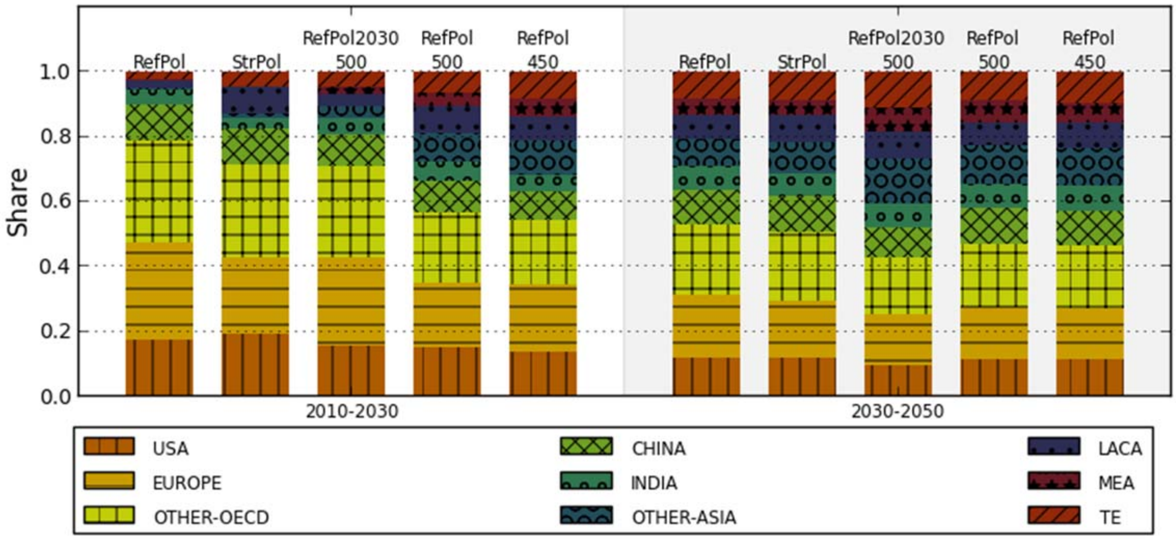

Figure 5: Regional shares of cumulative R&D investments in carbon free fuel for the near and medium terms.

Still focusing on the non-electric sector, it is useful to assess the consequences of the R&D investments by comparing the resulting backstop price with the price of oil, which is its main market competitor. In 2010, the carbon-free fuel is assumed to enter the energy scene with a price 13 times the price of oil. Thanks to the R&D efforts, its unit cost decreases at an average rate of 4-6%/yr to 2050, depending on the scenario and on the region. Simultaneously, oil price increases with its increasing cumulative extraction, in such a way that the two prices meet between 2025 and 2035, depending on the scenario. After that point, the backstop provides an alternative cheaper than oil for the rest of the century to the non-electric (mainly transport) energy needs.

6. Assessing the chances of an R&D deal to get us to 2° degrees

In the previous section, the optimal energy R&D response as proposed by the WITCH model was studied in the context of a set of idealized scenarios. These scenarios assume a policy commitment by all the regions, albeit fragmented and not particularly ambitious till 2025. However, the current state of international negotiations is dominated by huge uncertainties, and it is possible that a global consensus might not emerge under the Durban action platform negotiation round. The aim of this section is to analyze alternative policy designs which target innovation rather than emission reductions in the short term.

We thus consider two additional scenarios, based on an R&D based policy which might provide a trade-off between the inertia of regional political systems to seriously commit to climate change policies and the willingness to limit the GDP loss in view of a long-term acceptable climatic target. In these scenarios, called RD-Deal-450 and RD-deal2030-500, countries replace the fragmented commitment to reduce emissions till 2025 or 2035, respectively, with an agreement to cooperate on energy R&D. Specifically, investments in both energy efficiency and low carbon technologies R&D are set to the optimal levels. Optimal levels are computed from first best runs in which full cooperation starts already in 2015. Thus, these R&D policies are assumed to enter into force already in 2015. After this initial period, where no mitigation action happens and only accumulation of energy R&D knowledge is enforced[6], a globally harmonized carbon tax ensures that a carbon budget compatible with 450 or 500 ppm-eq respectively is met. The RD-deal-450 thus mimics a policy case in which, at the UNFCCC conference of parties in 2015 in Paris, countries decide to immediately adopt R&D investment objectives - maybe because of difficulties in agreeing upon short term emission reduction targets - for a transition period of 10 years, after which they decide to cooperate on the objective of achieving 2°C with high probability. The RD-deal2030-500 case mimics a case of prolonged difficulties in setting emission reduction objectives, and in which countries decide instead to focus on R&D cooperation for 20 years (e.g. from 2015 to 2035), and to cooperate afterwards. These two cases are direct counterparts of the RefPol-450 and RefPol-2030-500, against which they will be compared in what follows.

We also tried to run scenarios with a procrastinated agreement on R&D, but found that the 2°C could not be met[7]. Specifically, we have found that R&D deals to 2030 and 2040 are incompatible with attaining 2°C with likely (e.g. 450ppm-eq) and as likely as not (e.g. 500ppm-eq) probabilities respectively. This is an important result by itself,

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[6] As detailed in Kriegler et al., this issue, beyond carbon emission constraints, the reference policy has explicit regional targets on the amount of renewable energy over the total final or electrical energy production after 2020, and of wind and nuclear capacity installed by 2020. These targets are retained in the RD deal scenarios, allowing for a more direct comparison with the corresponding RefPol ones. We also run the RD deal cases without these technology pledges, and we found negligible impacts on the results. Thus, in this framework it is appropriate to solely focus on the distinction between early mitigation and early innovation commitments.

[7] The model could not find a feasible solution to these programmes.

which shows a fundamental trade-off between investing for better future technologies and locking in currently dirty ones. The R&D agreement sets the right incentives for the first issue, but not for the second; as a result, carbon intensive capital is continued to be built while climate R&D investments are carried out. Due to the long term nature of energy investments, the RD deal - if carried out for too long - jeopardizes the chances of meeting the stringent carbon budget consistent with 2°C, even if it provides a more favorable technological future[8].

We begin our investigation of the R&D policy deals on the levels of investments in R&D. These are shown in Figure 6 for the two R&D deal scenario, and their respective Durban Action platform LIMITS scenarios. For energy efficiency (left panel), the chart shows that R&D investments are below the optimal levels (at which the RD deal scenario are set by design) till the time of inception of full cooperation on climate mitigation (2020 or 2030). For R&D aimed at making carbon free fuel competitive, investments are lower than optimal before full cooperation, but higher afterwards, in an effort to compensate the missed opportunity of starting to abate earlier. Investments eventually align between the RD deal and the Durban Action scenarios, as expected since in the long term the objective to collectively reduce emissions dominates the climate action strategy. The timing of investments is different between energy efficiency and decarbonization; for the former, investments continue to increase over time, since they represent continuous and gradual improvements in energy efficiency enhancing technologies. For the latter, investments peak and then revert to a common optimal level of investments. The initial peak, which would be even more notable if measured in share of GDP, is needed to bring down the cost of the breakthrough technology, so as to make it competitive with fossil alternatives. Once this happens, investments are somewhat reduced, though only to a limited extent, since the stock of knowledge needs to be maintained to keep the low carbon alternative in the market.

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[8] It should be remarked that in this version of the model we don't feature R&D processes for innovative CO2 absorbing technologies such as Direct Air Capture (DAC). Allowing for such an option could potentially provide additional leverage to the R&D deal, as more negative emissions can be done later in the century, though it would also increase the chances of exceeding the temperature target. For a discussion about the impact of DAC for climate stabilization in the WITCH model, see Chen and Tavoni (2013).

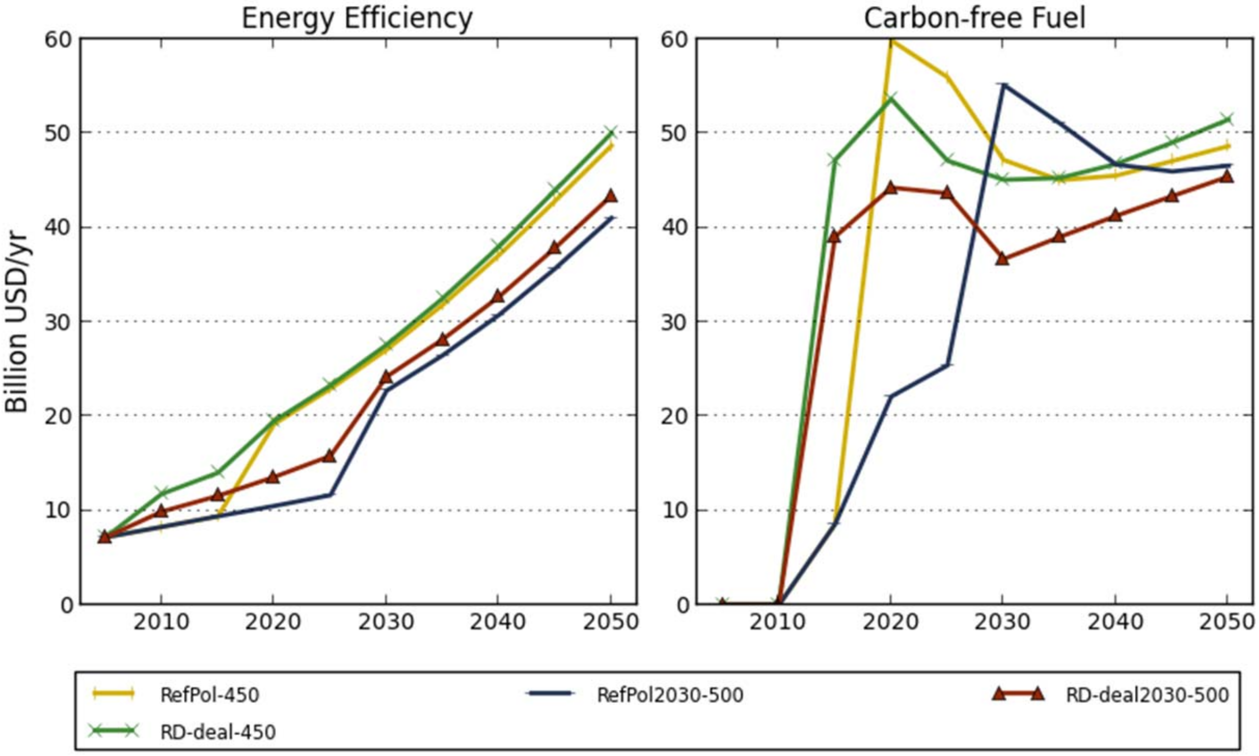

Figure 6: Time profile of the annual global investments in energy R&D in second-best scenarios.

Policy-efficiency considerations can be formulated by looking at Figure 7, which allows comparing the costs of the policies under discussion, assuming as a measure of cost the GDP loss with respect to the base case. The chart shows that till 2050 (left panel), policy costs are essentially identical for the 450 scenarios. This is reasonable since the two policies differ only in the strategies to 2020. For the 500 cases in which we assumed that full cooperation is enforced only after 2030 (precisely in 2035), the difference between the two scenarios is more clear. The R&D deal cases is as expected cheaper in the short term, since R&D investments are cheaper than actual mitigation measures, albeit at a reference policy levels[9]. The higher initial costs in the RefPol2030-500 are due to the partial cooperation on the Copenhagen commitments, which are assumed to be achieved independently for all regions with no opportunity to trade emission reductions. This leads to a diversity of regional carbon prices, with an associated efficiency loss. Over time, though, the RD-deal2030-500 policy turns out to be more expensive, due to the higher abatement needed to comply with the given concentration target (500ppm-eq) and the lower abatement carried out before 2030. Looking beyond 2050 (right panel), the cost difference persists in the 500 cases, whereas it remains negligible –or even changes sign- for the 450 scenarios. If policy costs are looked in terms of net present values over

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[9] If measured in Consumption losses rather than GDP losses, policy costs for the R&D deal scenario would be higher in 2020 and 2035, due to the crowding out of consumption. On the other hand, in 2030 the opposite would hold, since by then R&D investments in the RefPol2030 case is higher than the ones in the RD-deal scenario, as shown in Figure 6.

the whole century, the RD-deal policy marginally underperforms the Copenhagen commitments for discount rates up to 8%.

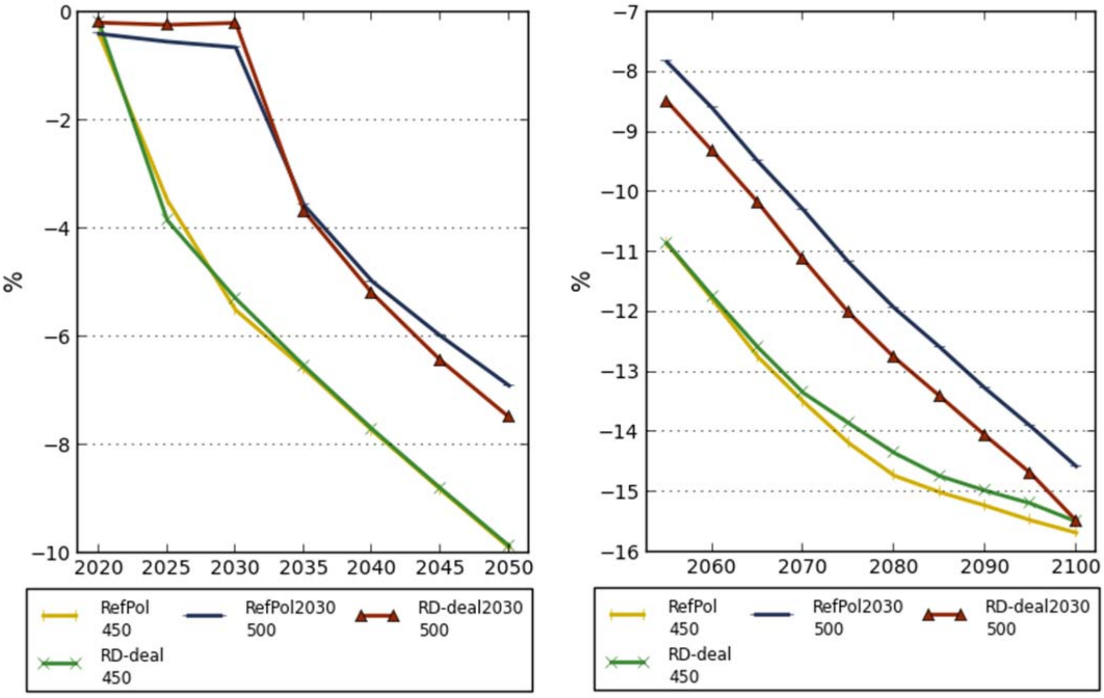

Figure 7: Time profile of the world GDP loss in second-best scenarios expressed as a percentage with respect to the GDP of the Base case. The two panel show costs for the periods 2020-2050 and 2050-2100 respectively.

While excessive emissions due to delayed mitigation makes the RD-Deal worse off, such a policy may still be beneficial on the long term with respect to a potential carbon lock-in of the energy system. By investing more in R&D, more advanced technologies are available, and the energy system is capable of faster and deeper rates of decarbonization than what would be possible in a less innovative future. This is confirmed both in terms of emissions per unit of GDP and emissions per unit of final energy. These indicators decrease in the second part of the century by at least 5% and 2% respectively in the RD-deal2030-500 scenario with respect to the RefPol2030-500 case. Also final energy per unit of GDP benefits from the RD-deal, with a relative decrease between 1% and 3% in the second half of the century with respect to its counterpart.

Thus, two main points emerge from our results. If there is willingness to commit to a stringent global climate policy rather quickly (e.g. after 2020), then the actions undertaken before than - be them either some mild fragmented mitigation or a collaborative international R&D programme - do not have a major economic impact once full cooperation is enacted. In the very long term (after 2060), the R&D deal strategy might be actually preferable, since it would allow for more deployment of advanced technologies. If on the other hand the international community opts for deferring global action to post 2030, then a strategy focusing on R&D would be preferable (in economic terms) till 2035, and worse after then. The ultimate choice between an agreement on innovation as opposed to a fragmented mitigation action would thus depend on the time preferences of the legislators, as well as on their aversion to a potential lock-in to a set of economically and environmentally suboptimal technologies. In both cases, however, delaying cooperation increases policy costs.

7. Conclusions

This paper has tried to provide some answers to two key questions related to the interplay between climate change mitigation and clean energy innovation policies. 1. What are the clean energy R&D investment needs to get to 2°C? 2. In the short term, is an international agreement on R&D better suited at preparing the ground for climate stabilization than continuing with fragmented and moderate emission reduction measures? Both questions are of high policy relevance for the Durban negotiation process which is assessed in the LIMITS special issue, to which this paper contributes. To our knowledge, both questions have not been yet addressed with the tools of integrated assessment modeling.

We have tackled these policy relevant questions by means of the WITCH integrated assessment model, which features endogenous technical change and multiple externalities. We have run a set of Durban Action Platform scenarios, integrating them with two additional ones based on a clean energy R&D climate deal, meant to replace early emission reduction Copenhagen commitments with early high R&D investments efforts. A series of key findings emerge.

i. We find that in order to attain 2°C with sufficiently high probability, a strong decarbonisation of the energy system is required, and mitigation actions call for an increased financing in climate R&D. We quantify the global climate mitigation R&D investment needs for attaining 2°C is approximately 1 USD Trillion cumulatively over the period 2010-2030, and 1.6 USD Trillions in the period 2030-2050.
ii. The investments would be initially concentrated in the industrialized countries, but would balance off with those of developing economies after 2030. The largest share of investments would be concentrated for the development of low carbon alternative fuels, though energy efficiency investments would also play an important (and growing) role.
iii. We find that focusing on an international clean energy R&D effort slightly underperforms a continuation of the fragmented mitigation effort outlined by the Copenhagen pledges for the sake of climate stabilization. Nonetheless, the actual ranking between fragmented mitigation or R&D investments in the short term depends on the time preference of the legislators, and on their aversion to a potential carbon lock-in.
iv. An exclusive focus on R&D at the expenses of mitigation is however incompatible with climate stabilization if maintained for too long. Specifically, R&D deals to 2030 and 2040 do not attain 2°C with likely (e.g. 450ppm-eq) and as likely as not (e.g. 500ppm-eq) probabilities respectively.

These considerations lead to some direct policy implications. If the chances of getting to a global climate agreement before 2030 remain slim (as they appear to be today), then one could consider shifting the focus of short term policy from emission reduction targets towards an R&D investment objective, if the latter has better chances of being legislated. This policy shift would not significantly affect the ultimate objective of climate stabilization, which in any case requires full cooperation on emission reductions no later than 2030. An agreement on R&D and innovation might have more political capital given the current debate on competitiveness, and has been proposed in the past as way out of the backlog of climate negotiations (De Coninck et al., 2008b; Newell, 2008b). Actual experiences in the field of climate, such as the 'Asia-Pacific Partnership on Clean Development and Climate (APP)', have not yielded significant results, but the same can be claimed for some emissions reductions programs. A refocus towards innovation could generate a risk of 'policy lock-in', which for the case of R&D we showed would eventually jeopardize the chances of meeting climate stabilization. However, the study has clearly highlighted the importance of dedicating significant investments - either by means of specific R&D policies or indirectly by the incentives induced by carbon pricing - to innovating for energy efficiency and decarbonization. These investments - of the order of 50 USD Billions per year - are an essential pre-requisite for meeting the huge transformation of energy and land use required by climate stabilization. The effectiveness of these investments remains conditional to the need of achieving a comprehensive agreement on GHGs mitigation by 2030, if the 2°C target is to be met.

This analysis is limited by the assumptions embedded in the specific model which we have used. The multi model ensembles carried out by the modeling community over the past few years, of which LIMITS represents an important contribution, has invariably shown that models differ widely in terms of results, for many key variables. Thus, single model assessments should be taken with care. Moreover, the difficulty of understanding and representing the process of technical change poses considerable challenges for the modelers involved in the type of analysis presented in this paper. More work, both on empirical and modeling sides, is needed to improve our grasp of climate innovation, and our ability to represent it as a result. Hopefully, more modeling papers and more multi model ensembles will address the fundamental issue of innovation and climate in the future.

Appendix

$$ES_{n,t} = \left[\alpha_{HE} HE^{\rho}_{n,t} + \alpha_{EN} EN^{\rho}_{n,t}\right]^{1/\rho} \tag{1}$$

$$Z_{n,t} = a_n IRD^{b}_{n,t} HE^{c}_{n,t} SPILL^{d}_{n,t} \tag{2}$$

$$HE_{n,t+1} = HE_{n,t}(1-\delta) + Z_{n,t} \tag{3}$$

ES	energy services (input to gross domestic production)
EN	energy supply (input to energy services production)
HE	stock of energy efficiency knowledge (input to energy services production)
IRD	investments in energy efficiency knowledge
Z	flow of new ideas that adds to the previously cumulated stock
$\alpha_{HE}, \alpha_{EN}, \rho$	parameters of the energy services CES
a, b, c, δ	parameters of the energy efficiency knowledge stock update equations
n	region
t	time period

$$SPILL_{n,t} = \frac{HE_{n,t}}{\sum\limits_{n' \in nHI} HE_{n',t}} \left(\sum_{n' \in nHI} HE_{n',t} - HE_{n,t} \right) \tag{4}$$

where nHI is the set of OECD countries, representing the technology frontier.

$$\frac{P_{n,t}}{P_{n,0}} = \left(\frac{KRD_{n,t-2}}{KRD_{w,0}}\right)^{-r} \left(\frac{\sum_{t' \in [0,t)} K_{w,t'}}{K_{w,0}}\right)^{-s} \tag{5}$$

$$Z_{n,t} = a_n IRD^{b}_{n,t} SPILL^{d}_{n,t} \tag{6}$$

$$KRD_{n,t+1} = KRD_{n,t}(1-\delta) + Z_{n,t} \tag{7}$$

P	average cost of backstop
KRD	stock of backstop knowledge
IRD	investments in backstop knowledge
K	stock of backstop used
Z	flow of new ideas
r	learning-by-researching index
s	learning-by-doing index
w	world
0	first time period

	Energy Efficiency	Carbon-free Advanced Biofuels (Backstop)
r (Learning-by-researching index)	0.20	0.20
s (Learning-by-doing index)	n.a.	0.15
a	(average) 0.04	1.00
b	0.18	0.85
c	(average) 0.39	n.a.
d	0.15	0.15
δ (Depreciation of knowledge capital)	5%	5%
Regional initial stock of knowledge (OECD) [USD Billions]	(average) 20	0.5
Regional initial stock of knowledge (Non-OECD) [USD Billions]	(average) 1	0.5
World initial stock of experience [TWh]	n.a.	278

Table 3: Parameter values for the R&D equations

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