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Report on the feasibility and costs of the 2°C target as a function of technology and policy

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1. Introduction and Overview

Meeting the internationally-agreed 2°C target and achieving the necessary international cooperation is both a technological and a political challenge. Rigorous analysis of the implications of implementing the 2°C target can uncover the subtleties of this challenge and provide useful insights for analysts of technology development efforts, policy design, and international negotiation processes. The EU-funded LIMITS project has performed a range of studies contributing to such analysis.

As part of LIMITS Work Package 1 (WP1), which assesses global mitigation pathways for limiting the global temperature increase below 2°C, this report presents findings on the role of technology and policy and on regional mitigation requirements. This report investigates the role of technology, investment needs, and regional economic costs associated with 2°C mitigation pathways and expands on the findings in the previous WP1 reports: D1.1 "Report on the range of mitigation requirements for the major economies that are compatible with a global 2°C target under varying assumptions" and D1.2 "Report on the assessment of compensation mechanisms and burden sharing regimes for achieving the 2°C target".

Report D1.1 already included findings on the role and diffusion of key technologies for 2°C mitigation pathways. In Section 2 of this report, we add key insights from the Stanford Energy Modeling Forum 27 (EMF27) study, which was utilized by LIMITS partners to explore the role of individual mitigation options for the achievability and the implementation of the 2°C target. LIMITS has coordinated its technology work with EMF27 to exploit available synergies, and LIMITS partners have contributed extensively to the overview and model comparison analysis as documented in the associated publications.

Section 3 of this report summarises the findings of WP1 on the role of policy frameworks for the implementation of the 2°C target, with a focus on the major economies. This synthesis draws on the results of the LIMITS integrated assessment model comparison study on Durban Platform Scenarios as published in Climate Change Economics. Individual results from the study were presented in Deliverables D.1.1 and D.1.2. The synthesis article by Tavoni et al. expands on this work by investigating regional carbon budgets, emissions peaking, mitigation effort and costs, investment requirements and implications of two burden sharing regimes. They show that achieving 2°C at a minimum global cost would require emissions to peak by this or next decade at the latest in all major economies and highlight the uneven distribution of regional mitigation costs in the absence of transfers. On the other hand, burden sharing combined with a large carbon trading market could reduce cost differences and finance the investments gap in green energy. Based on the analysis of these issues, Tavoni et al. suggest that policy approaches are promising which seek to align national interests with climate cooperation. These could include:

a) Linkages and extensions of carbon markets
b) Climate finance to fill the investment gap
c) Issue linkage with national policy priorities

This report concludes the deliverables under LIMITS work package 1 (WP1). With its focus on technology, policy and regional distribution challenges for the achievability of the 2°C target, WP1 has generated results with direct relevance to the international climate policy coordination process.

2. Technology's relevance for the achievability and costs of reaching the 2°C target

The implications of the availability of key mitigation technologies have been explored by the Stanford Energy Modeling Forum's EMF27 project. The LIMITS team contributed to the design and analysis of the scenarios assessed in EMF27 with the goal to examine specific technology requirements of implementing the 2°C target. Due to the coordination between LIMITS and EMF27, the latter performed technology sensitivity analyses of a 450 ppm CO_2e climate target that is consistent with the more stringent 2°C target among the LIMITS scenarios. As a result of the contribution by LIMTS partners to EMF27, six of the papers in the EMF27 special issue of the journal *Climatic Change* acknowledge support from LIMITS and provide insights on the role of energy technologies and energy resources in 2°C scenarios that are compatible with the LIMITS context. These papers are (LIMITS authors indicated in bold font):

Kriegler, Weyant et al. (2014) The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies, *Climatic Change* 123(3-4) 353-367, DOI: 10.1007/s10584-013-0953-7.

Krey, Luderer et al. (2014) Getting from here to there: energy technology transformation pathways in the EMF27 scenarios, *Climatic Change* 123(3-4) 369-382, DOI: 10.1007/s10584-013-0947-5.

Blanford, **Kriegler, Tavoni** (2014) Harmonization vs. Fragmentation: Overview of climate policy scenarios in EMF27, *Climatic Change* 123(3-4) 383-396, DOI: 10.1007/s10584-013-0951-9.

McCollum, Bauer et al. (2014) Fossil resource and energy security dynamics in conventional and carbon-constrained world, *Climatic Change* 123(3-4) 413-426, DOI: 10.1007/s10584-013-0939-5

Luderer, Krey et al. (2014) The role of renewable energy in climate mitigation: results from the EMF 27 scenarios, *Climatic Change* 123(3-4) 427-441, DOI: 10.1007/s10584-013-0924-z.

Rose, **Kriegler** et al. (2014) Bioenergy in energy transformation and climate management. Climatic Change, *Climatic Change* 123(3-4) 477-493, DOI: 10.1007/s10584-013-0965-3.

Kriegler, Weyant et al. provide an overview of the impact of key technology on the feasibility and costs of climate targets, including meeting the 2°C target with high likelihood (limiting atmospheric greenhouse gas concentration to 450 ppm CO_2e by 2100). They find that this would require a complete decarbonization of the global energy system within the 21st century. Robust characteristics of the energy transformation for meeting the 2°C target are:

- **Increased energy intensity improvements:** In 450 ppm CO_2e scenarios, energy intensity improvements are accelerated to 1.3–2.9% (model median: 2.3%) per year compared to the 1970–2010 global rate of 1.3 % per year.
- **Decarbonization of the electricity sector and electrification of energy end use:** Model runs of 450 ppm CO_2e scenarios generally show that decarbonization is achieved most swiftly for electricity generation, a sector for which many non- or low-emissions technologies are available, and then substitution of electric power and end-use efficiency for fossil fuel use in end-use sectors. Since non-electric energy end use is hardest to decarbonize, particularly in the transport sector, electrification of end use is an important element of decarbonization,

although substantial residual use of solid fuels in industry and liquid fuels in transportation remains in most models, calling for compensation from negative emission technologies.

- **Negative emissions technology:** The availability of a negative emissions technology, represented in the models by the combination of carbon capture and storage and bioenergy (BECCS) seems to be a key element for meeting the climate targets due to the ability to compensate fossil fuel emissions across sectors and time.

The cost of the energy transformation needed for achieving the 2°C target is sensitive to variations in technology availability. A cost-optimal 2°C scenario would see substantial contributions from all of the above-mentioned factors (energy intensity improvements, decarbonized electricity and electrification, negative emissions technology). Within the electricity sector, the importance of individual low-carbon technologies (such as nuclear or wind power) is relatively limited due to the many alternatives in that sector. However, the ability to generate substantial negative emissions via BECCS depends on the availability of carbon capture and storage (CCS) and on the supply of bioenergy. If either is constrained or unavailable, meeting the 2°C target can become dramatically more costly or outright infeasible (see Figure 1).

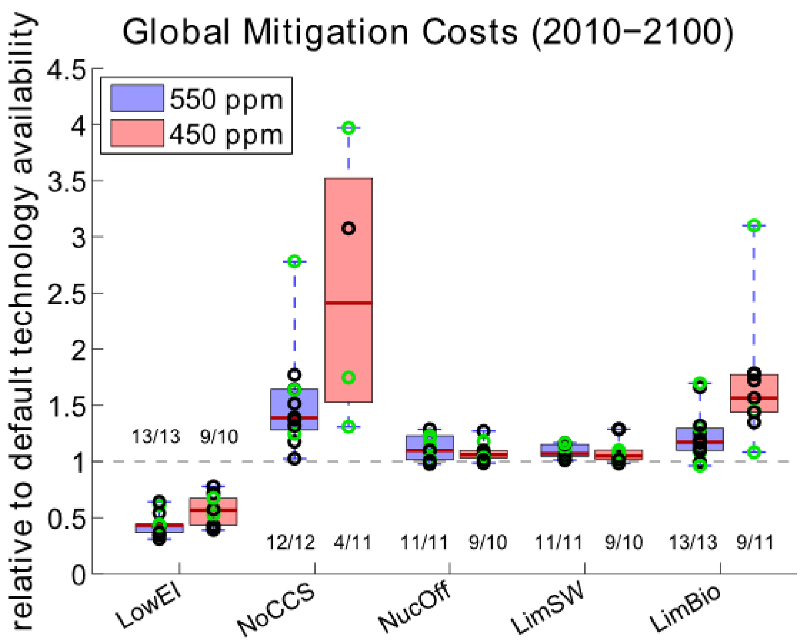

Figure 1: Global mitigation costs in different technology scenarios relative to the default case of full technology availability. LowEI stands for low energy intensity, NoCCS for a technology portfolio without carbon capture and storage, NucOff for a scenario without new nuclear power plants, LimSW for a 20% limit to the share of solar and wind in electricity production, LimBio for a limit of 100 EJ/yr to the global primary bioenergy supply. The costs are shown in net present value (discounted at 5%) for reaching 550 ppm CO_2e or 450 ppm CO_2e by 2100. This figure is adopted from the Kriegler et al. (2014) paper of the EMF27 project (listed at the end of this section).

On top of EMF27, the LIMITS model intercomparison study of Durban Platform Scenarios has added additional insights on important technological and resource availability aspects of 2°C scenarios. The LIMITS overview paper by Kriegler et al. (2013)[1] shows that the availability of BECCS becomes yet more crucial if delayed implementation of the 2°C target leads to high near-term emissions and to an overshoot in radiative forcing that must be compensated for with negative emissions.

[1] Kriegler et al. (2013) What does the 2°C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios. *Climatic Change Economics* 04, 1340008, DOI: 10.1142/S2010007813400083.

The study by van der Zwaan et al. (2013)[2] assesses technology diffusion dynamics in 2°C scenarios and confirm findings from EMF27 regarding the critical role of emissions-free electricity as well as the importance of options for negative emissions. Van der Zwaan et al. find that power sector CO2 emissions should become deeply negative from around 2050 onwards in order to compensate for GHG emissions in other sectors where abatement is more costly. While there may only be a limited portfolio of technologies that can generate negative emissions, the options for decarbonizing the power sector are otherwise varied. Zwaan et al. find that the model results strongly diverge in decarbonization technology deployment in the electricity sector, which suggests that a range of promising options exists and that there is considerable uncertainty about the most cost-effective abatement technology mix. Nevertheless, a robust case for the contribution of bioenergy to 2°C mitigation scenarios is made in the study by Calvin et al. (2013)[3]. This confirms the role of bioenergy in stringent mitigation scenarios found by EMF27 (see Figure 1). Bioenergy is not only important as part of the negative emissions option BECCS, but also as a versatile fuel that can contribute to low-carbon non-electric energy supply. Overall, these results from the EMF27 study on the role of technologies and the LIMITS study on Durban Platform scenarios highlight the key role of technology for the achievability the 2°C target in the long run.

[2] Van der Zwaan et al. (2013) A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target, *Climatic Change Economics* 04, 1340013, DOI: 10.1142/S2010007813400137.
[3] Calvin et al. (2013) A multi-model analysis of the regional and sectoral roles of bioenergy in near- and long-term CO_2 emissions reduction, *Climatic Change Economics* 04, 1340014, DOI: 10.1142/S2010007813400149.

3. Post-2020 climate agreements in the major economies assessed in the light of global models

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Abstract

This article assesses the implications of post-2020 international climate policy architectures for the major economies. We assess scenario results from a recent model inter-comparison project (MIP) involving several land-energy-economy-climate models, and put it into the context of the existing modeling literature. We show that achieving 2°C at a minimum global cost would require emissions to peak by this or next decade at the latest in all major economies, and to manage regional carbon budgets of few hundreds GtCO2. We highlight the uneven distribution of regional mitigation costs in the absence of transfers, and show that a large carbon trading market to be established by 2030 could reduce cost differences and finance the investments gap in green energy. We conclude with recommendations for climate policy design.

Motivation and objectives

So far, international climate policy has been largely ineffective in curbing the rise of global greenhouse-gas emissions. Still, ambitious climate targets such as the internationally agreed upon 2°C target require a phase-out of global emissions by the end of the century, and an active participation of all world regions in climate policy[1]. Given the many obstacles to global cooperative action on climate change, the question remains how diverse national climate policies can be coordinated and strengthened globally. Within the United Nations Framework Convention on Climate Change (UNFCCC), the Durban Platform for Enhanced Action[2] seems to provide the most important opportunity for a post-2020 international climate agreement, which is needed urgently if the 2°C ceiling is not to be breached. It contains several innovative elements, most notably a focus on the major economies that goes beyond the traditional divide between Annex I and non-Annex I countries. The Durban platform calls for a new climate treaty to be agreed in 2015 and implemented as early as 2020. Despite encouraging signs such as the recent commitment of the US administration to put a cap on emissions, aligning the incentives of the major economies in pursuing climate policies remains a challenge - as demonstrated in the recent UNFCCC Conference of the Parties (COP-19) in Warsaw. In this paper, we aim at assessing the implications of post 2020 climate policies with specific reference to the major economies. We provide quantitative estimates of regional emission budgets, timing of emission peaking, and distribution of mitigation costs. We examine the role of carbon markets and different burden sharing schemes to alleviate distributional inequalities and finance the investment needs in low carbon mitigation technologies. In order to quantify these policy relevant variables, we avail of the use of global models.

Integrated assessment models (IAMs) are tools designed to investigate the implications of achieving climate and other objectives in an integrated and rigorous framework. They are numerical models that account for major interactions among energy, land-use, economic and climate systems. Their results are driven by maximization of a welfare function or minimization of energy costs – through either optimization or simulation process. Models generate global long-term scenarios for a number of regions or countries that can be used to inform climate and energy policies and to translate long-term climate objectives into potential medium-term courses of actions[4–10]. Scenarios from IAMs provide important input to scientific reviews such as the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Environment Programme (UNEP) Emissions Gap Report. Given the focus of this review on climate mitigation policies, the models reviewed are employed to assess the implications of cost-effective policies to achieve a given climate goal (like in the IPCC), rather than to determine the appropriate ambition of such a goal in a cost-benefit setting. In other words, the potential damages from climate change costs are not considered explicitly here, putting our analysis outside the controversial discussion regarding climate impacts.

In order to generate conclusions that are robust to different models' specifications, IAM teams have engaged in model inter-comparison projects (MIPs), in which a variety of models implement a common study protocol. Though cross-model comparison literature has developed fast, it has so far mostly reported on global issues[7,11,12,45]. Information from an MIP regarding the regional impacts of post 2020 climate policies is limited. This review aims at synthetizing insights from the most comprehensive MIP on this subject, the LIMITS project[13,14,98]. Though other MIPs have explored the role of fragmented regional mitigation effort and staged accession to climate cooperation (EMF22[33], AMPERE[34], EMF27[1]), globally delayed participation (RECIPE[35], ROSE[36], AMPERE[12]), and burden-sharing schemes (RECIPE[37]), none except of LIMITS has focused on potential outcomes of the Durban platform negotiations, i.e. a period of fragmented moderate climate policy followed by global cooperative action towards a 2C climate target after 2020 under different assumptions about burden sharing regimes. In addition, in LIMITS results are reported at a high regional resolution (for 10 regional aggregates which best match the native model regions), short term climate and energy policies are well detailed, the likelihood of achieving 2°C is relatively harmonized (using the MAGICC climate model) and a new burden sharing scheme is introduced and evaluated. Though we will use LIMITS as guiding example throughout the paper, the insights are framed by and compared with all the relevant literature on climate policy modeling[3,15–20].

Box 1. International climate policy through the lens of IAMs

International climate policy involves complicated negotiations among different parties over a wide range of activities. As international climate agreements are voluntary, they need to be self-enforcing. The formation of such deals can be studied by model-based analysis of the incentives for joining or leaving these agreements. This has led to a specific strand of literature based on game theory and strategic interaction[21–26], which includes IAM applications[27–3132]. More often, though, the formation mechanism of the policy agreement is taken as given. Models explore the implications of regional or global, comparing them, for instance, with a counterfactual world in which such policies are absent.

The LIMITS MIP can be used to illustrate how this is done in practice. A set of scenarios are implemented in the six participating models (GCAM,IMAGE,MESSAGE,REMIND,TIAM-ECN,WITCH). These include 1) the extent and date of implementation of climate and energy policies, 2) the stringency of the regional emission pledges, 3) the long-term climate objective, and 4) the way the climate policy burden is shared across regions (see the Table S2 for the scenario description). First of all, a counterfactual scenario with no climate policies is built ('No Policies'). Second, the study analysed a reference case representing the current situation of regionally fragmented mitigation efforts, based on extrapolation of the weak Copenhagen pledges throughout the whole century ('Weak Pledges', see Table S3 for their exact definition). In addition, a successful outcome of the Durban Platform negotiations was modeled by global cooperation after 2020 on either a long-term CO2 concentration objective of 450 ppm-eq or 500 ppm-eq. These levels correspond to either a likely (>66%) or as-likely-as-not (>50%) chance of achieving 2°C.

The stabilization scenarios are implemented in a cost effective way, with emissions reduced at the margin where it is cheapest to do so. Different burden-sharing regimes across regions have been considered, to allow regions to be compensated for their emission reductions. Thus, in addition to the case of globally harmonized carbon tax (without allowing for transfers between regions, e.g., via the trade of emission permits), we considered the assignment of emissions permits based on either convergence to equal per capita emissions or equalization of regional mitigation costs as a share of output.

Emission reductions: when, where, and how?

One of the most valuable uses of integrated assessment models is in the translation of mitigation policies into climate outcomes, and conversely the translation of global climate objectives into regional commitments and timing of emission reductions. This allows the 'when' and 'where' questions that are key elements of climate policy considerations to be addressed.

Figure 1 provides insights on the 'when' question, reporting the year of peaking of greenhouse gas emissions in 10 major economies for different policies (see Table S1 for a definition of the 10 regional aggregates). The emission peak year is an important indicator for policy, as it signals by when emissions should start to fall. Without explicit mitigation policies, models project emissions to increase until very late in the century in essentially all regions. This result is based on the expectation of continued economic growth and availability of fossil fuels. Weak mitigation pledges, based on the extrapolation of those made under the Cancun Agreement beyond 2020[38], would lead to differentiated peak years that depend on the stringency of the commitment and the growth of baseline emissions, which is driven largely by economic growth rates[39]. Here, industrialized economies are projected to keep emissions below current levels, but several developing country regions would see emissions rising until the second half of the century. A marked difference is observable when moving to climate stabilization targets around 2°C. In order to minimize global costs, emissions would need to peak by the end of this decade in all major regions in order to have more than a 66% chance of limiting temperature increase to 2°C (i.e. 450 ppm-eq). Relaxing the chances of meeting 2°C to 50% (i.e. 500 ppm-eq) would buy some time, i.e. on the order of 10-15 years for some developing countries.

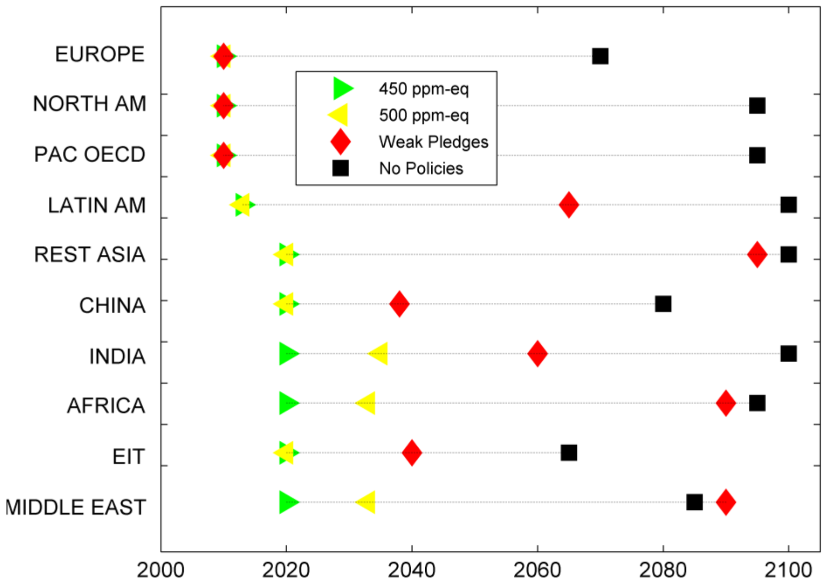

Figure 1: Peak Year: timing of regional maximum emissions (Kyoto gases, median across models). "2100" denotes an increasing emissions trajectory throughout the 21st century until the end of the time horizon of the models. Model time step is typically 5 to 10 years. Full set of results by model is available in Figure S1.

A useful metric for quantifying climate change is that of cumulative emissions, or carbon budgets, which simply are the sum of emissions over time. These have been shown to be strong, linear predictors of global temperature increase[40–42]. The emission scenarios from the integrated assessment models provide a split into regional budgets under the assumption of cost efficient implementation. Clearly, even under this assumption there is considerable uncertainty about the cost-effective regional split of emissions budgets as it depends on, inter alia, baseline emissions, regional mitigation potentials, differences in the global emissions reduction rate and terms of trade effects, all of which can vary substantially across models and regions[14,33,43].

Figure 2 provides estimates about regional cumulative emission budgets, as well as the historical contribution to emissions of the major economies. It indicates that in the No Policies scenario, unabated emissions of major economies like China or regions such as the OECD would by themselves exhaust the entire global budget compatible with 2°C. This would remain true even if countries committed to weak mitigation pledges, testifying to the crucial importance of a comprehensive climate agreement if the 2°C target is to be met. A limit of 2°C would require a significant reduction of carbon budgets in all major economies. No major economy would receive more than few hundred GtCO2. When looking at all GHGs (Figure S3), budgets would increase for all regions, especially under the stringent climate scenarios, since non-CO2 gases are assumed to be harder to abate.

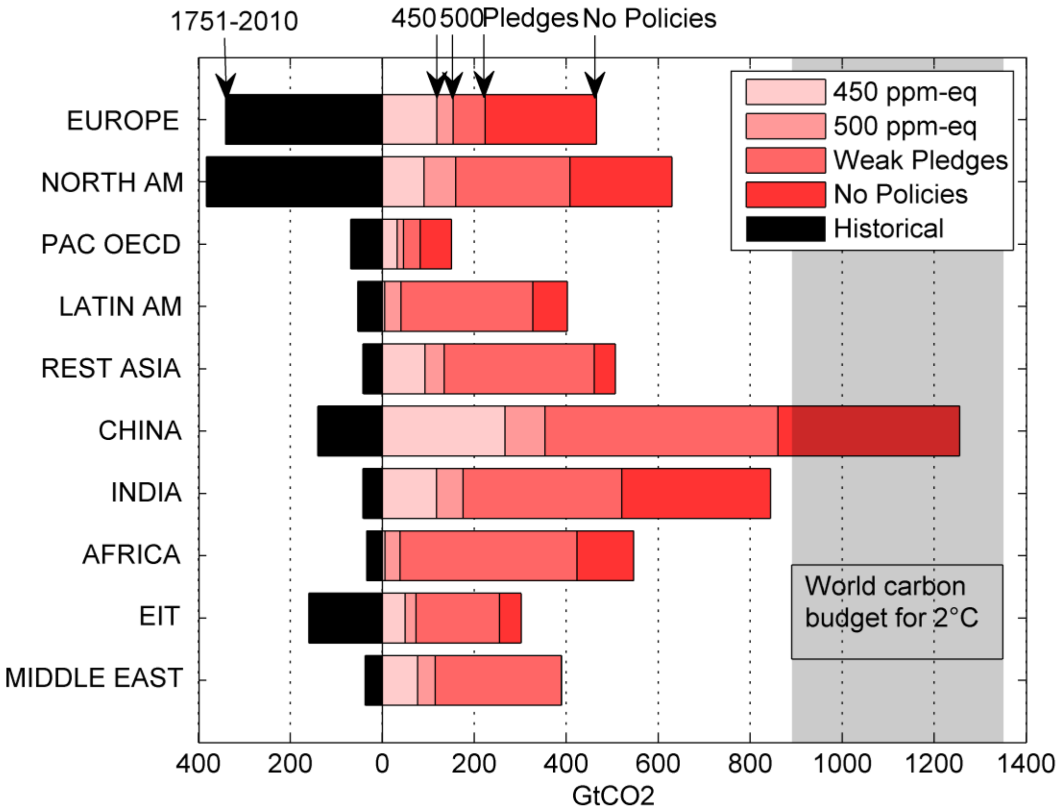

Figure 2. Regional carbon budgets, as cumulative CO2 emissions for the period 2010-2100. All numbers are median across models. Historical emissions are for the period 1751-2010 (source CDIAC). The shaded area show the World carbon budget range for 450 and 500 ppm-eq policies, median across models. Regional Kyoto budgets and full set of model results are available in FigureS2 and S3 respectively.

Figure 3 shows that cumulative emissions reductions relative to the No Policies scenario untill 2050 are quite similar across the major economies (percentage numbers above the bars). Slightly larger relative emissions reductions would be necessary for developing regions such as Latin America, India, China and EIT. The contribution of these regions in terms of absolute GtCO2-eq emission reductions is even larger, given the higher projected baseline emissions in developing economies and in particular in Asia[39].

IAMs can also be used to further inform about 'how' the regional mitigation effort might be achieved. Figure 3 indicates that according to the LIMITS models the largest share of mitigation by sector would take place in the energy supply sector, confirming results from bottom-up and top-down studies[13,44–47]

[48,49]. In Latin America, Rest of Asia and Africa also the land-use sector plays a major role in abatement, due to the large potential for forest-based mitigation, especially in some models[51,52]. Middle East has the largest potential on the demand side. This is consistent with the currently high energy intensity, in turn related to relatively low energy prices. Non-CO_2 gases contribute to 10-20% in terms of abatement, and represent a significant share of residual emissions, since some emissions such as CH_4 and N_2O gases from agriculture are hard to mitigate[53]. The overall picture is that, while energy supply has the highest mitigation potential, regional characteristics imply different patterns of mitigation across sectors[54], which will also be influenced by the stringency of the climate target[13,55].

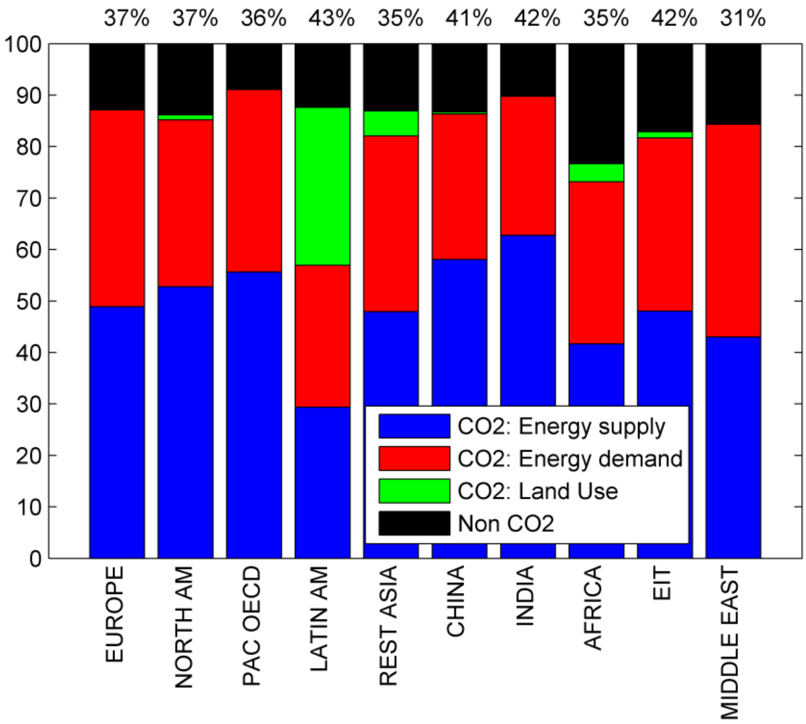

Figure 3. Share of cumulative mitigation (2010-2050) of Kyoto gases across sectors for the 450 ppm-eq policy, median across models. The numbers above each bar indicate the regional mitigation potential measured by median cumulative (2010-2050) emission reductions (%) from the No Policies scenario. Full set of model results is available in FigureS4.

Model variation is shown in Figures S1, S4 and S5. These figures show that the full cross-model range of estimates can reflect significant variation, especially for some factors, such as land use mitigation potential. Though essentially all the results so far are robust to such uncertainty, model variability should not be underestimated. A risk-management approach that explicitly reflects structural uncertainties can provide policy-makers with robust policy recommendations[56], though it has not generally been adopted by IAM analyses so far[57].

One of the most contentious topics in international climate negotiations is the distribution of the mitigation effort. Combined with emission trading, different allocation methods can incorporate different views of fairness while still resulting in an (almost) cost-optimal implementation, since in IAMs economic efficiency and equity are largely independent[59]. Despite this being a rough-and-ready approach that does not account for issues such as transaction costs, property rights, resource curse and institutional capacity, it nonetheless provides a convenient framework for thinking about the problem[60]. Many different allocation regimes have been proposed, mostly either based on the concepts of resource sharing (allocating the available emission space) or effort sharing (ensuring similar effort, such as equal costs)[58]. Many studies have assessed the implications of different regimes for the allocation of mitigation efforts[19,58,61], finding that allocations are influenced by both the equity principle adopted and the overall climate objective.

Figure 4 provides an example of how models project emissions allocations under different burden sharing schemes and the 2°C target as the climate objective. The *actual emissions* reductions that occur in cost-efficient scenarios assuming a globally harmonized carbon price (left) are contrasted with *emissions allowances* based on two burden sharing principles which aim to equalize per capita emissions allowances (by 2050) and regional mitigation costs respectively (these represent examples of a resource sharing and effort sharing regime, respectively). If a region has received an allowance above (below) its actual emissions, it can act as net seller (buyer) of emissions permits. The boundary case, where emissions allowances exactly match domestic emissions reflects a situation where all mitigation efforts are financed domestically, e.g. the imposition of regional emissions targets without international allowance trading or a globally harmonized GHG tax without transfers.

Figure 4 shows that for Europe and North America actual emissions and allowances in the per capita case would be similar and lower than the ones announced in the major economies forum meeting of 2009 (80-95% reductions). A per capita burden-sharing scheme would require a significant mitigation effort from China and some other regions such as the Middle East (in line with previous modeling studies[14,37,62–64]). The opposite would hold for India (and Africa, not shown), because of its low per capita emissions. The equal-cost burden-sharing scheme in which all regions pay the same price in terms of GDP reduction would require a stronger commitment from the OECD (close to 100% reduction) and an average 50% reduction for China, while allowing India an increase (as with the equal per capita regime). The most drastic change across the schemes would be for the Middle East: under an equal-cost scheme, it receives a much larger emission allocation to compensate for its higher mitigation costs, which would in part result from worse terms of trade for its fossil-fuel exports[65].

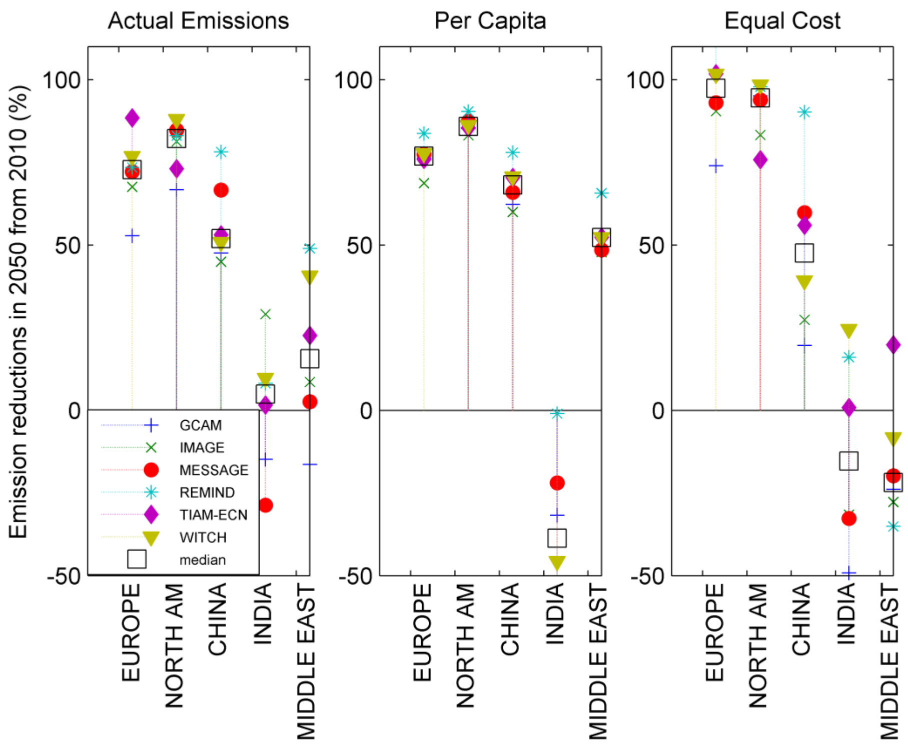

Figure 4. Actual emissions (left panel) and emissions allowances (center and right panels), in % reductions in 2050 from 2010 and for a 450 ppm-eq target. The two panels on the right show examples of allocation schemes with resource sharing (convergence to equal per capita rights by 2050) and effort sharing (equalization of relative mitigation costs) respectively. Full permit trading is allowed (leading to the cost-minimizing distribution of abatement activity across regions).

Economic and financial implications.

A key consideration in climate policy is how to distribute the economic effort of GHG mitigation. Even if overall mitigation costs were low, policymakers care and argue about the regional distribution of policy costs, since it impacts economic development, competitiveness and even political stability. The scenarios indicate that the costs of mitigation will vary significantly across countries[1,14,66–71]. ***Figure 5*** portrays this finding for the LIMITS models, showing that –in a cost effective framework with uniform carbon pricing but without carbon trading and compensatory transfers- mitigation costs in the OECD would be lower than global average, and the opposite would hold for developing economies, and especially for energy exporting regions, which would face adverse terms of trade effects[1,37,71–73]. This ranking is rather robust across climate targets, mitigation cost metrics and IAMs[14,74], though the ranges are considerably larger for developing economies.

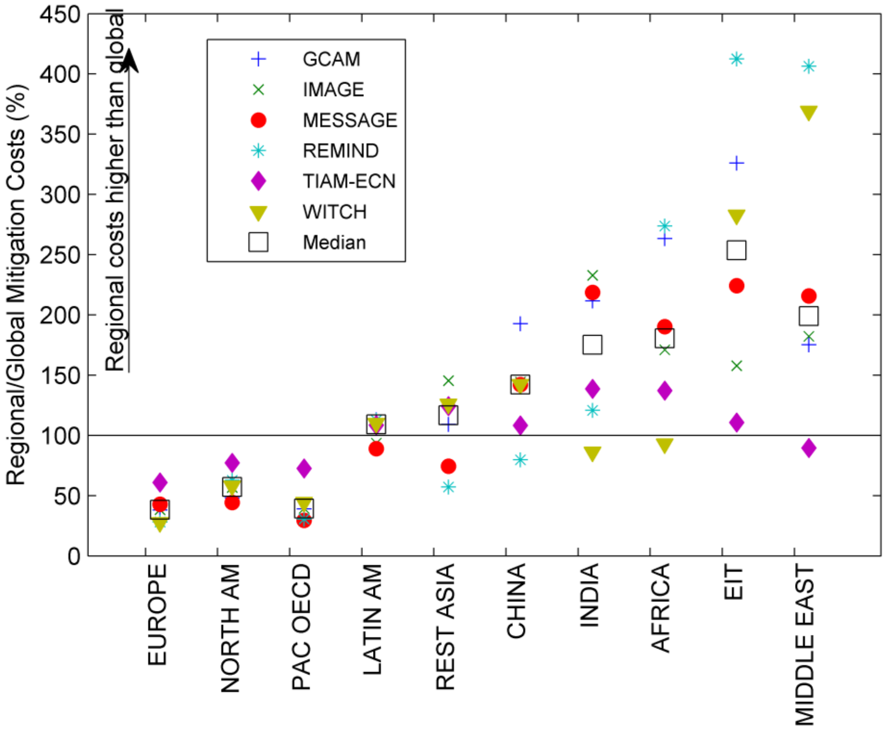

Figure 5. Regional over global mitigation costs for 450 ppm-eq without carbon trading and transfers. Costs are computed in net present value over the period 2010-2100, at 5% discounting.

The variation in these regional costs can be attributed to several factors, but especially to emission intensity, mitigation potential and international trade effects[14,75–77]. Using data from the EMF22 model comparison study, a higher ratio of emissions to GDP – the so called emission intensity- in the BAU has been shown to lead to lower marginal abatement costs but to higher total costs for a common carbon price[75]. Given the higher current and projected emission intensities of developing countries[39], these regions will have higher total mitigation costs.

It is not easy to devise a burden sharing scheme which can alleviate the inter-regional distributional tensions highlighted in Figure 5. When the carbon budget is tight, as it is the case in 2°C policies, even resource sharing schemes such as those based on per capita equalization would not compensate for the inequality in favor of OECD countries[14,78]. A particular challenge lies in the uncertainty about the relations between regional emission allocation and costs, which is much greater than the uncertainty in global mitigation costs. This uncertainty is likely a key barrier to the implementation of an emissions trading scheme with national caps based on a long-term burden sharing scheme. Rather, a pragmatic approach featuring various flexible mechanisms and a regular review of emission reduction and finance commitments seems more plausible[15].

In addition to macro-economic costs, an important question for policy is how to ensure investment flows. This relates to redirecting investments from the fossil fuel industries to sectors involved in low carbon energy technologies and energy efficiency, and to ensure mitigation action in the different regions worldwide. Some studies have quantified the investment gaps to achieve climate stabilization[55,79,80],[81], and finding that a considerable reallocation of investment is required. As shown in

Figure 6, investments in the fossil fuel extraction sector would be greatly reduced. This compensates to a large extent for the additional investment needs in low-carbon energy (renewables, nuclear, bioenergy). Additional investment would be needed to improve energy efficiency, the transmission and distribution grid and the transition to low-carbon technologies in other sectors such as transport. The LIMITS results show, for example, that investments in freely emitting fossil-power technologies remain substantial in the weak-pledge scenarios, while they drop in the 450 ppm-eq stabilization case. In particular, weak pledges would be insufficient to reduce investment in coal-fired power plants. But if the world credibly embarks on a path towards 450 ppm-eq stabilization, investors would largely shun further investment in coal plants, as shown in Figure S5.

Most of the investments would have to be made in developing countries where the largest absolute mitigation effort would take place. According to the model calculations, the global investment gap for transitioning from a weak pledge policy to one fully compatible with 2°C would require filling a global investment gap of about half a trillion USD per year for the next 40 years, two thirds of which in the developing economies. The gap would be even larger if the counterfactual scenario did not involve emission reduction pledges. In addition, investments in clean energy R&D would also need to be significantly scaled up, in order to prompt sufficient innovation in new technologies. Models estimate these to be about 50-100 USD Billion/year [82–86] over the first half of this century.

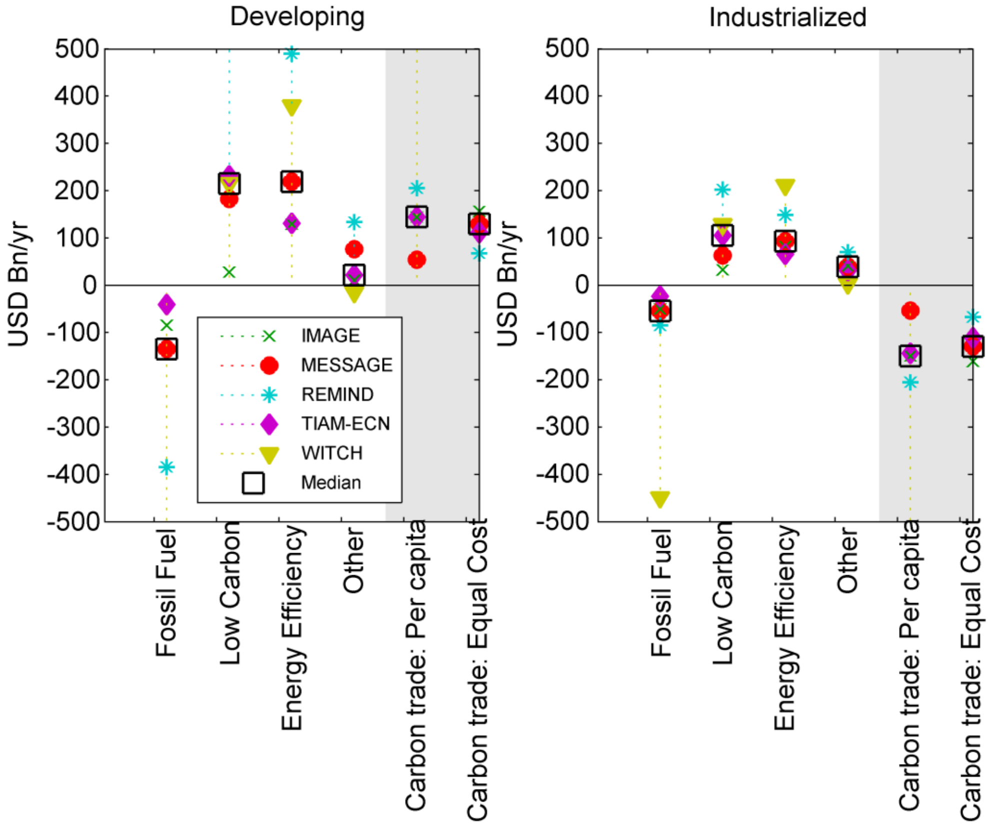

Figure 6: Additional annual investment in USD billion/yr (average over the period 2010-2050; no discounting) between the 450 ppm-eq case and the weak pledge case, for different sectors and two regional groups. The last two columns (shaded) report trade of CO2 permits (positive=selling) for the two burden-sharing schemes discussed above. The vertical axis is truncated at +/- 500 USD Billions.

The current level of green energy investments, estimated at roughly 250 USD billion in 2013 by Bloomberg New Energy Finance, falls significantly short of filling this gap. How can the rest be raised? Several opportunities exist. Removing energy subsidies would free up resources of the same order of magnitude as the gaps[87,88]. Alternatively, climate policies could provide sufficient fiscal revenues within each region to finance total investment in energy supply, while also providing incentives to the private sector to raise finance[89]. Climate finance can assist developing economies in filling the investment gap and in alleviating the distributional inequalities. It is worth noting that the financing gap is not large relative to the increases in investment rates seen in several major emerging-market economies, including China and India, over recent years. Such countries have the capacity if necessary to utilize domestic saving, although the question of whether this would be equitable would remain.[89]

Figure 6 suggests that revenues from the international sales of CO2 permits could cover an important fraction of the investment gap of developing economies, provided industrialized countries committed to such large transfers. However, in order to work, a large and well-functioning carbon market would need to be established in the next 20 years, capable of handling permits for several GtCO2-eq and hundreds of billions of U.S. dollars of trades per year[14,67,70]. Such an emission market would be an order of magnitude larger than the one currently supporting the Clean Development Mechanism (CDM) and would require strong institutional support. The latter represent the type of barriers that are not analysed by IAMs. The experience with CDM has already highlighted implementation difficulties at a much lower level of ambition[90].

Finally, IAM scenarios indicate that climate policies are likely to affect other objectives of policy-makers; not all of these impacts are monetized in the models' cost calculations. For example, climate policies would lead to reduced energy imports and increased energy security in some major economies such as China, India and the E.U.. This would not be the case for the USA and current energy exporters[91]. Climate policies could also lead to more resilient energy systems in terms of diversity of energy options, preservation of fossil resource 'buffers' and decreased sensitivity to GDP fluctuations[65,92]. Transformation pathways spurred by climate policies would also foster air pollution[93,94], with particular benefits for China and India[95,96]. Although the magnitude of co-benefits related to air quality is uncertain[97], their current importance in major economies such as China could lend support to post-2020 climate policies.

Conclusions: modeling input to the Durban negotiation process

The challenge of achieving a comprehensive agreement to reduce emissions is often portrayed as either technologically insurmountable or simply a matter of lack of sufficient political will. Rigorous analysis of the implications of implementing mitigation measures can help characterizing the subtleties of this challenge, supporting a differentiated view on the future of global climate policy and providing useful insights for policy design and on the negotiation process. Such an analysis needs to focus on all the key emitting regions and account for the uncertainties characterizing emission reduction opportunities.

In this article, we show that scenarios generated by energy-economy-climate models via a model inter-comparison project can help in this task, providing vital information to the ongoing policy debate on a post-2020 climate agreement. The use of multiple models (MIPs) can help ensuring that key uncertainties are taken into account by using a diversity of different models and model assumptions. Reviewing a recent MIP focused at international climate policy in the context of broader literature, we have provided details on regional carbon budgets and emission reduction potentials. We used the information as well to highlight the major challenges in sharing the economic effort associated with reducing emissions equitably. The results show that emission trading via carbon markets may help to alleviate some –but not necessarily all- of the unequal distribution of mitigation costs across countries depending on the burden sharing scheme. In addition, a gap in investment into clean energy was identified in the modelling studies which would need to be filled to initiate the necessary transition of the energy system to achieve significant emissions reductions.

Our review indicates that the focus on the major economies reflected in the Durban platform process can help policy-makers to formulate recommendations that at least partly take into account the different regional incentives. Still, aligning national interests towards climate cooperation is by no means straightforward. The numerical estimates by the MIPs reviewed in this article highlight some critical areas of the climate policy process, which include the regional diversity of mitigation opportunities and costs, the linkages and extensions of carbon markets, the climate finance to fill in the investment gap, the issue linkages with national policy priorities, the relevance of specific sectors for emission reductions. Progress in all these key areas will be needed to motivate enhanced national ambition in reducing emissions in the next decades.

This review has assessed mitigation challenges and opportunities without considering the regional benefits of reducing GHG emissions, mostly because a robust quantification of the latter is not yet available in the literature. Similarly, some potential additional strategies for dealing with climate change, such as adaptation and geo-engineering, have not been considered in these model exercises. Hopefully these topics will also be examined in the near future, using similar common protocols and availing of a large number of integrated assessment models.

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Supplementary information.

AFRICA	*countries of Sub-Saharan Africa; some models also include North African countries, others do not; for REMIND and WITCH South Africa is included in the REST_WORLD region*
CHINA	*countries of centrally-planned Asia; primarily China; for some models this may also include Cambodia, Vietnam, North Korea, Mongolia, etc.*
EUROPE	*countries of Eastern and Western Europe (i.e., the EU27); some models (except REMIND and WITCH) also include Turkey*
INDIA	*countries of South Asia; primarily India; for some models this may also include Nepal, Pakistan, Bangladesh, Afghanistan, etc.*
LATIN_AM	*countries of Latin America and the Caribbean; Mexico, Brazil, Argentina, and other countries of Central and South America*
MIDDLE_EAST	*countries of the Middle East; Iran, Iraq, Israel, Saudi Arabia, Qatar, etc.; for some models this may also include countries of North Africa (e.g., Algeria, Egypt, Morocco, Tunisia); for REMIND the former Soviet states of Central Asia are included*
NORTH_AM	*countries of North America; primarily the United States of America and Canada; for REMIND Canada is included in the REST_WORLD region, for WITCH it is included in the PAC_OECD region*
PAC_OECD	*countries of the Pacific OECD (Organisation for Economic Co-operation and Development); for most models this primarily includes Japan, Australia, and New Zealand; for REMIND only Japan is included, Australia and New Zealand are included in the REST_WORLD region; WITCH does not include Australia, which is instead part of the REST_WORLD region; WITCH also includes Canada in the PAC_OECD*
EIT	*countries from the Economies in Transition of Eastern Europe and the Former Soviet Union; primarily Russia, Ukraine, Kazakhstan, Azerbaijan, etc.; for WITCH Turkey is also included; for REMIND this region only includes Russia*
REST_ASIA	*other countries of Asia; South Korea, Malaysia, Philippines, Singapore, Thailand, Indonesia, etc.; for WITCH South Korea is included in the REST_WORLD region*

Table S1: Definition of regional aggregates used in the paper.

Scenario class	**Scenario Name**	**Scenario Type**	**Near-term Target / Fragmented Action**	**Fragmented Action until**	**Long-term Target**	**Policy implementation**
No policy baseline	No Policies	Baseline	None	N/A	None	-
Fragmented action	Weak Pledges	Reference	Lenient	2100	None	No carbon price harmonization
Durban Platform scenarios without trade of CO2 across regions	450 ppm-eq	Climate Policy	Lenient	2020	450 ppm-eq	Carbon price harmonization, no trading of emission permits
	500 ppm-eq	Climate Policy	Lenient	2020	500 ppm-eq	Carbon price harmonization, no trading of emission permits
Durban platform scenarios with trade of CO2 across regions	450 ppm-eq, PC	Climate Policy	Lenient	2020	450 ppm-eq	Carbon price harmonization, with trading of emission permits. Permits allocated on equal per capita (linear transition from todays per capital emissions to equal tons per capita by 2050)
	450 ppm-eq, EE	Climate Policy	Lenient	2020	450 ppm-eq	Carbon price harmonization, with trading of emission permits. Permits allocated on equal regional cost. Relative mitigation costs (e.g in % GDP losses wrt to No Policies) are equalized across regions in each time period.

Table S2. The set of LIMITS scenarios reviewed in this paper, with their main characteristics.

Region	GHG emissions reduction in 2020[(1)]	GHG intensity reduction in 2020[(2)]	Modern Renewable share in electricity[(3)]	Installed renewable capacity in 2020 [(4)] (Wind, solar)	Installed nuclear power capacity [(5)]	Average GHG emissions intensity reduction after 2020[(6)]
EU27	-15% (2005)	N/A	20% (2020)	-	N/A	3%
China	N/A	-40%	25% (2020)	200 GW; 50GW	41 GW (2020)	3.3%
India	N/A	-20%	-	20 GW; 10GW	20 GW (2020)	3.3%
Japan	-1% (2005)	N/A	-	5 GW; 28GW	N/A	2.2%
USA	-5% (2005)	N/A	13% (2020)	-	N/A	2.5%
Russia	+27% (2005)	N/A	4.5% (2020)	-	34GW (2030)	2.6%
AUNZ	-13% (2005)	N/A	10% (2020)	-	N/A	3%
Brazil	-18% (BAU)	N/A	-	-	N/A	2.7%
Mexico	-15% (BAU)	N/A	17% (2020)	-	N/A	2.8%
LAM	-15% (BAU)	N/A	N/A	-	N/A	2.1%
CAS	N/A	N/A	N/A	N/A	N/A	2.6%
KOR	-15% (BAU)	N/A	-	8 GW; -	N/A	3.3%
IDN	-13% (BAU)	N/A	7.5% (2025)	-	N/A	2.1%
SSA	N/A	N/A	N/A	-	N/A	2.3%
CAN	-5% (2005)	N/A	13% (2020)	-	N/A	2.4%
EEU	N/A	N/A	N/A	N/A	N/A	2.6%
EFTA	N/A	N/A	N/A	N/A	N/A	3.5%
MEA	N/A	N/A	N/A	-	N/A	1.5%
NAF	N/A	N/A	20% (2020)	-	N/A	1.5%
PAK	N/A	N/A	N/A	N/A	N/A	1.9%
SAF	-17% (BAU)	N/A	N/A	N/A	N/A	2.8%
SAS	N/A	N/A	N/A	-	N/A	2.9%
SEA	N/A	N/A	15% (2020)	-	N/A	2.1%
TUR	N/A	N/A	-	20 GW;-	N/A	2.3%
TWN	N/A	N/A	N/A	N/A	N/A	3.3%

Abbreviations:
AUNZ = Australia and New Zealand
LAM = Latin America
CAS = Central Asia
KOR = South Korea
IDN = Indonesia
SSA = Sub-saharan Africa
CAN = Canada
EEU = Eastern Europe
EFTA = European Free Trade Association (Lichtenstein, Iceland, Norway, and Switzerland)
MEA = Middle East
NAF = North Africa
PAK = Pakistan
SAF= South Africa
SAS = South Asia
SEA = South-east Asia
TUR = Turkey
TWN = Taiwan

(1) Including Land-use Change, Land-use Change and Forestry (LULUCF) and relative to 2005 or business as usual (BAU) as specified in brackets. (If GHG emissions in baseline is lower, baseline trajectory is adopted for the region concerned.)

(2) Including LULUCF and relative to 2005 (If GHG intensity reduction in baseline is higher, baseline trajectory is adopted for the region concerned.)

(3) Reference quantity is always electricity production except for EU27 where it is final energy.

(4),(5) Capacity targets are minimum targets; target year is specified in brackets.

(6) %/year; GHG intensity improvement rates calculated based on Kyoto GHG equivalent emissions including LULUCF relative to GDP. (If GHG emissions (intensity) reduction in baseline is higher, baseline trajectory is adopted for the region and period concerned.)

Table S3: 2020 *Targets in the weak pledges and Durban platform scenarios for 25 world regions, and post 2020 targets for the weak pledges scenario. See Ref. 13 for the implementation of the 2020 pledges and subsequent lenient policies in the various models participating in the LIMITS study.*

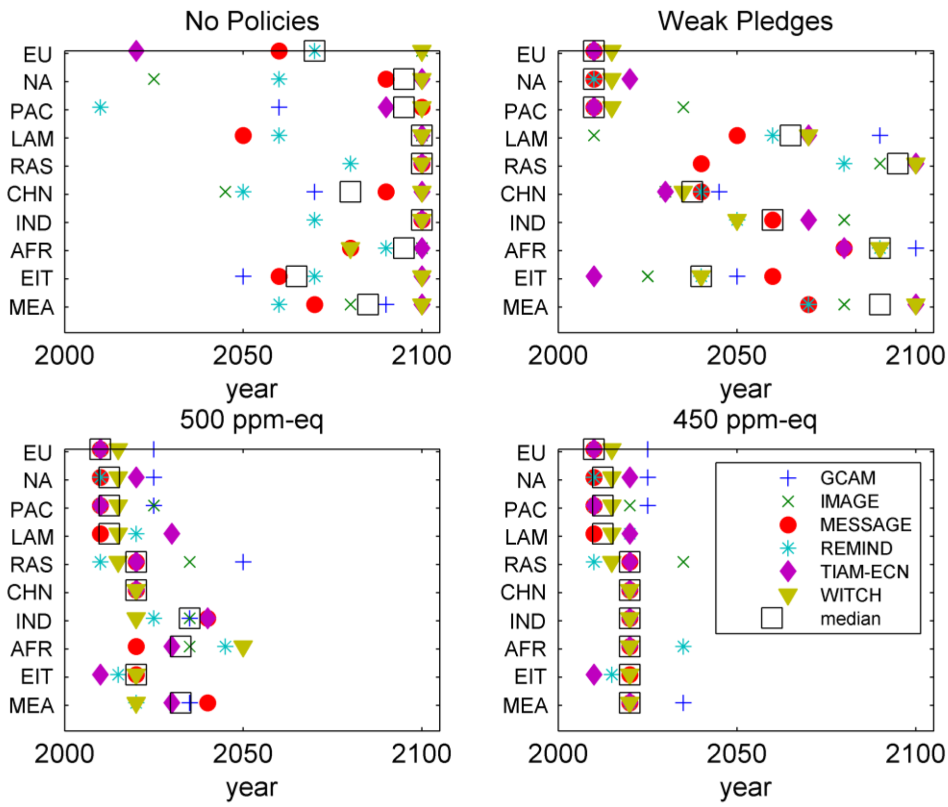

Figure S1: Timing of peak year emissions (as in Figure 1) for the full set of models.

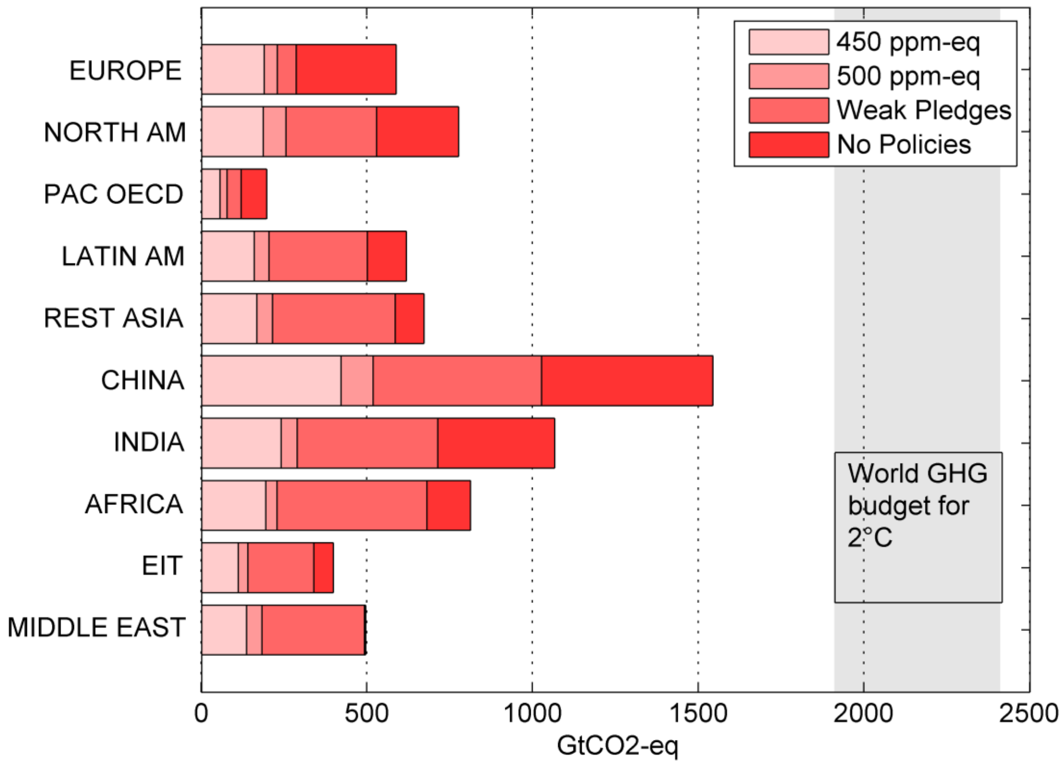

Figure S2: Cumulative GHGs (Kyoto) emissions (2010-2100), in GtCO2-eq. No historical emissions are reported given the uncertainties on non-CO2 gases.

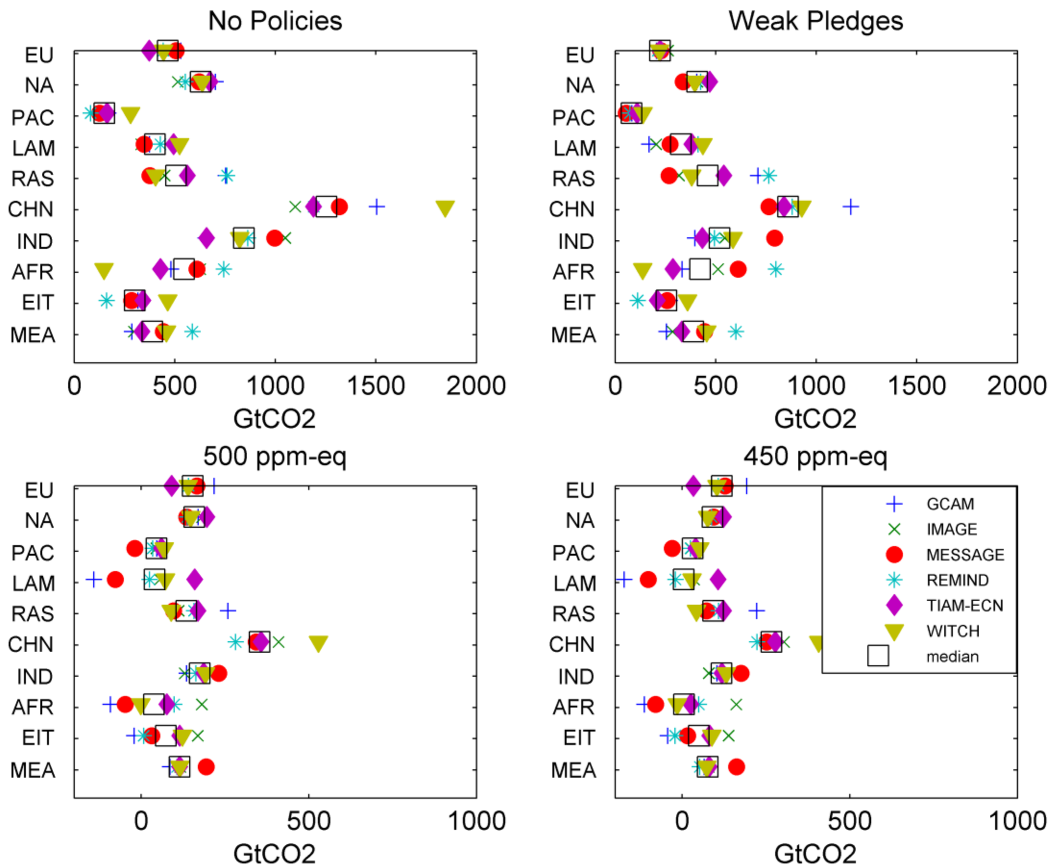

Figure S3: Cumulative CO2 emissions (2010-2100) (as in Figure 2) for the full set of models.

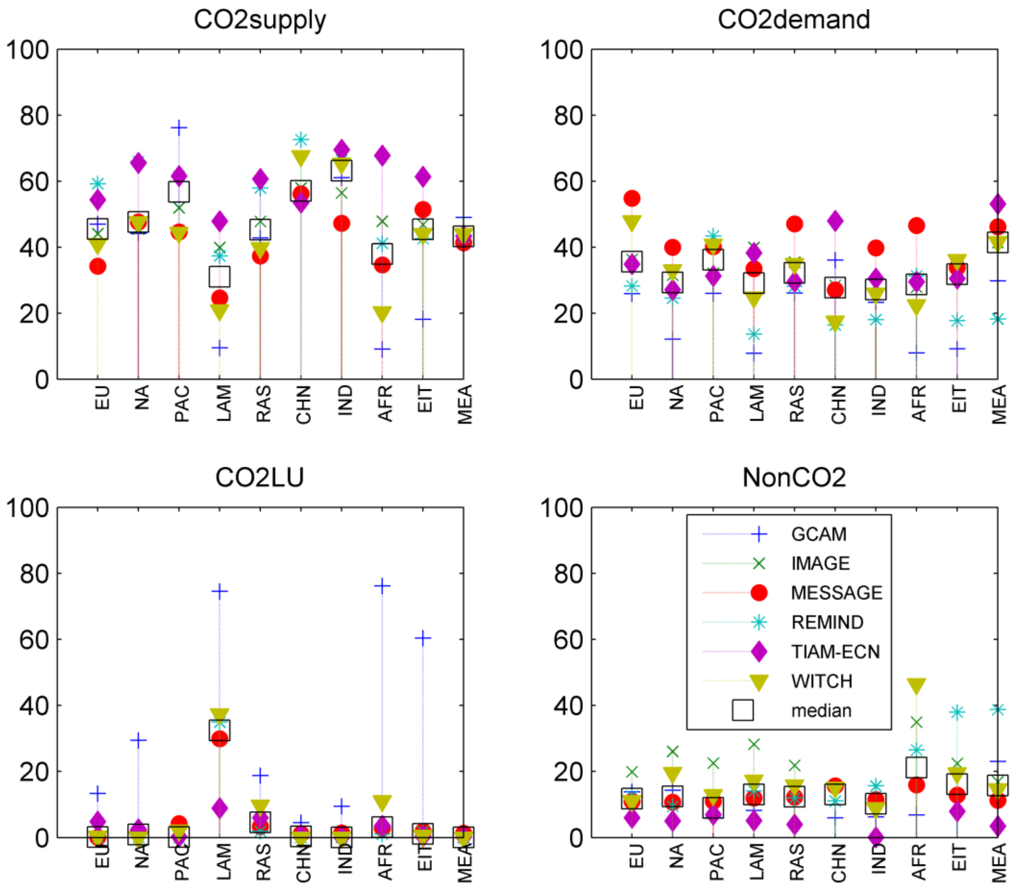

Figure S4: Share of cumulative mitigation (2010-2050) of Kyoto gases across sectors for the 450 ppm-eq policy (see Figure 3), for the full set of models.

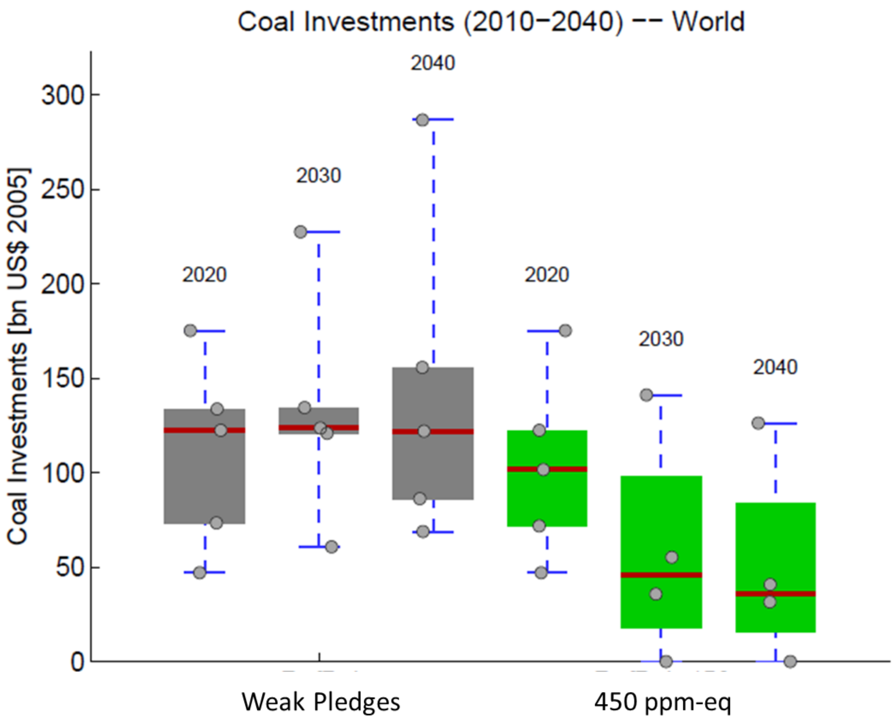

Figure S5: Investments in coal power generation (without CCS) in the Weak Pledge and 450 pp-eq scenarios, 2020 to 2040. The boxplot indicate the median, interquartile range, and full model range.