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

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Integrated assessment models can help in quantifying the implications of international climate agreements and regional climate action. This paper reviews scenario results from model intercomparison projects to explore different possible outcomes of post-2020 climate negotiations, recently announced pledges and their relation to the 2 °C target. We provide key information for all the major economies, such as the year of emission peaking, regional carbon budgets and emissions allowances. We highlight the distributional consequences of climate policies, and discuss the role of carbon markets for financing clean energy investments, and achieving efficiency and equity.

So far, international climate policy has been ineffective in curbing the rise of global greenhouse gas (GHG) emissions. Still, ambitious climate targets such as the 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] provides an important platform for a post-2020 international climate agreement. 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. The recently announced United States–China climate deal and the EU 2030 climate framework provide encouraging steps forwards, but aligning the incentives of the major emitters in pursuing stringent climate policies remains a challenge. In this Review, 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 resort to 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. Models differ in the economic, technological and sectoral representation and in the way they are solved, with some models maximizing an intertemporal objective function (such as economic activity) and others simulating a set of equilibria (see the Supplementary Material for individual model description and references to documentation). 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 action[3–9]. 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 used 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, setting our analysis outside the controversial discussion regarding climate impacts and the social cost of carbon.

In order to generate conclusions that are robust to different models' specifications, IAM teams have engaged in model intercomparison projects (MIPs), in which a variety of models implement a common study protocol. Although cross-model comparison literature has developed fast, it has so far mostly reported on global issues[6,10–12]. Information from a MIP regarding the regional impacts of post-2020 climate policies is limited. This Review aims at synthesizing insights from the most comprehensive MIP on this subject,

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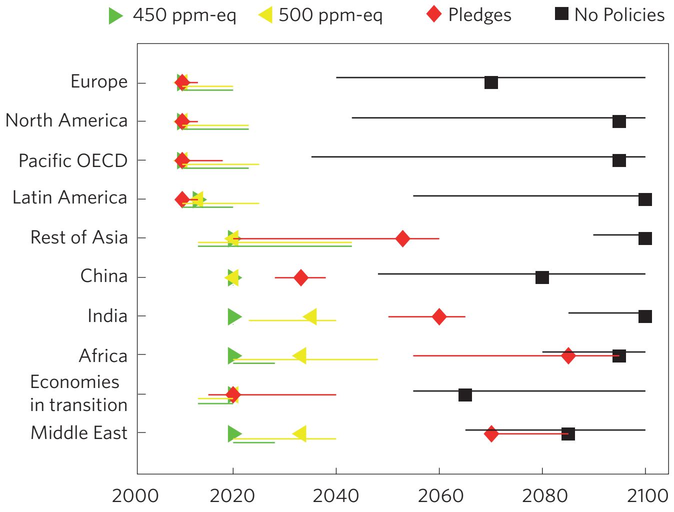

Figure 1 | Emission peaking time. Year of regional maximum emissions (Kyoto gases; markers show median across models, and lines show 10th–90th percentile ranges). '2100' denotes an increasing emissions trajectory throughout the twenty-first century until the end of the time horizon of the models. Models report information typically in 5-10 year steps. Full set of results by model is available in Supplementary Fig. S1.

the LIMITS project[13–15]. Box 1 provides information about the policy dimensions we assess. Although other MIPs have explored the role of fragmented regional mitigation effort and staged accession to climate cooperation (EMF22[16], AMPERE[17], EMF27[1]), globally delayed participation (RECIPE[18], ROSE[19], AMPERE[11]) and burden-sharing schemes (RECIPE[20]), none except for LIMITS has focused on potential outcomes of the Durban platform negotiations: that is, a period of fragmented moderate climate policy followed by global cooperative action under different assumptions about burden-sharing regimes. In addition, in LIMITS results are reported at a high regional resolution (for 10 regional aggregates that best match the native model regions), short-term climate and energy policies are well detailed, the likelihood of achieving the 2 °C target is relatively harmonized across model scenarios (using the MAGICC climate model) and a new burden-sharing scheme is introduced and evaluated. Although 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 modelling[21–27].

Regional mitigation strategies

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 into the 'when' question, reporting the year of peaking of greenhouse gas emissions in 10 major economies for different policies (see Supplementary 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 over the century in essentially all regions, although with significant model variation. This result is based on the expectation of continued economic growth and availability of fossil fuels. Mitigation pledges, based on extrapolation of the currently discussed targets[28], would lead to differentiated peak years that depend on the stringency of the commitment and on the growth of baseline emissions[29]. 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. Emissions in China would peak slightly later than 2030. It should be remarked that not all policy targets are included in the pledge scenario: for example, in the recently announced US–China deal, in addition to peaking emissions in 2030, China also pledged to meet 20% of energy demand with non-fossil sources. Depending on the metric used to convert nuclear and renewables into primary energy, this target is in line with what the LIMITS models foresee in the pledge or 2 °C scenarios.

In any case, a marked difference is observable when moving to climate stabilization targets around 2 °C. In order to minimize global costs, emissions would 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 (that is, 450 ppm

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[85–90], which includes IAM applications[91–96]. More often, though, the formation mechanism of the policy agreement is taken as given. Models explore the implications of regional or global policies, 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 Supplementary Table S2 for the scenario description). First of all, a counterfactual scenario with no climate policies is built ('No Policies'). Second, the study analyses a reference case representing the current situation of regionally fragmented mitigation efforts, based on extrapolation of the strengthened Copenhagen pledges throughout the whole century ('Pledges'; see Supplementary Table S3 for their exact definition). In addition, a successful outcome of the Durban Platform negotiations is modelled by global cooperation after 2020 on either a long-term CO_2-equivalent concentration objective of 450 ppm-eq or 500 ppm-eq. Given the uncertainty surrounding climate change, each of these concentration levels produces a probability distribution of temperature outcomes. By using the MAGICC climate model, 450 and 500 ppm-eq targets were found to correspond to a likely (>66%) and as-likely-as-not (>50%) chance of achieving the 2 °C target respectively.

The stabilization scenarios are implemented in a cost-effective way, with emissions reduced 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 a globally harmonized carbon tax (without allowing for transfers between regions, we considered the assignment and trade of emissions permits based on either convergence to equal per capita emissions or equalization of mitigation costs across regions (see Supplementary Table S2)).

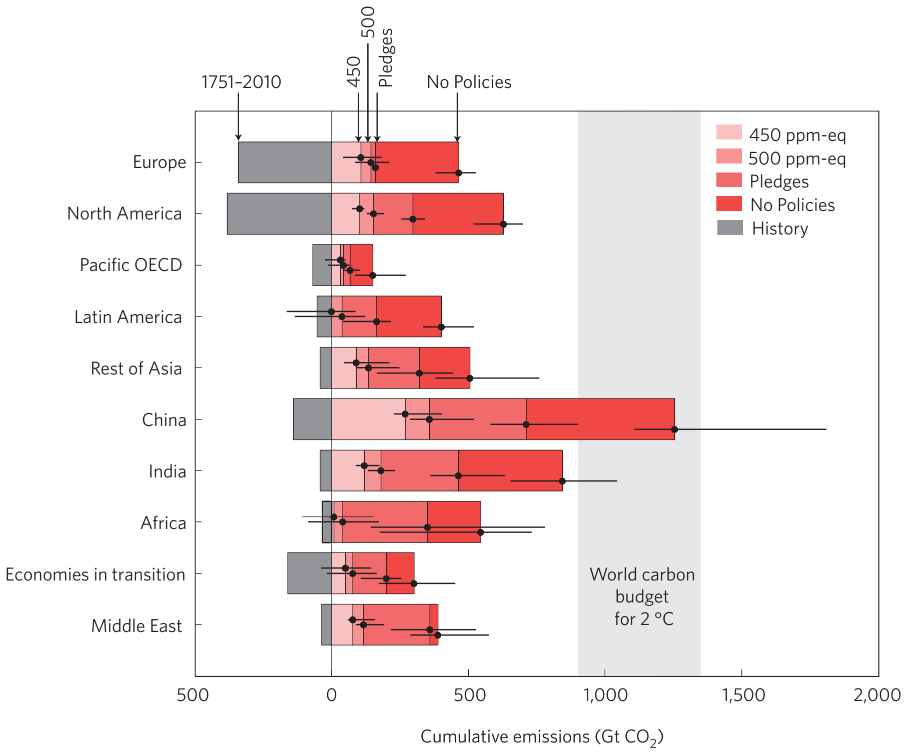

Figure 2 | Regional carbon budgets. Cumulative CO_2 emissions for the period 2010–2100 (bars show median across models; lines show 10th to 90th percentile ranges. Negative values are possible via negative emission technologies). Historical emissions are for the period 1751–2010 (source: Carbon Dioxide Information Analysis Center, cdiac.ornl.gov). The shaded area shows 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 Supplementary Figs S2 and S3 respectively.

CO_2-equivalent, ppm-eq). Relaxing the chances of meeting the 2 °C target to 50% (that is, 500 ppm-eq) would buy some time, of the order of 10–15 years for some developing countries. Reaching 2 °C after following the pledges until 2030 would still be feasible but would come at a significantly higher cost and transitional challenges[13].

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 good, linear predictors of global temperature increase[30–32]. 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[14,16,33].

Figure 2 addresses the 'where' question by providing 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 emerging economies like China or regions such as the OECD would by themselves exhaust the entire global budget compatible with achieving the 2 °C target. A commitment to mitigation pledges would reduce regional carbon budgets, but not at the levels needed for 2 °C. Asia will generate future warming of approximately 1 °C, which is comparable to historical contributions, predominantly made by OECD countries. A limit of 2 °C would require a significant reduction of carbon budgets in all major economies. No major economy would have a budget bigger than a few hundred gigatonnes of CO_2, most of it to be used in the first half of century assuming carbon neutrality in subsequent decades. When looking at all GHGs (Supplementary Fig. S3), budgets would increase for all regions, especially under the stringent climate scenarios, since non-CO_2 gases are assumed to be harder to abate.

Figure 3 shows that cumulative emissions reductions relative to the No Policies scenario until 2050 consistent with the 2 °C target are quite similar across the major economies, around 40% (percentage numbers right to the bars). The contribution of emerging regions in terms of absolute $GtCO_2$-equivalent emission reductions would be larger, given the higher projected baseline emissions in developing economies and in particular in Asia[29].

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[12,13,34–38]. In Latin America, Rest of Asia and Africa the land-use sector also plays a major role in abatement, owing to the large potential for forest-based mitigation[39,40]. These estimates vary widely across models, because of uncertainties about the effectiveness of land-based mitigation measures. 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, as some emissions such as CH_4 and N_2O gases from agriculture are hard to mitigate[41]. The overall picture is that, while energy supply has the highest mitigation potential, regional characteristics imply different patterns of mitigation across sectors[42], which will also be influenced by the stringency of the climate target[13,43].

Model variation is shown in Figs 1–3, and Supplementary Figs S1, S4 and S5. These indicate that the full cross-model range of estimates can reflect significant spread, especially for some factors, such as land-use mitigation potential, and in some regions, such as developing countries like Africa. Although the main results seem to be robust to such uncertainty, model variability should not be

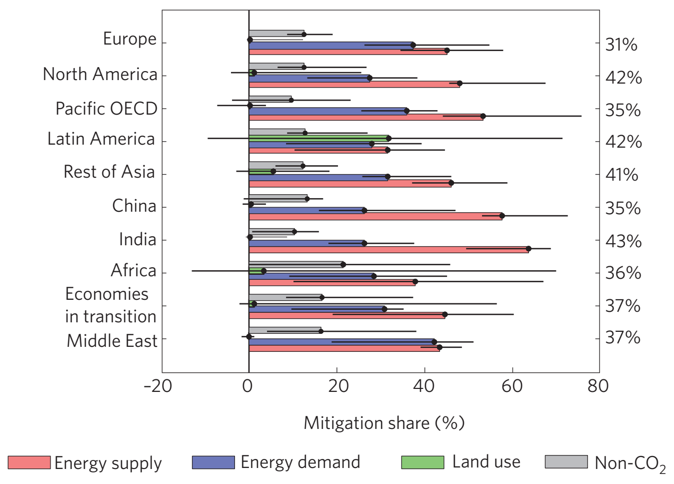

Figure 3 | Sectoral mitigation. Sectoral share of cumulative mitigation (2010–2050, in CO$_2$-equivalent using 100 year GWPs) of CO$_2$ across sectors and non-CO$_2$ for the 450 ppm-eq policy (bars show median across models; lines show 10th to 90th percentile ranges. Negative values show cases where sectoral emissions are higher in the policy scenario than in the baseline). The numbers to the right of each bar indicate the regional mitigation potential measured by median cumulative (2010–2050) Kyoto emission reductions (%) from the No Policies scenario (median across models). Full set of model results is available in Supplementary Fig. S4.

underestimated. A risk-management approach that explicitly reflects structural uncertainties can provide policymakers with robust policy recommendations[44], although it has not generally been adopted by IAM analyses so far[45].

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; in IAMs economic efficiency and equity are either assumed to be independent or found to be largely so, owing to limited impact of income effects[46]. Despite this being a stylized 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[47]. 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)[48]. Many studies have assessed the implications of different regimes for the allocation of mitigation efforts[26,48,49], 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 with 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 receives an allowance above (below) its actual emissions, it would still mitigate the same net emissions—given the equity-efficiency independence discussed above—but would be able to sell (buy) emission rights equal to the difference between emissions and allowances. The case where emissions allowances exactly match domestic emissions reflects a situation where all mitigation efforts are financed domestically. Carbon markets can then be used to redistribute income (in accordance with some given principle) while preserving economic efficiency.

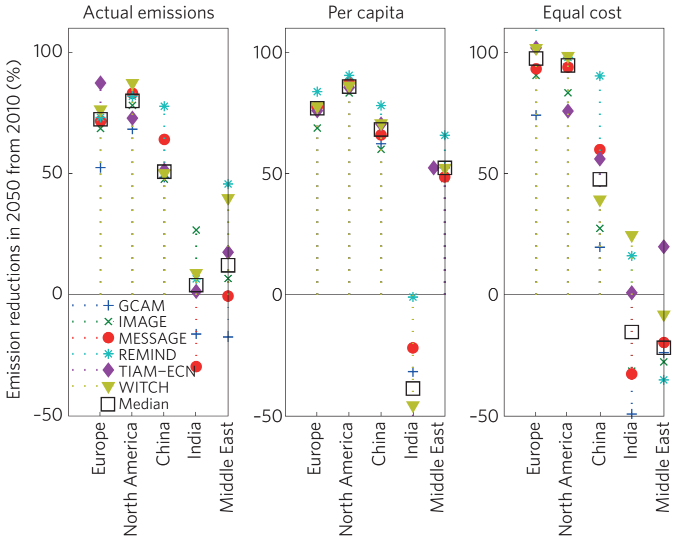

Figure 4 | Emission targets. Actual emissions (left panel) and emissions allowances (centre and right panels), in percentage reductions in 2050 from 2010 for a 450 ppm-eq target. The two panels on the right show examples of allocation schemes with resource sharing (convergence to equal per capita rights 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).

Figure 4 shows that for Europe and North America actual emissions and allowances in the per capita case would be slightly lower than those announced in the major economies forum meeting of 2009 (80–95% reductions over 1990). 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 modelling studies[14,20,50–52]). The opposite would hold for India (and Africa, not shown), because of 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 marked 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[53].

Economic and financial implications

A key consideration in climate policy is how to distribute the economic effort of GHG mitigation. Even if global mitigation costs were low, policymakers care and argue about the regional distribution of policy costs, as this affects economic development, competitiveness and even political stability. The scenarios indicate that the costs of mitigation will vary significantly across countries[1,14,20,54–58]. Figure 5 portrays this finding for the LIMITS models, showing that—in a cost-effective framework with uniform carbon pricing but without carbon trading or other 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[1,20,58–60]. This ranking is rather robust across climate targets, mitigation cost metrics and IAMs[14,61], although the ranges are considerably larger for developing economies.

The regressivity of regional costs can be attributed to several factors, but especially to emission intensity, abatement potential and international trade effects[14,62–64]. Using data from the EMF22 model comparison study, a higher ratio of emissions to GDP—the '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[62]. Given the higher current and projected emission intensities of developing countries[29], these regions will have higher total mitigation costs unless their abatement costs are significantly lower. Benefits from reduced warming and from other environmental issues such as local air pollution are likely to significantly affect the distribution of costs, but are not accounted for in this calculation.

The interregional distributional tension highlighted in Fig. 5 can be alleviated through emission endowments and trading. When the carbon budget is tight, however, as is the case for 2 °C policies, even resource-sharing schemes such as those based on per capita equalization would not compensate for the inequality in favour of OECD countries[14,65]. 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 to be 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[22].

In addition to macroeconomic 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[43,66–68], and found that a considerable reallocation of investments is required. As shown in Fig. 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 pledge scenarios, whereas they drop in the 450 ppm-eq stabilization case. In particular, 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 Supplementary Fig. 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, transitioning from a pledge policy to one fully compatible with the 2 °C target would require filling a global investment gap of about half a trillion US$ per year for the next 40 years, two-thirds of this 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 research and development would also need to be significantly scaled up, in order to prompt sufficient innovation in new technologies. Models estimate these to be about US$50–100 billion per year over the first half of this century[69–73].

The current level of green energy investments, estimated at roughly US$250 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[74,75]. Moreover, all models find that climate policies could provide sufficient fiscal revenues within each region to finance the totality of investment in energy supply, while also providing incentives to the private sector to raise finance[76]. 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 savings, although the question of whether this would be equitable would remain[76].

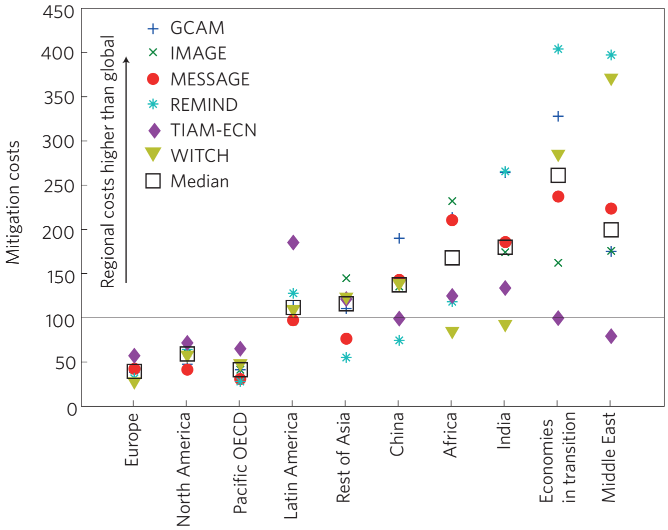

Figure 5 | Distribution of mitigation costs. Relative mitigation costs (percentage reduction of GDP) in each region divided by global mitigation costs (again in percentage reduction of GDP), for 450 ppm-eq without carbon trading and transfers. The line at 100 indicates the case in which all regions would face the same relative policy costs, as in the case of an 'equal cost' burden-sharing scheme. GDP is discounted over the period 2010–2100 at 5%.

Figure 6 suggests that revenues from the international sales of CO_2 permits could cover almost half of the investment gap of developing economies, provided that industrialized countries committed to transfers of the order of US$150 billion per year. In order to work, however, a large and well-functioning carbon market would need to be established in the next 20 years, capable of handling permits for several $GtCO_2$-equivalent and hundreds of billions of US dollars of trades per year[14,55,58]. 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. These represent the types of barriers that are not analysed by IAMs. The experience with CDM has already highlighted implementation difficulties at a much lower level of ambition[77].

Finally, IAM scenarios indicate that climate policies are likely to affect other objectives of policymakers; 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 independence in some major economies such as China, India and the EU. This would not be the case for the United States and current energy exporters[78]. 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[53,79]. Transformation pathways spurred by climate policies would also foster air pollution control[80,81], with particular benefits for China and India[82,83]. Although the magnitude of co-benefits related to air quality is uncertain[84], their current importance in major economies such as China could lend support to post-2020 climate policies.

Modelling input to the current negotiation process

The challenge of achieving a comprehensive agreement to reduce emissions is often portrayed as either insurmountable or simply a matter of lack of sufficient political will. Rigorous analysis of the

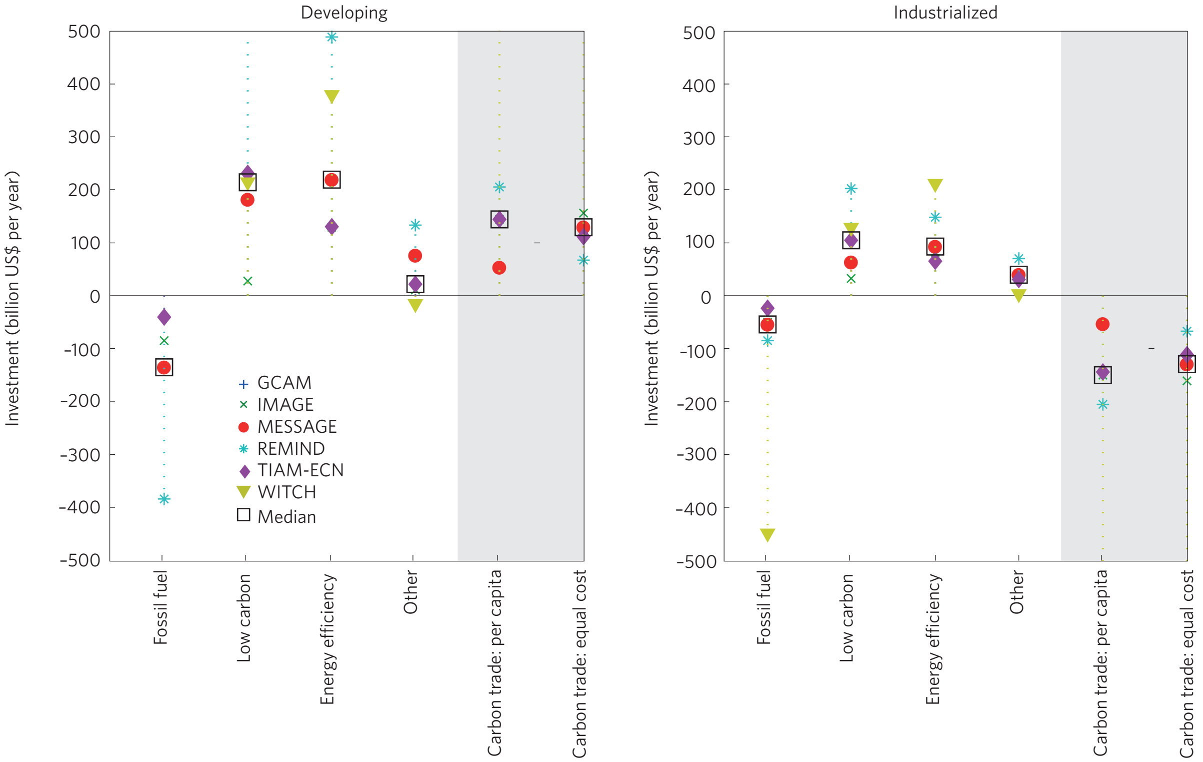

Figure 6 | Investments. Additional annual investment in US$ billion per year (average over the period 2010–2050; no discounting) between the 450 ppm-eq case and the pledge case, for different sectors and two regional groups. The last two columns (shaded) report trade of CO_2 permits (positive indicates selling) for the two burden-sharing schemes discussed above. The vertical axis is truncated at ±US$500 billion.

implications of implementing mitigation measures can help in 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 Review, we show that scenarios generated by energy–economy–climate models can help in this task, providing critical information to the ongoing policy debate on a post-2020 climate agreement. The use of MIPs can help to ensure that key uncertainties are taken into account by using a diversity of different models and model assumptions. Reviewing a recent MIP focused on international climate policy in the context of broader literature, we relate short- and long-term climate objectives to key regional indicators such as peaking of emissions, carbon budgets and abatement potentials. Our analysis highlights the main challenges in sharing the economic effort associated with reducing emissions equitably, while showing the importance of regional cooperation towards climate stabilization. The importance and limitation of markets is highlighted. Global carbon markets can alleviate some—but not necessarily all—of the distributional tensions in climate change mitigation. They can also provide much-needed revenues for filling investment gaps in clean energy, and if possible achieving other societal goals. Nonetheless, additional policy instruments will be needed to attain the technological and behavioural transformations to achieve climate stabilization.

The currently discussed targets, including those announced in China, the EU and the United States, are important steps forward; our analyses indicate that additional and more comprehensive efforts would be needed if we hope to keep temperature from exceeding critical thresholds. Still, expanding and strengthening climate cooperation while aligning national interests is by no means straightforward. The numerical estimates by the MIPs reviewed here highlight some critical areas of the climate policy process, which include the regional diversity of mitigation opportunities and costs, the institutional requirements for carbon markets, the best use of climate revenues, the linkages with national policy priorities, and the relevance of clean technology innovation and diffusion. 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 mitigation of short-lived gases, adaptation and geo-engineering, have not been considered in these model exercises. We hope that these topics will also be examined in the near future, using similar common protocols and making use of a large number of integrated assessment models.

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Author contributions

M.T., E.K., K.R. and D.V.V. conceived and designed the experiments. All authors performed the experiments. M.T. analysed the data and contributed materials and analysis tools. All authors wrote the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.