CLIMATE ECONOMICS

Assessing China's efforts to pursue the 1.5°C warming limit

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Given the increasing interest in keeping global warming below 1.5°C, a key question is what this would mean for China's emission pathway, energy restructuring, and decarbonization. By conducting a multimodel study, we find that the 1.5°C-consistent goal would require China to reduce its carbon emissions and energy consumption by more than 90 and 39%, respectively, compared with the "no policy" case. Negative emission technologies play an important role in achieving near-zero emissions, with captured carbon accounting on average for 20% of the total reductions in 2050. Our multimodel comparisons reveal large differences in necessary emission reductions across sectors, whereas what is consistent is that the power sector is required to achieve full decarbonization by 2050. The cross-model averages indicate that China's accumulated policy costs may amount to 2.8 to 5.7% of its gross domestic product by 2050, given the 1.5°C warming limit.

As part of the Paris Agreement, nearly all countries have agreed to take steps to limit the global surface average temperature increase to less than 2° or 1.5°C compared with preindustrial levels (*1*). Without stringent climate policy, global mean warming is likely to result in temperature increases greater than 2.5°C, which could decrease the world's per capita output by 15 to 40% (*2*), although those economic impacts are highly uncertain. The climate impacts in different regions are likely to show large differences (*3*, *4*), with some countries suffering disproportionately serious consequences without the adaptation of early and stringent climate change mitigation policies (*5*, *6*). For some less-developed states that are endowed with rich natural resources, half of their existing species may be in danger of extinction (*7*), and many coastal regions may be exposed to multiple risks of diseases resulting from climate change (*8*). Even worse, the imbalanced distribution of loss and damage will exacerbate the inequal trends of economic development across countries (*9*).

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Although both the 2° and 1.5°C goals have been discussed frequently since the Copenhagen Accord in 2009, most research efforts have focused on the 2°C target (*10*–*12*). The 1.5°C goal began to receive considerable attention only after it was formally adopted in the Paris Agreement, and a minority of studies since, particularly at the country level, have been conducted using it (*9*, *13*). Still, research has now shown that there are important differences between a 2° and 1.5°C warming (*14*, *15*); for example, the economic cost to reach the 1.5°C goal may be at least threefold that of the 2°C goal (*16*). The Intergovernmental Panel on Climate Change (IPCC) released a special report in 2019 on the impacts of global warming of 1.5°C above preindustrial levels and the related greenhouse gas emission pathways (*15*). Nevertheless, current studies on the 1.5°C goal are far from adequate to be enough for the sixth assessment report (AR 6) on climate change that is due to be released in 2022 (*17*, *18*).

At the same time, there is clearly no consensus on the attractiveness of a 1.5°C target, particularly given the uncertainty in associated mitigation costs. For instance, little attention has been paid to what this strict warming-stabilizing target means for China, particularly from the perspective of a multimodel comparison framework (*19*). The latest report released by the China Coal-Control Project provides a preliminary discussion of China's mitigation scenarios and technology pathways under the 1.5°C goal, emphasizing the importance of immediate mitigation actions followed by an annual decrease of nearly 400 million tonnes (Mt) in CO_2 emissions after 2020 and the first realization of negative emissions of the power sector in 2050 (*5*, *20*). It suggests that as a high population–exposed country, China may suffer substantially and more than other countries from the imbalanced distribution of adverse climate impacts. Therefore, we conducted this multimodel study to explore the consequences for China of doing its part to reach the 1.5°C warming target, based on the existing scenario from global models and new national modeling. The aim is to understand what results are model-robust, given different models that are widely used in both global and domestic climate policy research, and what results are most uncertain across models. Our findings are informative and insightful for China's long-term mitigation and carbon neutrality, as well as its contribution to global climate goals, and for identifying the need for future research.

Pathways of carbon and noncarbon emissions

Figure 1 reports the difference in emission trajectories across participating integrated assessment models (IAMs). For example, the range of the carbon emissions in 2050 under the "no policy" case is 10.2 to 19.8 billion tonnes of CO_2 ($GtCO_2$), and this is 1.9 to 2.3 $GtCO_2$ for the 1.5°C-consistent scenario. Except for the WITCH (World Induced Technical Change Hybrid) model, all the other models agree on China's carbon peaking in the no policy case, despite great uncertainty on peak values (from 10.9 to 17.5 $GtCO_2$) and timing (from 2035 to 2045). Based on the weak growth in coal consumption and the declining trend of CO_2 emissions in recent years, an emission peak during the period of 2035 to 2040 is certainly feasible, even in the absence of additional mitigation efforts (*21*). Despite limited convergence emission trajectories across models under the 1.5°C scenario, one highly consistent finding is that carbon emissions decrease steeply beginning in 2020. The majority of the IAMs will achieve near-zero or negative emissions by around 2050 (from –1.94 to 2 $GtCO_2$), a result in line with results from a global-scale analysis (*17*). We find that an early emissions peak followed by steep reductions thereafter reduces dependence on negative emission technologies (NETs) for realizing the 1.5°C target. As a consequence, an important trade-off exists between substantial early mitigation actions and reliance on NETs with uncertain performance, when developing pathways to realize the 1.5°C warming goal.

Carbon capture and storage (CCS) technologies, including conventional fossil fuel CCS and bioenergy with CCS (BECCS) technologies, play important roles in limiting global average temperature change in the year 2100 to 1.5°C (Fig. 1B), and this is consistent across various models (*22*). As seen from the results

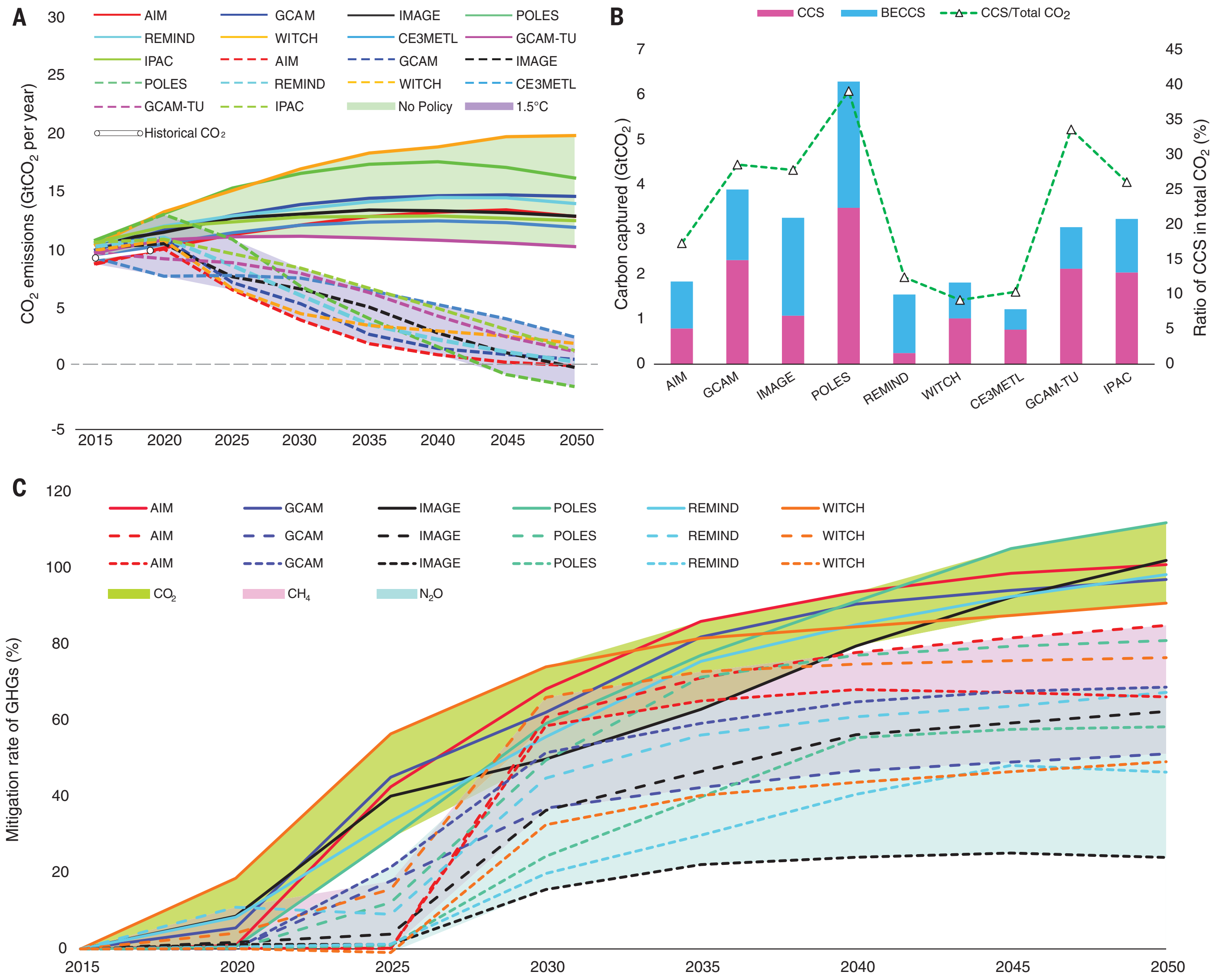

Fig. 1. Cross-model emission pathways of China. (**A**) Changes in total carbon emissions under both the no policy (solid lines colored with light green) and warming-limit scenarios (dashed lines colored with light purple). (**B**) The roles of the CCS for fossil fuels and biomass in attaining the 1.5°C goal by 2050. (**C**) Reduction ratios of carbon and noncarbon emissions across the models under the 1.5°C-consistent scenario (relative to the no policy case). GHGs, greenhouse gases.

for 2050, the lowest emission appears in the POLES (Prospective Outlook on Long-term Energy Systems) model, which has the greatest reliance on CCS and BECCS, with a share of total emissions reaching 39.2% (Fig. 1B). Similarly, the lesser use of CCS in the WITCH and CE3METL (Chinese Energy-Economy-Environmental Model with Endogenous Technological change by employing Logistic curves) models (less than 15%) largely explains their failure to reach net-zero or negative emissions by 2050. It is worth noting that the carbon emission for the AIM (Asia-Pacific Integrated Model) becomes negative in 2050, with a relative low ratio of CCS capture to total emissions, implying the substantial potential of carbon reduction associated with a low-carbon energy transition. Noncarbon emissions also need to be substantially curbed to ensure that the increase in the temperatures stays below 1.5°C (Fig. 1C). The multimodel comparisons reveal that the amount of noncarbon emissions, including primary CH_4 and N_2O, is rather small compared with that of the carbon emissions (12.8 to 16.1 Gt), with magnitudes of 70.7 to 98.9 Mt and 1.8 to 3.3 Mt, respectively. However, the reduction in noncarbon emissions still proves to be indispensable, particularly for attaining strict climate goals (*23*). Actually, carbon emissions must be reduced by more than 90% to hit the 1.5°C limit, and CH_4 and N_2O emissions are expected to decrease, on average, by 70.6 and 52.2%, respectively, in comparison to the no policy case (Fig. 1C).

Industrial CO_2 emissions and mitigation contributions

The mitigation challenges of the 1.5°C limit differ considerably across sectors in terms of both demand and supply levels (Fig. 2). From a demand perspective, industry is the main emission contributor, and this is a model-consistent finding. In the absence of additional mitigation policies, China's industrial emissions account for 48.7 to 75.2% of the total emissions of energy demand in 2030. As seen in the time scale (Fig. 2A), most of the models show declining trends in industrial emissions, and this decrease could be up to 37% from 2030 to 2050. When moving to the emission structure, we observe another model-consistent finding: The share of China's industrial emissions to total emissions of energy demand gradually declines to about 50% in 2050. This result is driven by three forces operating in China's industrial sector, i.e., structure adjustments, low-carbon transition of energy use, and substantial enhancement of energy efficiency. Indeed, China might be

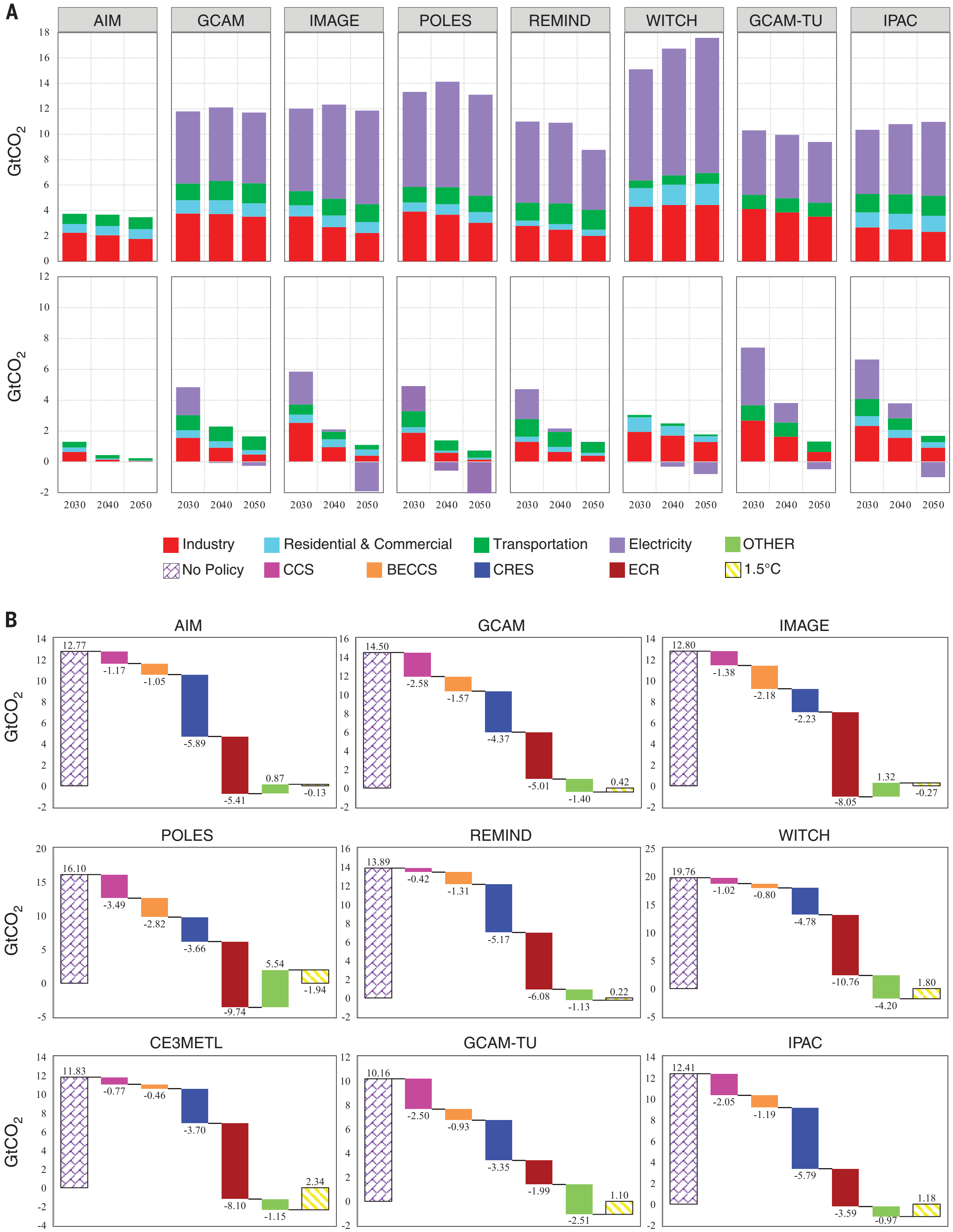

Fig. 2. Cross-model comparisons of China's emission reductions. (**A**) Sectoral carbon emissions from both the energy supply and demand sides across models. The top row shows the no policy baseline versus the 1.5°C-consistent scenario shown in the bottom row. No CO_2 data in the power sector were reported for the AIM model; emissions of heating were also absent for many models, and we therefore exclude it in this analysis. (**B**) Cross-model analysis of distributions of mitigation contributions under the warming limits in 2050. CRES denotes carbon emission reductions resulting from energy substitution (nonfossil energy for fossil fuels); ECR measures the emission abatement that is directly from energy consumption reduction. Other forms of change in carbon emissions (such as changes in land use) are included in the category OTHER.

expected to go through an energy-use transition even absent greenhouse gas emissions mitigation. Such energy transitions accompany economic development and its associated economic restructuring, air pollutant controls, and water and soil contamination treatment. In terms of energy supply, electricity production is the primary source of carbon emissions in China. As shown in Fig. 2A, emission pathways for power supply are not consistently decreasing across models. The emission structure of the supply side is quite stable when it is compared with that of the demand side, which implies the difficulty in carbon abatement arising from supply-side energy restructuring.

The 1.5°C warming limit directly leads to a pronounced decrease in sectoral emissions, which is consistent on both the supply and demand sides. On average, carbon emissions in the power sector will decline by 65.6% across models in 2030, and near-zero or negative emission status could be attained as deep decarbonization proceeds over time. The WITCH model appears to be the first to achieve negative emissions (in 2030), whereas the POLES and IMAGE (Integrated Model to Assess the Global Environment) models gain the highest values for negative emissions, i.e., 2.6 and 1.9 $GtCO_2$ in 2050. The cross-model analysis on the distributions of carbon emission mitigation shows that CCS plays a formidable role in achieving the 1.5°C goal (Fig. 2B), but it cannot be the dominant contributor to emission reduction. The largest proportion of the reduction comes from a substantial energy consumption decline, followed by the substitution of clean energy for fossil fuels, which is a highly consistent finding across all models. This implies that stringent energy demand control and substantial clean energy development are critical to hit the ambitious climate goal.

Challenges on the carbon intensity of end-use energy

Carbon intensity is an important indicator to weight the effect of policy interventions. Carbon intensity is defined as carbon emissions per unit consumption of end-use energy (tCO_2/tce). As depicted in Fig. 3, the 1.5°C limit calls for a substantial decrease in carbon intensity, with a cross-model consistent reduction of 60% relative to the no policy case. The declines in the GCAM-TU (Global Change Assessment Model–Tsinghua University), IPAC (Integrated Policy Assessment model for China), POLES, and REMIND (REgional Model of INvestment and Development) models could even be as high as 80%, leading to a high average decrease of 75.6% across participating models. As indicated by the absolute values, carbon intensity in most of the models is less than 1 tCO_2/tce (except IMAGE) in 2050, and it is the lowest in GCAM-TU, i.e., 0.3 tCO_2/tce. We could uncover two driving factors behind the decrease in carbon intensity: The first is both endogenous and exogenous energy efficiency enhancement for single-energy technology, and the second is the structure optimization of end-use energy consumption, including the electrification of the end-use energy system and transitions from carbon-based power to cleaner natural gas or renewables. Carbon intensity improvement may not be a direct objective of climate policy, which acts more on energy consumption control and clean technology development, but it is an important pathway through which energy policy operates.

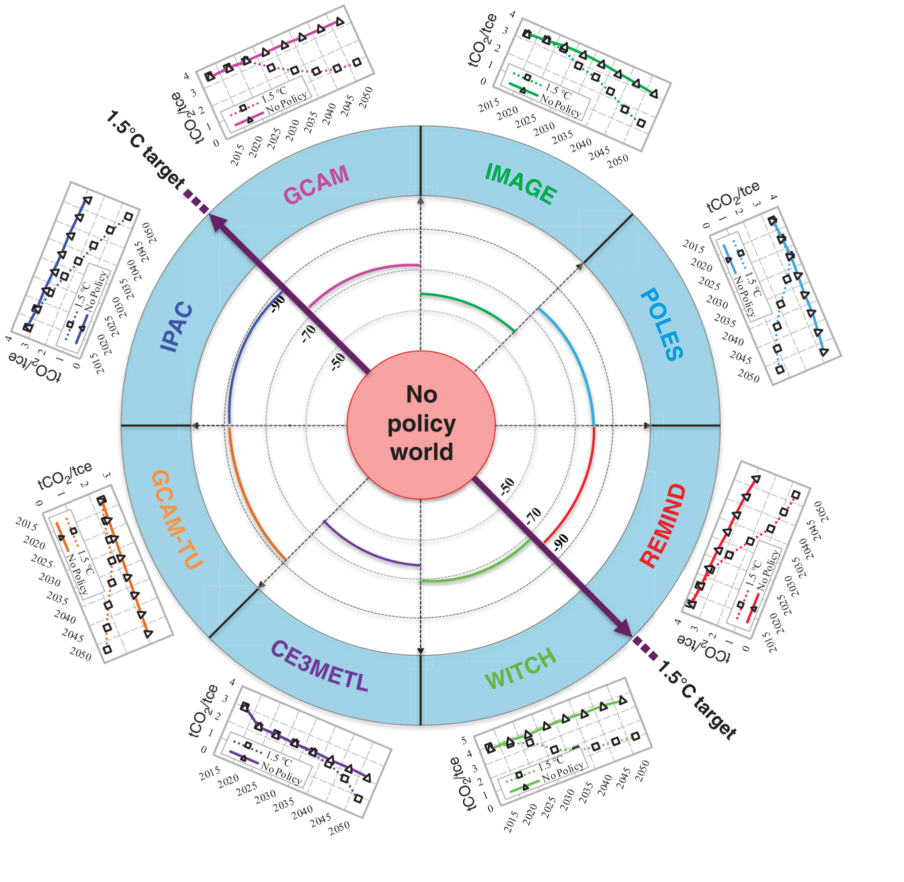

Fig. 3. Challenges regarding carbon intensity given the 1.5°C warming limit. The main chart depicts the percentages of carbon intensity improvement (relative to the no policy case) across the target IAMs in 2050, and the subfigures show the paths of the carbon intensity of end-use energy under a 1.5°C-consistent scenario.

Energy transformation and decarbonization

Attainment of the 1.5°C target largely depends on the substantial replacement of renewables for fossil fuels (*24*). Figure 4 shows that the 1.5°C goal requires a steep decrease in China's fossil energy consumption, and this decrease could be 4.04 Gt standard coal equivalent (Gtce) on average in 2050, 73.9% lower than the no policy case. In this context, China's nationally determined contribution (NDC) goal of non–fossil energy deployment can be realized early in 2025, and the share of non–fossil fuels in the total primary energy consumption (TPEC) could be further expanded to 30% in 2030 and 62.8% in 2050. By 2050, renewables will dominate China's primary energy supply, with a 1.3 Gtce increase in their amount and a 175% growth on average with respect to the no policy case. The leapfrog development of nuclear and renewables under the 1.5°C warming limit could also be consistently observed from independent model results (Fig. 4C). The aggregated impacts of the warming limit on TPEC could be demonstrated in detail by energy restructurings across various models (Fig. 4G). Our model comparison demonstrates the variety of possible energy transitions consistent with the strict 1.5°C temperature control. Some model-robust findings include a steep model-consistent reduction in coal consumption and a substantial development of biomass, wind, and nuclear power technologies. These results hold up well against changes in the cost of renewables (fig. S6).

As a main contributor to emission reduction, the electricity sector faces severe challenges in terms of restructuring and deep

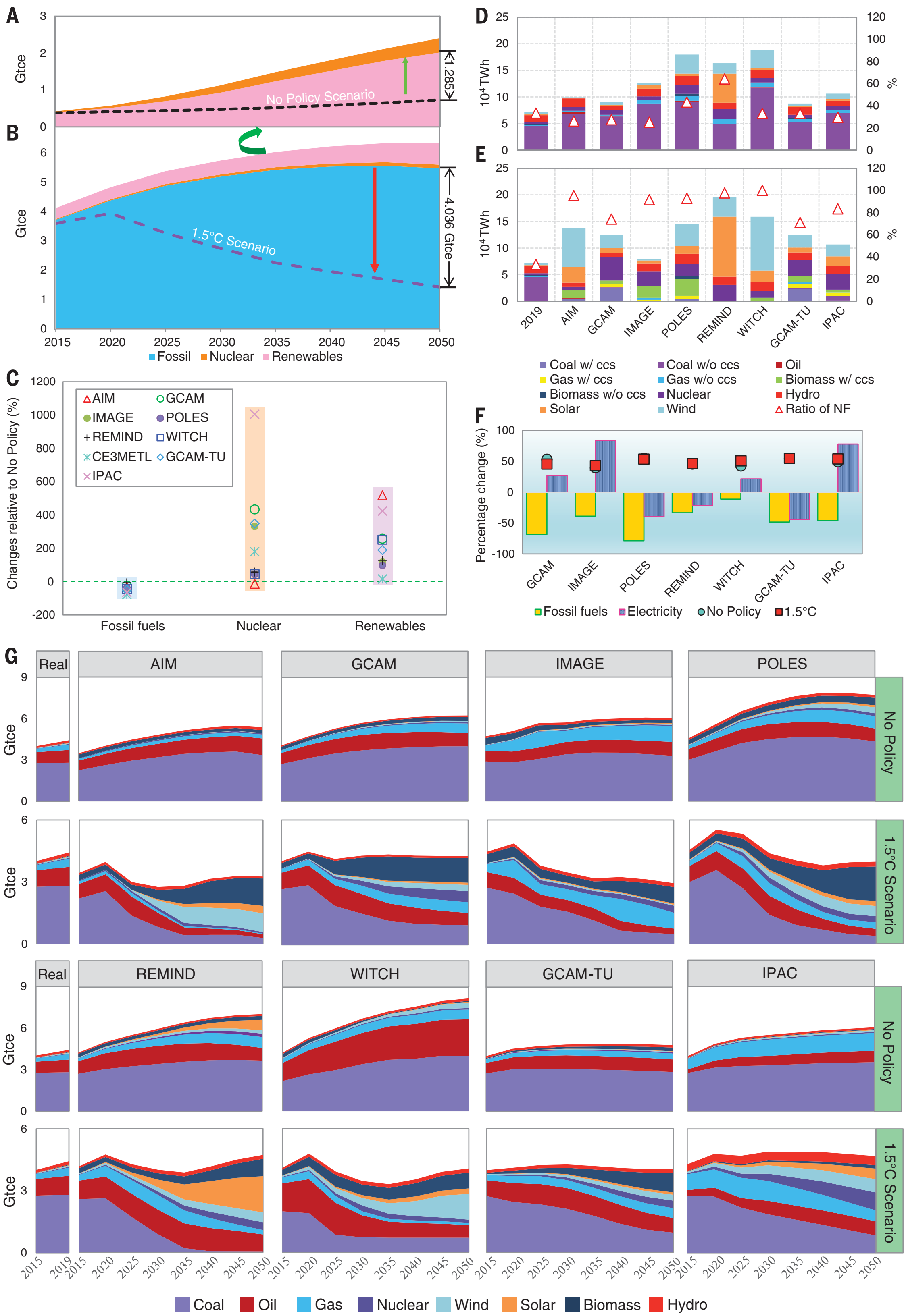

Fig. 4. Changes in the TPEC across models under the 1.5°C warming limit. (**A**) The growth in the magnitude of renewables under the 1.5°C scenario. The pink area represents the growth of renewables under the 1.5°C scenario, and the dashed black line shows the results under the no policy scenario; the green arrow indicates the magnitude of growth. (**B**) The decline in fossil energy demand necessary to hit the 1.5°C goal. The blue area represents the evolution of fossil fuels under the no policy scenario, and the dashed purple line shows the results under the 1.5°C scenario; the red arrow shows the magnitude of fossil fuel decrease under the 1.5°C scenario. The curved green arrow highlights the growth of renewables from the no policy scenario to the 1.5°C scenario. (**C**) Changes in fossil fuels, nuclear, and renewables across the models relative to the no policy levels. (**D** and **E**) The evolution of the secondary energy structure in 2050 under the no policy case (D) and the corresponding changes in the power structure under the 1.5°C case (E). The triangles in both subfigures denote the ratios of nonfossil power (NF) to total secondary power consumption. (**F**) Changes in industrial energy demand (relative to the no policy case). The bars in this figure show changes in industrial fossil fuels and electricity consumption in 2050 by comparing the 1.5°C case to the no policy case; circles and squares represent shares of the industrial final energy demand to the total final energy under the two scenarios, respectively. (**G**) Energy restructuring across the target models. The titles at the top and to the right give considered models and policy scenarios, respectively. Different energy consumption is uniformly measured by Gtce. On the left, "Real" provides the historical energy consumption in 2015 and 2019 from China's National Bureau of Statistics.

decarbonization in the presence of a strict warming limit. Although changes in energy demand across models are highly varied in the no policy case, fossil fuels consistently play a dominant role in the power sector. With the exception of the REMIND model, which is optimistic about the deployment of solar power, the share of fossil energy in sectoral TPEC for all the other models is more than 67% in the no policy scenarios (Fig. 4D). Figure 4, D and E, reports inconsistent cross-model impacts of warming control on energy consumption in the power sector. In effect, there are two typical factors driving the changes in the energy demand in the power sector. First, mitigation drives higher carbon prices, which increase end-use energy prices. Second, because the power sector has many ways to decarbonize, its price falls relative to fossil fuel prices in end use, which leads to a substitution of power for the direct use of fossil fuels. The latter is the electrification effect (*20*). The final changes in energy consumption in the electricity sector are contingent on the trade-offs of these two effects (see supplementary materials for further discussion). Two robust results emerge from this model intercomparison. First, China's power sector will achieve zero-coal status in 2050, though technology mixes vary widely across models. Second, of all the low-carbon technologies, wind and solar have observed the fastest increases in generation over recent years.

Industry is a primary sector of end-use energy consumption, and substantial changes in energy use must occur to reach deep decarbonization of the entire economy and realization of the given climate goals. Because the power sector has many low-carbon and no-emission technology options available and their future cost and performance are uncertain, models reflect a range of possible decarbonization pathways for this sector (Fig. 4F). What is interesting is that the ratio of industrial energy demand to total end-use energy demand is less affected and relatively stable, slightly fluctuating around the average level of 49% (42 to 55%) across all models under both scenarios. This largely reflects high internal consistency on the dynamic adjustment of China's industrial structure [e.g., share of industrial gross domestic product (GDP) in the economy] and energy efficiency enhancement in the industrial sector.

Economic analysis

We understand the economic implications of climate policy by considering three aspects, i.e., climate damage, the economic impacts of climate policy, and the social cost of carbon (SCC) for various climate targets. The first two indicators are usually measured by the proportion of GDP, and the SCC could be largely equivalent to the optimal carbon tax given exogenous warming and emission controls (*25*). Because most considered models do not report climate-related damage, we conduct our cross-model economic analysis by mainly considering policy costs and the SCC, as depicted in Fig. 5, A and B.

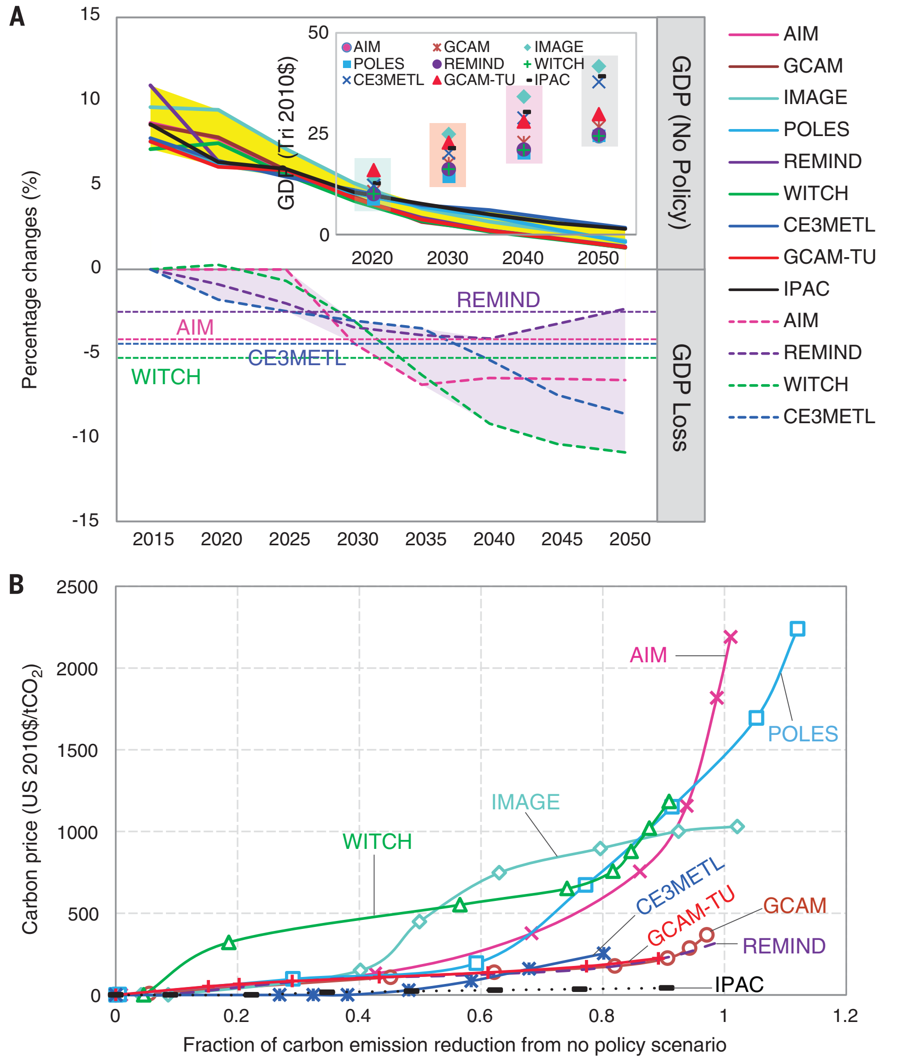

Fig. 5. Impacts of the 1.5°C goal on China's economy. (**A**) The top panel shows GDP growth rates under the no policy scenario (5-year averages from 2010–2015 to 2045–2050), with the magnitude of the GDP across all models embedded, and the bottom panel shows the yearly GDP losses (dashed lines with purple colored band) and cumulative GDP loss (the horizonal dotted lines, from 2020 to 2050 with a 5% discount rate) given the 1.5°C goal (percentage change relative to the no policy results). (**B**) Carbon prices required for China given the 1.5°C warming limit. The horizontal axis gives emission control rates relative to the no policy case.

The models do not tell a consistent story regarding the policy costs under the 1.5°C scenario (Fig. 5A). For example, the GDP losses associated with the 1.5°C warming limit could be as high as 10.9% and as low as 2.3% in 2050. This story is still true when moving to the accumulated perspective, with the GDP loss over the time frame ranging from 2.8 to 5.7% (with a 5% discount rate), and they are observably larger than the global levels (fig. S1). However, as seen in the model averages, we find a similar sized accumulated impact of the 1.5°C warming limit on China and the world, i.e., 3.3% (relative to the no policy level). Given that the no policy scenario is mostly counterfactual, the GDP loss could be understood as an upper-bound cost to hit the 1.5°C goal. Generally, increased GDP growth implies an increase in energy consumption. Although energy systems have long been dominated by fossil fuels in China, in this context, the attainment of the stricter climate target relies on a pronounced decrease in energy consumption, which inevitably plays a negative role in the economy (*26*). By contrast, substantial technological change not only effectively drives economic growth but also greatly helps to reduce the policy costs of climate governance, and this can be seen in the results of the CE3METL model in Fig. 5A.

All the models in this study report pathways of the SCC under the 1.5°C scenario, as informed in Fig. 5B, and we find a great cross-model uncertainty on China's SCC (from $315 to $2240 per tCO_2 in 2050), which repeats the result that has been clearly examined at the global scale (*19*). The notable difference in carbon prices is not surprising because there are many primary factors that lead to this difference, including the basic setting on costs and mitigation performance for various energy technologies, the substitutability of fossil fuels and alternatives, cross-regional trade modes, and the transmission mechanism of policy costs (see supplementary materials for more discussion).

Model-intercomparison findings

Based on the IAM-based multimodel analysis, we found that China's carbon-neutral announcement in 2060 is largely consistent with the 1.5°C warming limit, despite a greater challenge for the latter (fig. S7). Our model intercomparison produced several consistent insights. First, the global 1.5°C warming limit is associated with emission reductions exceeding 90% (90 to 112%) in China's total CO_2 emissions and an average decrease of 70.6% (51.3 to 85%) and 52.2% (24.1 to 68.8%) in CH_4 and N_2O emissions, respectively, as compared with the no policy level; the carbon intensity of end-use energy in 2050 needs to be reduced by at least 60% (60 to 87.1%). Second, our model comparison confirms the formidable role of CCS technologies, particularly fossil-based CCS and NETs, in keeping temperature from exceeding critical thresholds. Last, China's fossil fuels and TPEC need to be dramatically reduced by more than 73 and 39%, respectively, to hit the 1.5°C warming limit, and most models report that China's coal demand will be declining to near zero around 2050. The attainment of the 1.5°C goal calls for large-scale emission reductions resulting from the accelerated deployment of renewables and their substantial replacement of carbon-based fuels.

Uncertain implications

The emission pathways are sensitive to variation in model structure and technology assumptions that lead to variation in the date and magnitude of peak emissions, a finding that is largely in agreement with the global-scale findings (*27*, *28*). Although the 1.5°C target drives early mitigation action with steep reductions thereafter, the magnitude of the decrease greatly differs across participating models. The models in this study displayed a wide range of mitigation pathways, including differences in the role of the sectors. By 2030, the power sector is required to cut down its CO_2 emissions by about 66% and achieve full decarbonization by 2050. Nonetheless, models reported a wide variety of patterns in sectoral energy demand and structure. Similar variation exists in the final energy consumption of industry, though the ratio in the total final energy demand seems to be less affected. The model comparison also produced a wide range of policy cost estimates for compliance with the 1.5°C target, a feature reflected in the associated estimates of SCC, with a cross-model difference of more than 10-fold.

The model-consistent findings are mainly around changes in TPEC, emission reductions, and roles of NETs, given the 1.5°C temperature control, with variation in results at the sector level for emission reductions and energy restructuring, as well as for the economic cost of climate policy. Hence, to make the 1.5°C-consistent or carbon-neutral target attainable, explicit emission mitigation and clean-energy development goals at the industrial level in both the coming 14th Five-Year Plan and mid-term strategy are needed. Policy costs should also be paid central attention. This research suggests the need for an in-depth study of China's multimodel comparisons. Models need to improve their representation of technology, including updating the technical details (e.g., model harmonization based on the rapid decline of renewables' cost) and putting in place the mechanisms to sufficiently take the latest energy and climate policies into account (e.g., policy adjustments associated with China's carbon neutrality). In addition, models need to make a firm commitment to quantify the SCC by monetarizing the marginal damage of carbon emissions, which could reduce the uncertainty of policy cost evaluation (*29*, *30*).

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ACKNOWLEDGMENTS

We thank the China Energy Modeling Forum (CEMF) for organizing the second multimodel comparison exercise; the experts who substantially commented on the draft are also acknowledged. **Funding:** H.D., S.Z., and S.W. acknowledge financial support from the National Natural Science Foundation of China (71874177, 72022019, 71874096, and 71988101) and the National Key Research and Development Program of China (2020YFA0608603). S.F. acknowledges funding from The Environment Research and Technology Development Fund (JPMEERF20202002) of the Environmental Restoration and Conservation Agency of Japan. The results and conclusions in this research are those of the authors and do not necessarily represent the official position of the granting organizations. **Author contributions:** H.D. designed and produced an initial draft of this research, with substantial input from all authors. K.J. and S.W. coordinated and co-designed the research. S.Z., M.T., C.B., E.K., M.H., D.P.v.V., S.F., M.T., K.K., G.I., and J.E. contributed to the modeling results, comparison analysis, and manuscript preparation. X.M. and K.K. designed the figures and added supplementary analysis, respectively. All the authors were involved in interpreting the results and revising the manuscript. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Scenario data from global integrated assessment models were collected in the ADVANCE project, which received funding from the European Union's Seventh Programme FP7/2007-2013 under grant agreement no. 308329 (ADVANCE) and is accessible at https://db1.ene.iiasa.ac.at/ADVANCEDB/dsd?Action=htmlpage&page=welcome. The license under which the ADVANCE Synthesis scenarios are made available is adapted from the Creative Commons Attribution 4.0 International Public License, which keeps the licensed material always up-to-date and avoids the circulation of obsolescent data constituting substantial portions of the licensed material. Data that are not reported in this database are provided by the specific models, and all the model results, particularly from the models that are not participants of the ADVANCE project, are available at https://github.com/xmxming/China-1.5-degree-research. Codes and details for all the participating models can be provided upon request.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/372/6540/378/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S7
Table S1
References (*31*–*54*)

13 January 2020; accepted 22 March 2021
10.1126/science.aba8767

Science

Assessing China's efforts to pursue the 1.5°C warming limit

Hongbo Duan, Sheng Zhou, Kejun Jiang, Christoph Bertram, Mathijs Harmsen, Elmar Kriegler, Detlef P. van Vuuren, Shouyang Wang, Shinichiro Fujimori, Massimo Tavoni, Xi Ming, Kimon Keramidas, Gokul Iyer and James Edmonds

Science **372** (6540), 378-385.
DOI: 10.1126/science.aba8767

Change in the air

The 2016 Paris Agreement set the ambitious goals of keeping global temperature rise this century below 2°C, or even better, 1.5°C above preindustrial levels. Substantial interventions are required to meet these goals, particularly for industrialized countries. Duan *et al.* projected that China will need to reduce its carbon emissions by more than 90% and its energy consumption by almost 40% to do its share in reaching the 1.5°C target. Negative emission technology is an essential element of any plan. China's accumulated economic costs by 2050 may be about 3 to 6% of its gross domestic product.

Science, this issue p. 378

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