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A cost-effective climate mitigation pathway for China with co-benefits for sustainability

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Climate mitigation policies have broad environmental and socioeconomic impacts and thus underpin progress towards the United Nations Sustainable Development Goals (SDGs). Through national-scale integrated modeling, we explore the spillover effects of China's long-term climate mitigation pathways (CMPs) on achieving all 17 SDGs, and then identify a cost-effective CMP for China with co-benefits for sustainability. Our analysis indicates that the 9 original CMPs and 180 bundled CMPs can both substantially boost the SDGs, resulting in an increase of 6.33–8.86 and 5.90–9.33 points in overall SDG score (0=no progress, 100=full achievement) by 2060, compared to the Reference pathway of 70.75 points, respectively. The identified cost-effective CMP deals with the trade-offs among sustainability, CO_2 emissions and mitigation cost, and maximizes the synergies between them. This CMP can inform future directions for China's policy-makers to maximize the potential synergies between carbon neutrality and long-term sustainable development.

China has committed to the achievement of the United Nations Agenda (UN) 2030 and the Sustainable Development Goals (SDGs) since their adoption in 2015[1]. Over the past eight years, China has integrated the SDGs with its medium- and long-term development strategies and has made positive progress towards high-priority development goals such as eradicating poverty and hunger[2,3], sustaining macroeconomic growth[4], improving social security and services[4,5], and strengthening environmental protection[6]. However, despite achieving commendable socioeconomic progress and advances in environmental sustainability, combatting climate change remains a challenge. To this end, China updated its Nationally Determined Contributions (NDC) to the Paris Agreement[7], making an ambitious pledge to reach peak carbon emissions before 2030 and achieve carbon neutrality before 2060, which is now regarded as a basic long-term national strategy and is integrated into core environmental policy. To this end, several climate mitigation pathways (CMPs) have been proposed for China[8] (Supplementary Table 1). For example, Tsinghua University[9] led a comprehensive report of 1.5 °C and 2 °C compatible pathways for China; Energy Foundation China[10,11] released a synthesis report of existing China's energy transition routes from multiple Chinese and international energy modelings; and International Energy Agency[12], Energy Research Institute of Chinese Academy of Macroeconomic Research[13], and Global Energy Interconnection Development and Cooperation Organization[14] provided deep decarbonization roadmaps consistent with China's carbon neutrality goals. The level and type of climate action included in these pathways have far-reaching socioeconomic and environmental consequences for multiple diverse sustainability issues including greenhouse gas emissions[15], employment[16], and urban distribution[17].

The SDG framework has motivated significant research efforts dedicated to addressing sustainability bottlenecks at both national and global levels including assessing interactions among SDGs[18,19], evaluating progress toward SDG achievement[20,21], and assessing impacts of intervention policies on SDG[22,23]. A more extensive research review on

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SDG analysis is provided in Supplementary Table 2. Climate mitigation interventions are crucial for tackling climate change and have far-reaching effects on the SDGs more broadly. Several studies have addressed the linkages between climate change mitigation and the SDGs, most of which have focused on the nexus between climate action and a specific aspect of sustainability such as poverty and inequality (SDG1, SDG10)[24], food (SDG2)[25,26], health (SDG3)[27], water (SDG6)[28], economic cost (SDG8)[29], and biodiversity (SDG15)[30]. Other works have assessed the linkages between climate mitigation and multiple SDGs using quantitative methods (e.g., integrated assessment models [IAMs]). In particular, at the global level, von Stechow et al.[31] examined the synergies and trade-offs between climate mitigation and sustainable energy objectives; Soergel et al.[32] quantified the consequences of mitigation policies aimed at keeping global warming below 1.5 °C on SDG achievement; and Peng et al.[33] explored the potential spillover effects of sector-specific mitigation policy of accelerating power transition on future sustainability. At the regional and national levels, Moreno et al.[34] employed a package of IAMs to understand the energy- and carbon-related SDG outcomes of three decarbonization pathways in the European Union; and Liu et al.[35] discussed the effects of SDG-related climate policies under different policy scenarios in China. A more detailed review on climate change mitigation and SDG relationships is provided in Supplementary Table 3.

However, these studies about mitigation-SDG relationships only considered a specific SDG or a limited set of indicators and interlinkages, even when considering multiple SDGs (Supplementary Table 3). Specifically, two research questions arise from the literature: (i) What are the impacts of CMPs on achieving all the 17 UN SDGs? and (ii) How can we design a cost-effective climate pathway based on the existing CMPs envisioned to maximize the sustainability co-benefits associated with emissions reduction? China's current gaps in achieving the SDGs, especially in the environmental dimension[21], provide a space for creating synergies and opportunities through CMPs to enhance China's future sustainable development. Thus, we presented this study in the China's context to address the two research questions.

To address such gaps, based on the core iSDG model[36] we developed the iSDG-Climate-China model by modeling new climate mitigation interactions with other systems, such as the effects of carbon capture and storage (CCS) on the CO_2 emissions; and the effects of $PM_{2.5}$ atmospheric concentration on the $PM_{2.5}$-related premature mortality. Further, we enriched the SDG evaluation framework by extending the basic set of indicators (using 51 targets and 98 indicators) and customized the iSDG-Climate-China model to fit Chinese context by calibration with China's historical data. The resulting iSDG-Climate-China model is an integrated system dynamics model that encapsulates the nonlinear influence mechanisms between 30 sectors across the economy, society, and environment (Methods).

We focused on simulating and comparing an extensive range of CMPs against all available SDG indicators to identify a cost-effective CMP for China via the iSDG-Climate-China model. First, we selected 9 commonly used CMPs with diverse assumptions (Methods, Table 1, Supplementary Table 1), each of which consisted of a coherent set of policies covering energy efficiency, energy mix, and negative emissions (including land use, land-use change, and forestry [LULUCF] and CCS) (Supplementary Table 4). We then identified four policy clusters (i.e., energy efficiency, energy mix, LULUCF, and CCS), each of which consisted of the policies originating from these 9 CMPs (Supplementary Table 5). To explore other possible future policy directions for climate change mitigation, we selected one policy from each policy cluster leading to a total of 180 CMPs, called *bundled CMPs* (Methods). Second, we assessed the performance of the Reference pathway (i.e., a business-as-usual [BAU] scenario representing no new mitigation policy implementation) in achieving the SDGs. Further, we measured the impacts of the 9 original CMPs and 180 bundled CMPs on the SDGs through to 2060 (deadline for China's commitment to achieve carbon neutrality) (Supplementary Fig. 1), and then identified a cost-effective CMP which achieved the necessary CO_2 emissions mitigation at lower cost with co-benefits for sustainability. Performance against the SDGs was quantified by a normalized score between 0 and 100 (0 = no progress, 100 = full achievement), with individual and overall SDG scores (Methods). Socioeconomic development assumptions that were not included in the mitigation policies such as population, urbanization, and education were set according to BAU settings following Shared Socioeconomic Pathway 2 (SSP2)[37], referred to as *tailored SSP2* (tSSP2) (Methods).

Results

Mitigation policies effectively promote SDG achievement

When implementing mitigation policies (i.e., the 9 CMPs) without any other SDG interventions, we projected that China's overall SDG score would increase to 71.17–72.14 by 2030 and 77.08–79.61 by 2060 from 64.70 in 2022 (Fig. 1, Supplementary Fig. 2). Synergistic impacts of mitigation policies on SDGs far outweighed the trade-offs between them, resulting in an average improvement of 3.91 and 7.99 points in overall SDG score by 2030 and 2060, respectively, compared with the Reference pathway (Fig. 1). Of these, the CMPs that performed best in the short-term (2030) and long-term (2060) development differed, with the *NET-led* CMP performing best in 2030 while the *Updated NDC to Carbon Neutrality* CMP performing best in 2060. The *Below 2 °C* CMP performed worst in both 2030 and 2060 (Fig. 1, Supplementary Fig. 2).

Our results show that three types of mitigation policies (i.e., energy efficiency, energy mix, and negative emissions) were all effective for improving overall SDG scores under the 9 CMPs, with an average increase of 1.48, 1.91, and 0.52 (2.47, 3.73, and 1.79) points by 2030 (2060) compared against the Reference pathway (Fig. 1). Notably, the drivers of overall SDG score advances varied across CMPs, with the main differences in energy mix and negative emissions policies. By 2060, the share of the overall SDG score improvement contributed by the energy mix policy ranged from 41.2% (*NET-led* CMP) to 60.9% (*Below 2 °C* CMP), and the share from the negative emissions policy ranged from 0 (*Below 2 °C* CMP) to 30.4% (*Updated NDC to Carbon Neutrality* CMP). These results reflect the focus of the *Below 2 °C* CMP on energy system transformation towards renewables while the *NET-led* and *Updated NDC to Carbon Neutrality* CMPs relied upon large-scale negative-emissions technologies such as CCS and reforestation which generate remarkable environmental co-benefits to achieve CO_2 reduction (Fig. 1).

Individual SDG co-benefits vary across climate mitigation pathways

Wide-ranging impacts caused by climate change mitigation policies embodied in the 9 CMPs were observed across several individual economic, social, and environmental SDGs. By 2060, compared with the Reference pathway, the average scores for five environmental SDGs including clean water and sanitation (SDG6), affordable and clean energy (SDG7), responsible consumption and production (SDG12), climate action (SDG13), and life on land (SDG15) were improved by 5.43, 15.69, 32.22, 51.13, and 8.60 points on average by 2060 (Fig. 2, Supplementary Fig. 3). In addition, mitigation policies improved the performance against four socioeconomic SDGs including no poverty (SDG1), zero hunger (SDG2), industry, innovation and infrastructure (SDG9), and sustainable cities and communities (SDG11), by 10.47, 8.70, 7.63, and 20.02 points on average by 2060. Progress was mostly driven by easier access to renewable energy, reduced pollution, increased efficiency in energy use, and more sustainable agricultural management, which thereby reduced mortality and malnutrition and avoided deleterious effects on industrial infrastructure and supply-chain networks. However, climate mitigation was

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Table 1 | The 9 original CMPs

CMP	Source	Organization	Assumption and plan	End year
Announced Pledges	An Energy Sector Roadmap to Carbon Neutrality in China[12]	International Energy Agency	Sets out a pathway to carbon neutrality in China's energy sector in which emissions of CO_2 reach a peak before 2030 and fall to net zero in 2060, in line with China's stated goals.	2060
Below 2 °C	China Renewable Energy Outlook 2019[68]	Research Institute of Academy of Macroeconomic Research/NDRC China National Renewable Energy Center	Shows a pathway for China to achieve the ambitious vision an ecological civilization and the role China could take in the fulfillment of the Paris Agreement.	2050
Carbon Neutrality	Research Report on China's Carbon Neutrality by 2060[14]	Global Energy Interconnection Development and Cooperation Organization	Outlines a pathway to achieve carbon neutrality for all sectors of society, including the energy system.	2060
Carbon Neutral Scenario 2	China Energy Transformation Outlook 2022[13]	Energy Research Institute Chinese Academy of Macroeconomic Research	Provides a roadmap for China to achieve the ambitious vision for an ecological civilization and the pathway China could take towards carbon neutrality.	2060
NET-led	Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modeling study[69]	Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University (lead)	This CMP explores the maximum usage of negative emission technologies under constraints of resource availability and technology costs, with the goal of carbon neutrality in 2060.	2060
PEAK30	Assessing the energy transition in China towards carbon neutrality with a probabilistic framework[41]	Institute of Energy, Environment and Economy, Tsinghua University	Assumes China's CO_2 emissions peak at 2030, and simulates numerous possible sectoral decarbonization pathways under different cumulative carbon budgets.	2050
RE-led	Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modeling study[69]	Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University (lead)	This CMP assumes that negative emission technologies are replaced by renewable and low carbon energies as much as possible, with the goal of carbon neutrality in 2060.	2060
Updated NDC to Carbon Neutrality	Synthesis Report 2022 on China's Carbon Neutrality: Electrification in China's Carbon Neutrality Pathways[10], and Synthesis Report 2020 on China's Carbon Neutrality[11]	Energy Foundation China	Explores the implications of reaching net CO_2 emissions peak before 2030 and net-zero greenhouse gas emissions in 2060.	2060
1.5 °C	China's Long-Term Low-Carbon Development Strategies and Pathways: Comprehensive Report[9]	Institute of Climate Change and Sustainable Development of Tsinghua University (lead)	Based on the goals of controlling global warming to within 1.5 °C and realizing carbon neutrality, this CMP demonstrates the possibilities and pathway options for the realization of net-zero emissions of CO_2 and deep reductions of other greenhouse gas emissions by 2050.	2050

accompanied by non-trivial economic concerns including decreased labor income share, expenditures on water protection, and reduced government surplus, which were primarily reflected in the reduced inequalities (SDG10), life below water (SDG14), and partnerships for the goals (SDG17) with the average SDG score declining by 4.13, 9.14, and 15.94 by 2060 (Fig. 2, Supplementary Fig. 3).

The 9 CMPs had comparable performance across several socioeconomic SDGs such as SDG1, SDG2, and SDG9 due to similarity in some energy efficiency and energy mix policies (e.g., temperature control) (Supplementary Fig. 4). Differences in overall SDG score for the 9 CMPs can be explained through five goals where mitigation policies had the most influence, including four environmental goals (SDGs 7, 12, 13, and 15) and a socioeconomic goal (SDG 17) (Fig. 2). Energy mix policy was the biggest factor in shaping SDG7. Specifically, the *Below 2 °C* and *NET-led* were the best and worst performing CMPs which involved the share of renewables in primary energy supply at 83.3% and 35.3% by 2060 (Supplementary Table 6) and drove increases in scores of 18.46 and 10.77 for SDG7 compared with the Reference pathway by 2060, respectively (Fig. 2). Based on policies of improved material consumption efficiency, renewable electricity, electrification level, and negative emissions, the efficient use of natural resources and mitigation of waste releases including CO_2 emissions were improved (SDGs 12 and 13) (Supplementary Fig. 4). The *Below 2 °C* and *RE-led* CMPs which ignored the use of negative emissions technologies were the only CMPs that failed to meet China's 2060 carbon neutrality target, with 1.25 and 0.064 $GtCO_2$ emissions in 2060 (Supplementary Table 6). This explained why these two CMPs received scores of only 57.53 and 78.27, and 65.77 and 85.67 for SDGs 12 and 13 by 2060, significantly lower than the average score across the 9 CMPs of 75.13 and 93.56 (Fig. 2, Supplementary Fig. 2). In addition, the *Carbon Neutrality*, *Updated NDC to Carbon Neutrality*, and *1.5 °C* CMPs which made efforts in afforestation (i.e., LULUCF policy), effectively increased forest cover from 37% in the Reference pathway to 39.8%, 43.9%, and 47.8% by 2060 (Supplementary Table 6), respectively, and hence progressed against SDG15 compared with other CMPs. Finally, by 2060, the 9 CMPs with different mitigation investment increased government deficit as proportion of GDP from 4.6% in the Reference

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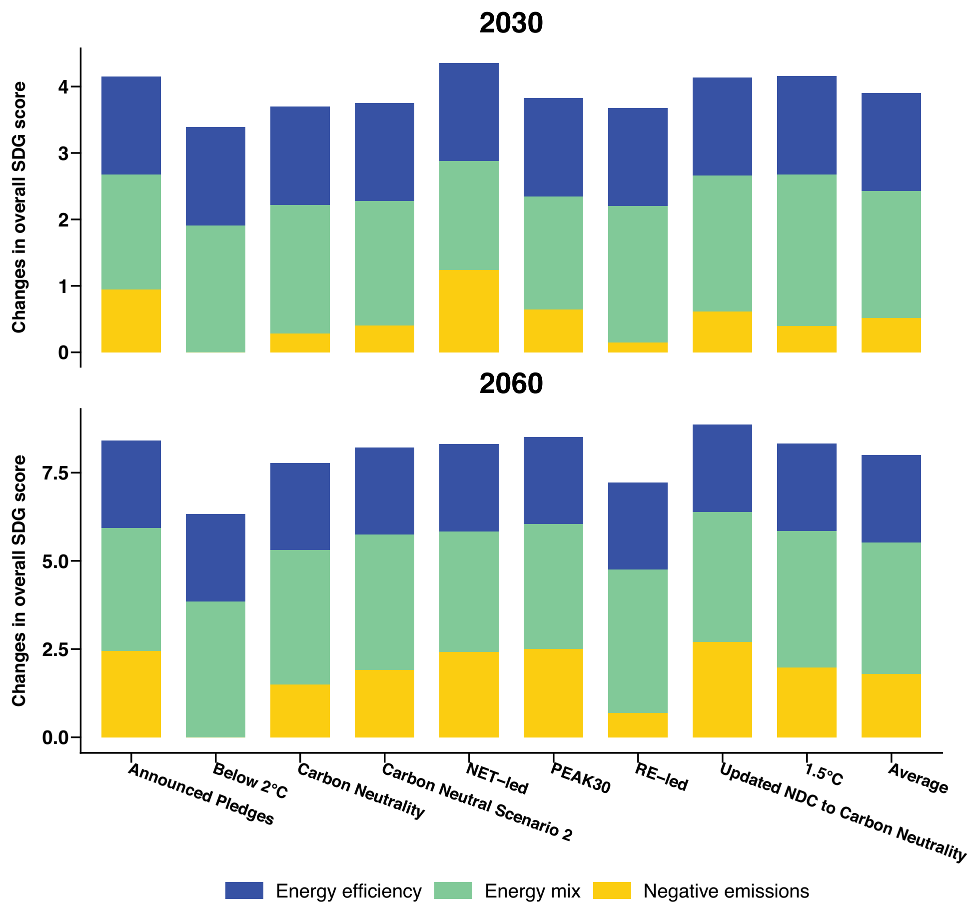

Fig. 1 | Sustainability performances of CMPs in terms of overall SDG scores by 2030 and 2060. The colored bars indicate the absolute changes in overall SDG scores of 9 CMPs after implementing energy efficiency, energy mix, and negative emissions mitigation policy orderly, compared to the Reference pathway.

pathway to 7.1%–8.5% (Supplementary Table 6), resulting in a significantly decrease in performance against SDG17 from 13.85–17.78 points (Fig. 2).

Greater gains through bundled climate mitigation pathways

We assessed the impacts of 180 bundled CMPs on SDGs, each of which is a combination of four policies (energy efficiency, energy mix, LULUCF, and CCS) chosen from the 9 original CMPs (Supplementary Table 5). Bundled CMPs generated greater synergies towards achieving the SDGs than the 9 CMPs themselves. By 2060 and considering all CMPs (180 bundled CMPs and the 9 original CMPs), the most remarkable progress towards the SDGs was made under the EE_{mature}, $EM_{RE\text{-}led}$, $LULUCF_{1.65}$, and CCS_2 CMP (a CMP characterized by mature energy efficiency, energy mix that follows *RE-led* CMP, 1.65 $GtCO_2$ in LULUCF carbon removal, and 2 $GtCO_2$ in CCS carbon removal), with an overall SDG score improvement of 9.33 points compared to the Reference pathway (Fig. 3).

In addition, total CO_2 emissions and mitigation costs are critical indicators to weigh the effectiveness of CMPs. By 2060, the best CMP (EE_{mature}, $EM_{1.5\,°C}$, $LULUCF_{1.65}$, and $CCS_{4.2}$) in CO_2 emissions achieved negative emissions (-4.59 $GtCO_2$) and allowed for a cumulative total of 14.95 Gt in CO_2 emissions reductions from 2022 to 2060. The EE_{mature}, $EM_{NET\text{-}led}$, $LULUCF_{BAU}$, and CCS_{BAU} CMP performed best in mitigation cost at average \$0.09 trillion yr^{-1}, but also the worst CMP in CO_2 reduction with 3.22 Gt CO_2 emissions in 2060 (Supplementary Fig. 5).

Considering the sustainability, CO_2 emissions, and economic pressure, we developed an SDG-emissions-cost index (overall performance of SDGs, CO_2 emissions, and mitigation cost) and calculated the performance of the 9 original CMPs and 180 bundled CMPs on a scale of 0–100 (Methods). The projected SDG-emissions-cost index scores of the 9 original CMPs ranged from 42.47 to 69.09 points by 2060, with the best performer of the *Updated NDC to Carbon Neutrality* CMP and the worst performer of the *Below 2 °C* CMP. Compared to the 9 original CMPs, the 180 bundled CMPs presented a broader range of the SDG-emissions-cost index scores from 9.11 to 76.15 points by 2060 (Fig. 3).

Based on the SDG-emissions-cost index, we identified the EE_{mature}, $EM_{RE\text{-}led}$, $LULUCF_{1.65}$, and CCS_2 CMP to be the cost-effective CMP as it dealt with the trade-offs among sustainability, CO_2 emissions, and economic cost, and maximized the synergies between them. As a result, the cost-effective CMP had the highest SDG-emissions-cost index at 76.15 by 2060, with an improvement of 19.90 points compared to the average of the 9 original CMPs assessed (Fig. 3). More specifically, the cost-effective CMP made the most remarkable progress towards overall SDG score (80.08), exceeded the carbon neutrality goal with -2.22 Gt in CO_2 emissions in 2060, and incurred a mitigation cost of average \$0.36 trillion yr^{-1} from 2022 to 2060. (Fig. 3, Supplementary Fig. 5). This cost-effective CMP performed relatively modestly against several SDGs in 2030 including infrastructure-related (SDG9) and climate-related goals (SDGs 12 and 13). However, these modest performances were reversed by 2060. Finally, the cost-effective CMP performed better across the individual SDG scores than almost all of the 9 original CMPs except the water-related goal (SDG6) by 2060 (Supplementary Fig. 6). The reason is that the cost-effective CMP with a more rational and ambitious combination of the usage of negative emissions technologies and renewables significantly reduced greenhouse gas and $PM_{2.5}$ emissions with affordable cost and then obtained greater gains towards achieving SDGs, but at the expense of increased water withdrawal in the long term.

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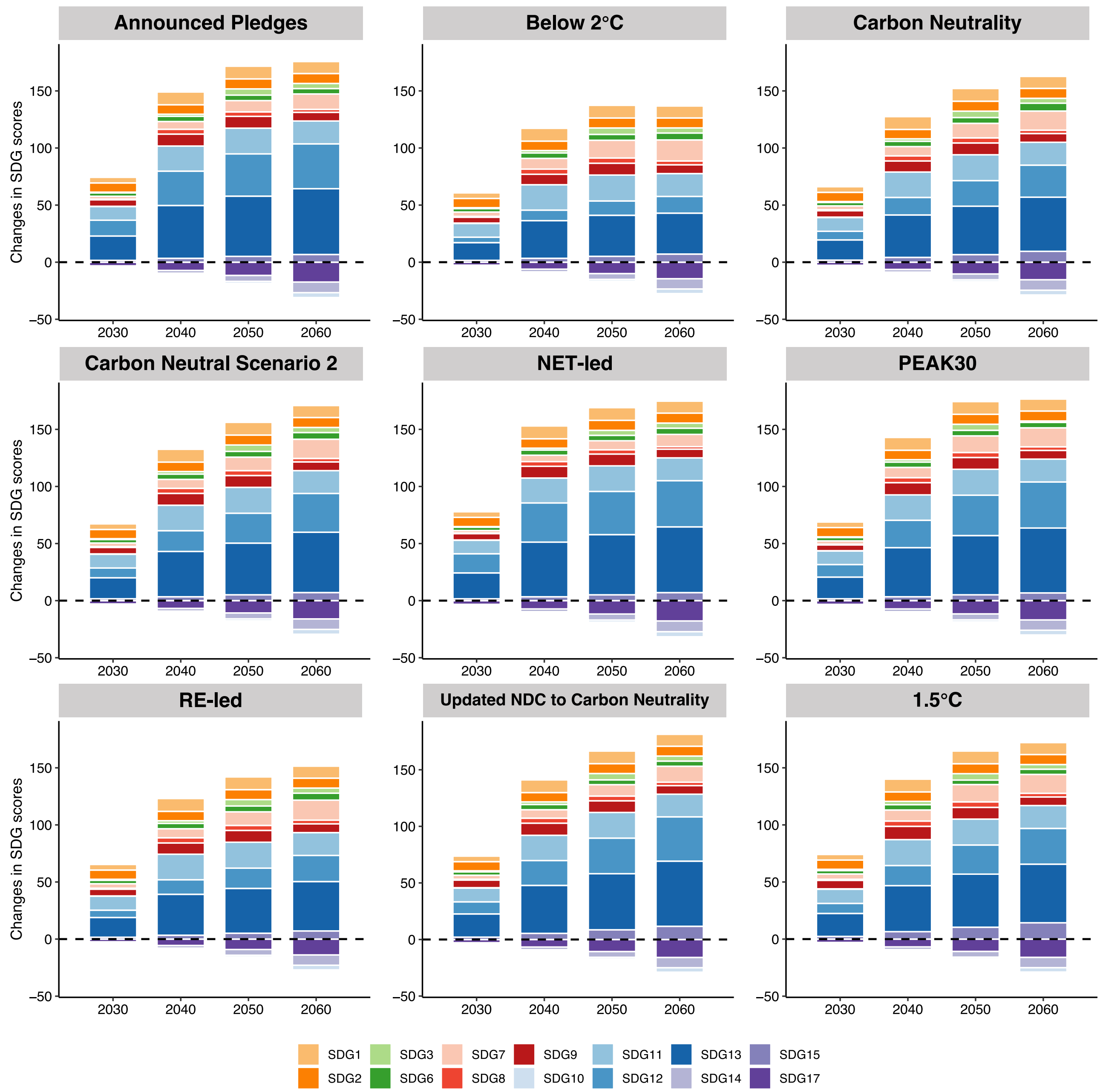

Fig. 2 | Performances of CMPs against individual SDGs by 2030, 2040, 2050, and 2060. In each plot, colored bars represent the absolute changes in related SDG scores between the corresponding CMP and the Reference pathway. This figure does not show three goals (SDGs 4, 5, and 16) where the individual SDG score changes were small (between −1 to 1).

Uncertainty analysis

To analyze the effects of policies and socioeconomic outlook uncertainties on CO_2 reduction and SDGs, we further assessed the CO_2 emissions projections and SDGs performance under the 9 original CMPs and the cost-effective CMP with different energy efficiency levels under the five tSSPs (Supplementary Methods, Supplementary Table 7). Under different energy efficiency levels and five tSSPs, the ranges of SDGs performance, SDG-emissions-cost index, and CO_2 emissions are observed in Supplementary Figs. 7–10. By 2060, our results show that the *Updated NDC to Carbon Neutrality* CMP was still the best option among the 9 original CMPs with an overall SDG score of up to 82.31, but the cost-effective CMP performed better than all 9 CMPs with an overall SDG score up to 82.84. For the five tSSPs, the "sustainability" socioeconomic future (tSSP1) had the best performance in overall SDG scores, while the "regional rivalry" socioeconomic future (tSSP3) performed worst (Supplementary Fig. 7, Supplementary Discussion). Additionally, the cost-effective CMP still had the highest SDG-emissions-cost index compared against the 9 original CMPs by 2060, with scores of up to 85.76, 85.94, 82.56, 84.70, and 85.30 points under tSSP1, tSSP2, tSSP3, tSSP4, and tSSP5, respectively (Supplementary Fig. 8).

Discussion

Using the iSDG-Climate-China model, we quantified the co-benefits and trade-offs between CMPs (9 original CMPs and 180 bundled CMPs) and SDGs for China, and assessed China's climate actions and SDG achievement, providing guidance to advance progress towards long-term sustainability and climate mitigation. Our research

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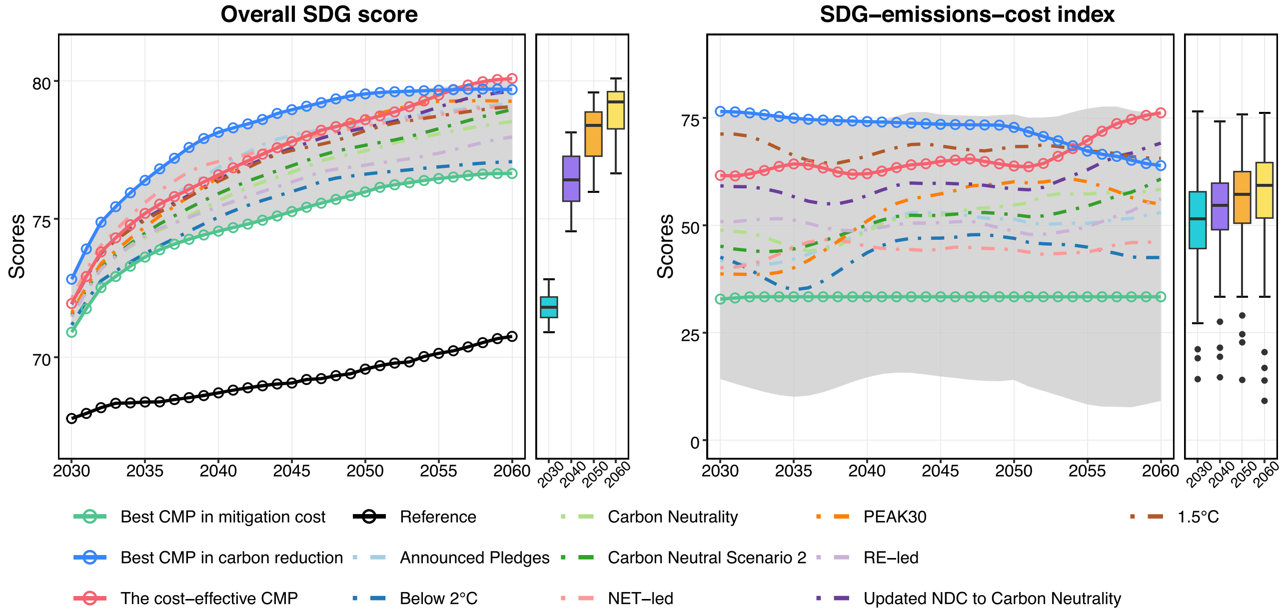

Fig. 3 | Performances of the bundled CMPs in overall SDG score and SDG-emissions-cost index from 2030 to 2060. The gray shading indicates the score range of all CMPs (180 bundled CMPs and 9 original CMPs) over time. The boxplots indicate value distributions of all CMPs in 2030, 2040, 2050, and 2060.

complemented the literature in this area in various ways. First, by modeling complex interlinkages between climate mitigation and SDGs and calibrating against China-specific historical data, we updated the core iSDG model to provide a deeper understanding of those dynamics at the national level. Second, by considering multi-sectoral linkages covering economy-social-environment systems, we provided more comprehensive insights for understanding the spillover effects of climate actions on a wide range of SDG indicators. Third, we systematically analyzed the impacts of the CMPs with different mitigation technological characteristics on SDGs, CO_2 reduction, and mitigation cost; and then identified a cost-effective CMP to trigger multi-system transformations towards a sustainable and low-carbon future.

Our analysis supports the view that mitigation can significantly promote SDG achievement, resulting from the synergies between climate mitigation policies and SDGs outweigh the trade-offs between them (Figs. 1 and 2). First, the CMPs directly advanced several environmental goals (SDGs 6–7, 12–15) by reducing fossil fuel usage and greenhouse gas emissions and by improving natural area protection and afforestation. Second, heatwave slowdown and increased expenditure on climate adaptation could reduce natural disasters and improve the resilience of vulnerable people to climate-related shocks (SDG1). Third, advances in biofuels and low-emissions agriculture were be realized via the introduction of new technologies and knowledge, leading to improved and more sustainable agricultural production (SDG2). Fourth, decreased air pollution significantly reduced premature mortality associated with $PM_{2.5}$ exposure (SDG3). Finally, increased investments in clean, energy-efficient, and low-emissions technologies accelerated the development of reliable and sustainable infrastructure and industries (SDG9), and led to improved air quality in cities and hence improved the health of citizens (SDG11). These multi-sectoral synergies across several beneficial SDGs highlight that progress towards carbon neutrality can significantly impact sectors such as energy, climate action, poverty, infrastructure, and health, thereby contributing to the broader sustainable development of the country. A better understanding of these linkages can support collaboration among relevant government departments and contribute to the design of effective top-down mitigation and sustainable policies. Therefore, enhancing policy coherence across different governance departments can be key to accelerating the process towards achieving the SDGs. For example, climate hazards (e.g., floods and hurricanes) increase the exposure and vulnerability of China's lower-income communities and coastal cities, which can prevent energy accessibility and asset accumulation by affecting infrastructure services and chronically impact food security, health, and employment opportunities in the long term[38]. Overall, more effective climate mitigation actions need to be supported by cross-cutting climate response services and contribute to the development of multiple SDGs.

Conversely, there were major challenges to China's long-term climate action for inequality (SDG10), life below water (SDG14), and government fiscal deficit (SDG17). This is due to the economic cost of mitigation technology innovation and rollout at scale leading to a stagnant economic outlook, and thereby perpetuated the gap between the bottom and average incomes; and the government's financial tension leads to a reduction in expenditure on water and underwater life protection. Hence, efforts are required to address the trade-offs between mitigation and SDG10, SDG14, and SDG17 in China. Measures could be implemented to promote progress towards SDG10, such as creating new jobs to boost household incomes in deprived areas through participation in forest carbon offset markets and developing large-scale renewable energy projects[39], accelerating social security services and extending support for the lower income, and enhancing the implementation of national strategies (e.g., the Western Development Strategy[40]) to promote the narrowing of regional development gaps. Expanding marine exclusion zones and controlling wastewater from industrialization to strengthen water quality[21] can help advance SDG14. For SDG17, establishing a comprehensive climate finance system to share the mitigation cost through mobilizing more social and international capital to participate in carbon emissions reduction, as well as expanding and improving the carbon trading scheme and carbon pricing policies[41,42] could counter the trade-offs of climate change mitigation.

Our results indicated that the cost-effective CMP (EE_{mature}, $EM_{RE\text{-}led}$, $LULUCF_{1.65}$, and CCS_2) was the best CMP for balancing sustainability, CO_2 mitigation, and economic costs in China, resulting from the maximum value of the SDG-emissions-cost index, compared with the 9 original CMPs and other bundled CMPs. The cost-effective CMP could gain the direct benefit of CO_2 emissions (-2.22 Gt CO_2) and the co-benefits of SDG development (80.08 points of overall SDG score) under the relatively low mitigation cost of average \$0.36 trillion yr^{-1} by 2060.

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The cost-effective CMP in this study was identified by searching through a large policy space, i.e., 180 bundled CMPs designed based on 9 original CMPs. It emerged from a combination of three original CMPs, replacing the LULUCF and CCS policies of the *RE-led* CMP with those of the *1.5 °C* and *Updated NDC to Carbon Neutrality* CMPs, respectively. Compared against the 9 commonly used CMPs, such extensive scan of the syntheses of different CMPs could inform future policy directions in China's carbon neutrality and long-term sustainable development.

However, the implementation of the cost-effective CMP needs to overcome several technical and policy challenges for China. First, improving energy efficiency requires substantial financial investment and the collaboration among policy-makers, researchers, and engineers to promote technological breakthroughs for increased efficiency in energy consumption. Second, the transition from a fossil-fuel-dominated energy mix to a renewable energy-led one requires coordinated support from different supply (e.g., power generation) and end-use sectors (industry, transportation, service, agriculture, and building) to prevent lagging sectors from impeding emissions reduction efforts. Finally, the deployment of bioenergy with CCS demands even more flexibility in matching biomass stocks, existing coal power plants, electricity demands, and carbon storage potentials[43]. However, evidence suggests that the deployment of CCS is still some way off in China[44], and our analysis further stresses that China needs to accelerate the deployment of CCS. Notably, this cost-effective CMP sets ambitious objectives for both energy mix and negative emissions and implies that policy-makers should effectively manage the potential conflicts of water and land resources use among various mitigation policies. The conflicting interests of renewable energy, especially for wind and solar energy, and negative emissions technologies on water and land use under limited resource conditions need to be addressed with caution. Otherwise, the conflicts could crowd out water and land for agriculture and jeopardize food security[45–47]. Moreover, the installed capacity of new coal-fired power plants has increased significantly in the last two years to safeguard electricity demand (about 218 GW of new coal-fired power plants have been permitted since 2022)[48], which implies that there is a mismatch between short-term needs and China's long-term carbon-neutral policy because of an over-prioritization of current challenges. Therefore, we suggest that China's short-term decisions should be compatible with the cost-effective CMP because of its remarkable co-benefits in sustainability.

Due to the limited scope of the iSDG-Climate-China model, there exist several limitations to our work. First, the CMP scenarios only partially cover future uncertainties. For example, they did not consider carbon trade schemes, carbon pricing policies, or transnational climate financing. Therefore, a key task going forward is to incorporate the interactions around present carbon price effects on the levelized cost of electricity and carbon emissions to improve the iSDG-Climate-China model. Second, when measuring mitigation costs, we considered key mitigation technologies such as renewable energy and negative emission costs. A more comprehensive estimation of the cost of mitigation technologies covering low-carbon energy, energy efficiency, energy access, and carbon removal costs, would provide further insights. Third, we only considered the dominant type of carbon sink in China, i.e., forests sink (LULUCF policy), in the future more specific analysis of other types of carbon sink such as soil and ocean would better reveal the diversified mitigation patterns. The iSDG-Climate-China model is designed to capture the nonlinear influence mechanisms from policies (i.e., CMPs) and exogenous assumptions about impacts (i.e., SDGs) in what-if style scenario projections. Therefore, simulation results should not be considered as precise predictions of the impacts of future climate mitigation, as this exceeds the capability of the iSDG-Climate-China model. Nonetheless, this assessment can inform forward-looking actions for policy-makers to maximize the synergy between the carbon neutrality goal and long-term sustainable development in China.

Finally, the iSDG-Climate-China model provided a general framework for analyzing the impacts of the mitigation policies on the SDGs at the national scale, and thus can be adapted for other countries through the calibration and customization process. Considering that the UN SDGs is a global initiative, future research should explore the SDG implications of potential CMPs at an aggregated global scale, which could be achieved based on some global-scale tools such as CMIP6[49] and FeliX[50].

Methods

Overview of the model

Core iSDG model. The core iSDG model, developed by the Millennium Institute, is a broad and integrated system dynamics tool to support long-term national policy design, testing, and monitoring. It is built upon the Threshold 21 (T21) model[51], which has been applied by over 40 countries and has evolved over 20 years through research and application[52–54]. The core iSDG model has a stock-and-flow structure and is codified as interrelated differential equations, which can capture complex linkages with time delay, non-linear behavior, and multi-component aggregation (e.g., the population is divided into 101 age cohorts and 2 genders). As a result of the variety of domains covered, the core iSDG model is a large volume model comprising 30 sectors (10 economic sectors, 10 social sectors, and 10 environmental sectors), and includes a large number of variables covering 78 SDG indicators and all 17 SDG goals. The structure of the individual sectors is based on well-established research, and modeling logic is consistent with domain specifications and common sense in real systems[36]. All sectors are dynamically interacting, and thus policies targeting specific sectors have cross-sectoral impacts that spread throughout the model via several thousand non-linear links, which can help enhance the understanding of intrinsic linkages and complexities across SDGs. In addition, the time horizon for simulation starts in 2000 and can be extended to 2030 or beyond. To some extent, the core iSDG model is well suited for policy analysis and comparative assessment of alternatives about SDGs, given its integrated nature and broad SDG coverage, as confirmed in a comparative study of modeling tools[55]. We presented key interactions among 30 sectors in Supplementary Fig. 11. The details of the assumptions and formulations used in each sector, and user guide of iSDG model can be found in the iSDG documentation[36], and the full core model can be shared by the Millennium Institute upon request for research purposes.

The iSDG model has the flexibility to be customized for different countries through historical data calibration, and several national studies that applied the iSDG model have been published such as Australia[23], Ivory Coast[56], and Tanzania[57].

iSDG-Climate-China model. To assess the impacts of climate mitigation policies on SDGs in China, we developed an updated iSDG model tailored specifically for China climate change mitigation (iSDG-Climate-China). The improvements we have made to the core iSDG model fall into the following three categories. First, we integrated additional links about the impacts of climate mitigation policies on various sectors into the model, for example, CCS impacts on carbon emissions, biomass yield, economic cost, and water withdrawal, as well as $PM_{2.5}$ atmospheric concentration impacts on $PM_{2.5}$-related premature mortality. These newly created cross-sectoral links are visually represented in Fig. 4, with detailed calculations of the corresponding causal relationships provided in Supplementary Methods. These new links are based on well-developed research and hold applicability beyond China, offering insights for other countries or economies. Second, to provide a broader and more accurate evaluation of SDG performance, we expanded the SDG evaluation framework to include 17 goals, 51 targets, and 98 indicators. Third, we customized the model to align with the unique context of China and to reflect the historical trends of China's economy, society, and environment by further calibrating the model against a large set of main variables.

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The iSDG-Climate-China model is established upon the core iSDG model. Similar to the core iSDG model, Cobb-Douglas production functions are used to determine economic production in agriculture, industry and services. Endogenous total factor productivity includes drivers such as education, health, governance, infrastructure, and climate change. The energy and emission-related sectors are particularly relevant for assessing CMPs impacts in this study (Fig. 4). The energy consumption module covers drivers of national final energy demand from agriculture, industry, services, residential, transportation, and other uses. The electricity generation sector simulates total production from fossil fuels, nuclear, hydropower and other renewable sources to meet future electricity demands. The choice of the type of capacity to be constructed depends on the levelized cost of electricity, additional subsidies, and renewables expenditure. The energy supply sector represents primary energy supply of gas, oil, coal, biomass, and electricity, calculated through a demand-driven approach. The emissions calculation is based on fossil fuel consumption and physical conversion factors. In this study, policies that made up the CMPs were implemented by setting the corresponding parameters or variables, as presented in Fig. 4. Specifically, the energy efficiency policies were implemented by changing energy emission factors, material use efficiency and government expenditure; the energy mix policies were worked through energy-related strategies in the power sector and the end-use sectors; and the negative emission policies were realized via financial inputs for afforestation and the use of capture technologies such as CCS, which ultimately affected all aspects of long-term environmental and socioeconomic development via dynamic cross-sectoral feedbacks. In addition, the values and influence paths for the parameter inputs are provided in Supplementary Table 8 and Supplementary Discussion SI2.1, respectively. The simulations with the iSDG-Climate-China model were conducted using the system dynamics modeling language in Stella Architect software[58] (version 3.0.0).

Building upon the fundamental structure of core iSDG model and the modeling introduced for climate and China, the resulting iSDG-Climate-China model provides a comprehensive framework to analyze the interactions of the SDGs, and to estimate the impacts of different climate mitigation policies on these SDGs.

Indicator selection. The SDG evaluation framework that was incorporated into the iSDG-Climate-China model contains 17 goals, 51 targets, and 98 indicators (Supplementary Table 9). We established 98 indicators with reference to the United Nations' official list in 2030 Agenda[59], the Sustainable Development Report[20], initial indicators included in the Millennium Institute's iSDG model[23], and the scientific literature[31,32] following three selection rules. First, the selected indicators must be consistent with the need for sustainable development in China and can be measurable. Second, the selected indicator must be quantifiable in the iSDG-Climate-China model. Third, the selected indicators must be able to estimate the quantitative achievement thresholds for measuring SDGs.

Model calibration. We assessed the iSDG-Climate-China model's validity through two general validation procedures for system dynamics models called structural and behavioral tests[60]. Structural tests assess the validity of the model structure by comparing it with knowledge about real systems. Informed by expert reviews and scientific literature, we reviewed the mathematical equations and logical relationships in the iSDG-Climate-China model to ensure that the model structure was realistic and reflected empirical evidence. Next, we used a behavioral test (i.e., fit to historical data) to assess whether the model could reproduce the China's developments over the last two decades. We calibrated a large number of variables from the iSDG-Climate-China model based on the historical time series from 2000 to the most recent year available. Supplementary Fig. 13 and Supplementary Tables 10 and 11 show the goodness-of-fit statistics for simulated and actual data of 56 SDG indicators whose historical data is available and 16 main macro-variables using plotted graphs and error statistics (coefficient of determination, mean error, root mean squared error, mean absolute error, mean percentage error, mean absolute percentage error, and percentage deviation). Historical data are sourced mainly from international and Chinese government official databases, such as the Food and Agriculture Organization of the United Nations, the World Bank, the International Monetary Fund, the International Energy Agency, the China Statistical Yearbook. See Supplementary Discussion SI2.3 for more details about the data use in the iSDG-Climate-China model.

Scenario framework

Scenarios were constructed to be used as iSDG-Climate-China inputs through to 2060, each of which represented a possible future projection including a certain CMP and socioeconomic development assumptions. In this study, we developed 189 CMPs, including 9 original CMPs and 180 bundled CMPs. The Reference pathway was a continuation of the historical trends without additional policies and changes. The construction of the 9 original CMPs, 180 bundled CMPs, and the socioeconomic development assumptions are provided as follows.

CMP selection and description. Recently, several influential universities, institutions, and think-tanks have proposed various CMPs for China that are consistent with the Paris Agreement goals and China's carbon neutrality pledge, which were published in the form of journal articles and synthesis reports. Those CMPs provided insights into the supporting policies and decarbonization strategies needed to realize China's carbon reduction goals. Based on that, we selected 9 commonly used CMPs following four rules: (1) The CMP should focus on China's long-term (by 2050 or 2060) actions for low carbon development for meeting the 1.5 °C (2 °C) temperature target, or carbon neutrality pledge; (2) The CMP should contain three key pillars of policies for carbon reduction (improving energy efficiency, accelerating the transition of the energy mix [including multiple end-use and energy supply sectors], and promoting the use of negative emissions technologies[42,61,62]); (3) The CMP can be derived from published and widely used scientific literature or authoritative organization reports; (4) The CMP can be implemented quantitatively in the iSDG-Climate-China model.

Advanced technologies (energy efficiency policy) and innovation in renewables (energy mix policy) are the critical backbone of carbon reduction[42,63]. Negative emissions in the past have been used as backup resources, which are anticipated to be an important pillar in a future carbon-neutral world[64]. In this study, a coherent set of policies that made up the CMP were divided into three types: energy efficiency, energy mix, and negative emissions. The energy efficiency policy included all measures related to benefits generated per unit of energy input. The energy mix policy was mainly related to the power sector and end-use sectors, which contained specific policies such as the share of non-fossil fuels in electricity generation, the electricity generation capacity of different primary energy, electrification in final energy consumption, and final energy consumption of different energy sources. The negative emissions policy included carbon removal by LULUCF and CCS (both conventional fossil fuel and bioenergy). Among 9 original CMPs, all energy mix-related, and negative emission-related policy settings were taken from the text or images in the corresponding journal articles and reports. While for the energy efficiency policy, we qualitatively set energy efficiency as "Mature" in the future based on the descriptions and expectations of energy efficiency in the corresponding journal articles and reports, because there was no uniform and specific definition of energy efficiency in different studies. The settings and details of all policies across energy efficiency, energy mix, and negative emissions for the 9 original CMPs are presented in Supplementary Table 4.

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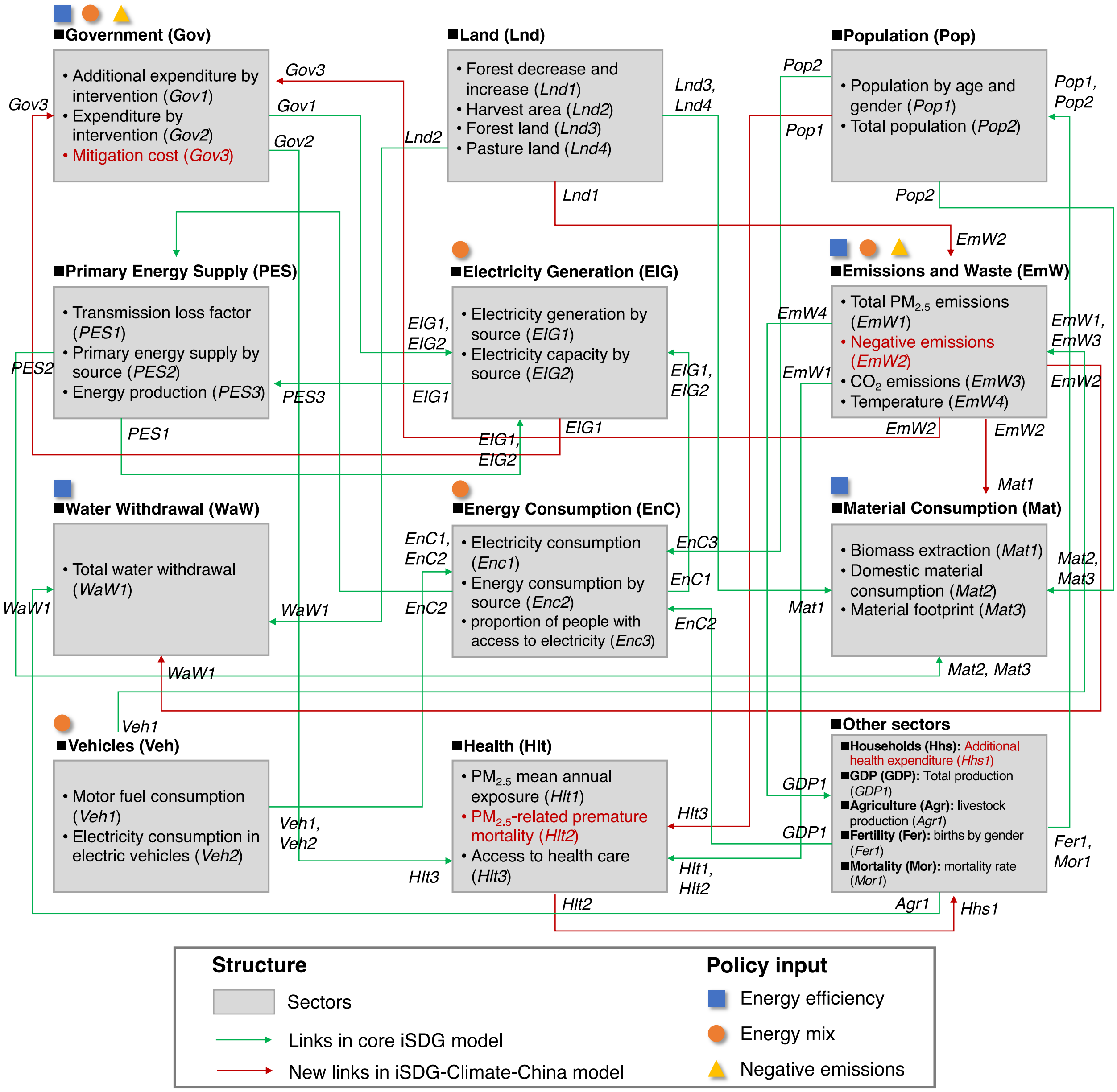

Fig. 4 | Overview of key sectors relevant to climate mitigation in the iSDG-Climate-China model. Gray boxes represent different sectors in iSDG-Climate-China model. Bolded black text presents the names of sectors, with the official abbreviation in the iSDG documentation[36] of each sector in parentheses. The italicized characters in parentheses denote the proxy symbols for the variables in the corresponding sectors. Each sector is linked with multiple directly connected variables, and each line with arrow connects two variables from two sectors, which indicates that the variable at the end point is affected by the variable(s) at the starting point(s) of the line. New variables and cross-sectoral links added to the core iSDG model in this study are shown in red. For example, the negative emissions (*EmW2*) variable of Emissions and Waste (EmW) sector affects the mitigation cost (*Gov3*) variable of Government (Gov) sector. See Supplementary Methods SI1.1-SI1.8 and Supplementary Fig. 12 for more details about the newly added links in the iSDG-Climate-China model.

Some of the CMPs had inconsistent policy end times, for example, the *Below 2 °C*, *PEAK30*, and *1.5 °C* CMPs focus on mid-term (2050) outlooks, but the rest CMPs give the long-term pathway by 2060. We extended the policies of these three CMPs (*Below 2 °C*, *PEAK30*, and *1.5 °C*) to 2060, following a linear trend from 2022 to 2050 to ensure temporal consistency between CMPs.

Constructing bundled CMPs. We identified four policy clusters including energy efficiency, energy mix, LULUCF, and CCS, which were mutually independent. Each policy cluster consisted of a set of policies representing different levels of ambition (Supplementary Table 5). Policies in each policy cluster were mutually exclusive and originated from the 9 original CMPs. Specifically, the energy efficiency policy cluster had only one policy level at "Mature", resulting from the positive predictions of all 9 original CMPs for energy efficiency improvements. The energy mix policy cluster had 9 policy levels that originated from the 9 original CMPs, respectively. The LULUCF policy cluster included four policy levels at "BAU", 1.05 $GtCO_2$, 1.3 $GtCO_2$, and 1.65 $GtCO_2$, which followed the historical trend, *Carbon Neutrality* CMP, *Updated NDC to Carbon Neutrality* CMP, and *1.5 °C* CMP, respectively. The CCS policy cluster included five policy levels at "BAU", 0.94 $GtCO_2$, 2 $GtCO_2$, 3.22 $GtCO_2$, and 4.2 $GtCO_2$, which were informed by the historical trend, *Carbon Neutrality* CMP, *Carbon Neutrality* CMP, *Announced Pledges* CMP, and *NET-led* CMP, respectively. By combining policies from distinct policy cluster[65], we derived 180 ($1 \times 9 \times 4 \times 5$) bundled CMPs that were formed by selecting one policy from each policy cluster (Supplementary Fig. 1, Supplementary Table 5).

Socioeconomic development. The Shared Socioeconomic Pathways (SSPs) are the commonly used conceptual framework to design long-term plausible trajectories of socioeconomic development, which consist of both qualitative narratives and quantitative attributes. Content for the SSPs is developed in a range of assumptions across six elements including demographics, human development, economy & lifestyle, policies & institutions, technology, and environment & natural resources[37]. In this study, we removed several assumptions in the structural framework of SSPs that duplicated or conflicted with the climate mitigation policies such as carbon intensity, energy intensity, fossil constraints, and land use, thereby constructing five tailored shared socioeconomic pathways (tSSPs) (Supplementary Table 7) to depict China's future socioeconomic development pathways.

Calculating SDG scores

Normalizing SDG indicators, targets, and goals. In order to make the performance across different indicators comparable, the SDG indicator values are normalized to a standard scale ranging from 0 (worst performance) to 100 (best performance) as following based on the Sustainable Development Report[20]:

$$Ind_{i,j,k} = \frac{x_i - Low(x_i)}{Up(x_i) - Low(x_i)} \times 100, \quad (1)$$

where $Ind_{i,j,k}$ represents the normalized value of indicator *i* for target *j* and SDG *k*; x_i demotes the simulated value of indicator *i*; and $Low(x_i)$ and $Up(x_i)$ are the lower bound and upper bound of indicator *i*, respectively. If x_i is a positive indicator, $Low(x_i) < Up(x_i)$; and if x_i is a negative indicator, $Low(x_i) \geq Up(x_i)$ (Supplementary Table 9). If the simulated indicator value is worse (better) than its lower bound (upper bound), an indicator value of 0 (100) is given. Notably, we followed the official SDG evaluation framework of the United Nations[20,59] to collect positive indicators and negative indicators, without considering other forms of SDG indicators.

The lower bound of each indicator was set following three steps: (1) We adopted the lower bound used in the Sustainable Development Report[20] and scientific literature; (2) The lower bound was defined as the bottom 2.5th-percentile performer[20,21]; (3) For the remaining indicators, we set lower bound equal to the worst performer of China's historic data (2000–2015). In terms of upper bound, our method was similar to the approach used in the Sustainable Development Report using a five-step decision tree[20]: (1) We used relevant absolute quantitative thresholds, such as 'no poverty'; (2) Adopting the UN's principle of *leaving no one behind* to set the value of upper bound such as "measures of ending hunger"; (3) Using the upper bound in the Sustainable Development Report[20] and scientific literature; (4) The upper bound was defined as the average of top five or three performers; (5) Setting a reasonable percentage increase from the 2015 baseline based on the historical trends or experience. When determining the lower bound and upper bound as described above, if the condition for an earlier step was met, then all of the later steps were skipped.

The method adopted for weighting and aggregating SDG scores is critical for evaluating progress towards sustainable development[66]. Currently, there is no consensus on the best way to aggregate SDG performance into a single indicator, as confirmed by SDG reports published by the UN Sustainable Development Solutions Network[67]. In this study, the overall SDG score was calculated based on the stepwise arithmetic averaging across the SDG indicator system, which is widely employed in SDG scoring[20,21,23] and is in line with the concept of equal treatment of all goals in the SDG framework developed by the United Nations[1].

Specifically, the score of individual SDG target *j* was calculated as the average value of all the indicators that contribute to target *j* (Eq. (2)) and the score of SDG *k* was calculated as the average value of all the targets that contribute to the SDG *k* (Eq. (3)) based on the Sustainable Development Report[20].

$$Tar_{j,k} = \sum_{i=1}^{N_j} \frac{Ind_{i,j,k}}{N_j}, \quad (2)$$

$$SDG_k = \sum_{j=1}^{N_k} \frac{Tar_{j,k}}{N_k}, \quad (3)$$

where $Tar_{j,k}$ denotes the value of target *j* for SDG *k*, N_j denotes the number of assessment indicators used for target *j*, SDG_k represents the scores of SDG *k*, and N_k is the number of assessment targets for SDG *k*.

Finally, the aggregated SDG score (or *overall SDG score*) was calculated as the arithmetic mean of the individual SDG scores, which represents China's overall achievement towards SDGs. A higher score indicates a better performance towards achieving SDGs.

Calculating the SDG-emissions-cost index

The SDG-emissions-cost index represents the comprehensive performance of overall SDG score, CO_2 emissions and mitigation cost. First, the values of overall SDG score, CO_2 emissions, and mitigation cost of CMPs were rescaled from 0 (worst performance) to 100 (best performance) as following:

$$SEC_{SDG,p} = \frac{SDG_p - \min(SDG)}{\max(SDG) - \min(SDG)} \times 100, \quad (4)$$

$$SEC_{C,p} = \frac{\max(C) - C_p}{\max(C) - \min(C)} \times 100, \quad (5)$$

$$SEC_{MC,p} = \frac{\max(MC) - MC_p}{\max(MC) - \min(MC)} \times 100, \quad (6)$$

where $SEC_{SDG,p}$ ($SEC_{C,p}$, $SEC_{MC,p}$) denotes the normalized score of overall SDG score (CO_2 emissions, mitigation cost) for the CMP *p*, max(*SDG*) and min(*SDG*) (max(*C*) and min(*C*), max(*MC*) and min(*MC*)) represent the maximum and minimum values of overall SDG score (CO_2 emissions, mitigation cost) of all CMPs, respectively. And the SDG_p (C_p, MC_p) demotes the simulated value of overall SDG score (CO_2 emissions, mitigation cost) of the CMP *p*. Lower CO_2 emissions (mitigation cost) results in higher normalized score. Finally, the score of the SDG-emissions-cost index ranging from 0 (worst) to 100 (best) was calculated as the average value of normalized overall SDG score, normalized CO_2 emissions score, and normalized mitigation cost score.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data that support findings of this study are provided in Supplementary Information. Additional data including calibration datasets, input data, and output projections are available in the public repository (https://doi.org/10.5281/zenodo.13892796).

Code availability

The core iSDG model is owned by the Millennium Institute and can be made available from the Millennium Institute for research purposes on request. The custom codes built in this study and the codes for figure visualizations are available in the public repository (https://doi.org/10.5281/zenodo.13892796).

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Author contributions
L.G., Z.G., Y.D., E.A.M., and B.A.B. conceived and designed the study. M.C. and M.P. developed the iSDG-Climate-China model used in this study. M.C. and M.P. calibrated the iSDG–Climate-China model. M.C., L.G., Z.G., and Y.D. developed scenarios and conducted the results analysis. M.C. created the figures and tables. M.C., L.G., Z.G., and Y.D. prepared the manuscript. M.C., L.G., Z.G., Y.D., E.A.M., Y.X., K.L., W.L., J.Y., W.X., M.P., and B.A.B. revised the manuscript. Y.D., Y.X., and B.A.B. supervised the work. M.C., L.G., and Z.G. contributed equally to the work.

Competing interests
We declare no competing interests.

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