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Provinces with transitions in industrial structure and energy mix performed best in climate change mitigation in China

Zhifu Mi [1✉] & Xinlu Sun [1✉]

China has announced its goal of reaching carbon neutrality before 2060, which will be challenging because the country is still on a path towards peak carbon emissions in approximately 2030. Carbon emissions in China did decline from 2013 to 2016, following a continuous increase since the turn of the century. Here we evaluate regional efforts and motivations in promoting carbon emission reduction during this period. Based on a climate change mitigation index, we pinpoint the leading and lagging provinces in emission reduction. The results show that achievements in industrial transition and non-fossil fuel development determined the leading provinces. Thus, the recommended solution for carbon neutrality in China is to promote the transformation of industrial structure and energy mix. In addition, policymakers should be alert to the path of energy outsourcing to reduce carbon emissions. Consumption-based emissions accounting and interregional cooperation are suggested to motivate developed regions to take more responsibility for climate change mitigation.

[1] The Bartlett School of Sustainable Construction, University College London, London, UK. ✉email: z.mi@ucl.ac.uk; xinlu.sun.20@ucl.ac.uk

Global society is facing a mounting crisis from climate change. Among the various resources causing climate change, the excessive emissions of greenhouse gases have placed both environmental stability and human health at risk. It is desirable that immediate and effective actions be executed to mitigate greenhouse gases[1]. To restrict greenhouse gas emissions and achieve sustainable goals, many countries have established national targets to deliver net-zero emissions in response to the Intergovernmental Panel on Climate Change's proposal. In conjunction, China recently announced its goal of reaching carbon neutrality before 2060. This appears to be a challenging goal, as China is still on its way toward reaching peak carbon emissions in approximately 2030.

As the largest developing country in the world, China's energy consumption and carbon emissions have increased dramatically since the turn of the century[2]. Economic development has had a strong export orientation and concentrated on the manufacturing and construction industries. Such development was based on high coal consumption, and in the 2000–2013 period, coal consumption almost trebled in China[3]. This development mode has not only brought hundreds of millions of Chinese people out of poverty but also produced various environmental and financial risks to society[2,4,5]. Overreliance on energy-intensive heavy industries led to a continuous increase in carbon emissions in the 2000–2013 period, and in 2006, China became the largest carbon emitter in the world[6–8]. In 2012–2013, China's government realized the need for structural change, and the country gradually entered a new development phase called the "new normal". Achieving higher-quality economic growth at a lower rate and achieving progress in environmental sustainability are the main targets in this period. Strategic adjustment along with changes in the macroeconomic structure has brought profound and progressive changes to China's industrial and energy structure[2]. With this change, China's carbon emissions experienced a temporary peak in 2013 and then decreased from 2013 to 2016 (see Supplementary Fig. 1).

Exploring the drivers of carbon-emission reduction between 2013 and 2016 will provide insightful information to help decarbonize economic development in China. However, only a limited number of studies pay attention to this period. Guan et al. evaluated the drivers of the temporary peak through decomposition analysis and found that the decline in carbon emissions is associated with changes in industrial structure and a reduced share of coal used for energy[9]. Green and Stern highlighted the top–down shifts in strategies and policies and deep and wide-ranging changes in the economic structure since China's "new normal" phase began[2]. As a result, the downward tendency in the economic growth rate has led to plateaus in China's carbon emissions. Emission reduction in energy-intensive sectors, production-efficiency improvement, and consumption-oriented shifts in the final demand structure were also identified as the main reasons for carbon-emission reduction in China[10]. Although several studies have pointed out the main drivers of China's carbon-emission peak, they were designed at a national level, and many researchers believe that analyzing regional climate performance is necessary due to the considerable heterogeneity across regions, especially in China[11].

Regional efforts at a subnational level hold an important role in mitigating climate change by reducing carbon emissions in China. Subnational actors, including regions and cities, have become increasingly critical in the climate-change mitigation process[12]. The Paris Agreement and United Nations Framework Convention on Climate Change also pay more attention to nonstate actors[13,14]. Furthermore, there is a consensus that carbon emission reduction at the regional level is vital if China is to meet its national climate targets[15–17]. Although the central government often develops a climate-change action plan and allocates climate goals, regions and provinces need to provide the details for the plan. In essence, they are adopting their own climate policies and mitigation plans. In addition, regional capacity to implement climate policies varies greatly. Demographic, fiscal, and natural resource characteristics differ greatly between different areas of China. Regional structure formulated by the different socioeconomic and geographical conditions is crucial to reduce carbon emissions and allocate reduction responsibilities[17]. Exploring regional performance and regional motivations for climate-change mitigation actions can provide insightful information to help China achieve its national climate goals. In addition, it is helpful to highlight the innovative climate-policy solutions adopted by those regions taking preliminary climate actions[12]. To avoid aggregation bias, which overlooks regional heterogeneity, many researchers analyze decarbonization efforts at a regional level. A regional-leveled study that explored seven socioeconomic drivers of changes in China's carbon emissions showed that China's carbon emissions have plateaued since 2012 due to energy-efficiency gains and structural upgrades[17]. Similarly, the multi-regional input–output tables for 2012 and 2015 for 31 provinces in China were constructed to evaluate the disparities in and drivers of the decarbonization of eight regions in China[18]. The southwest and central provinces are highlighted as the main drivers of emissions embodied in trade. Declining intensity and industrial structure were also found to be determinants of the consumption-based carbon-emission plateau in 2013. Focusing on the relationship between coal-related carbon emissions and economic growth from the provincial perspective in China, the economic growth of 18 provinces was shown to achieve a strong decoupling from coal-related emissions by 2016[19]. These studies quantified the impact of socioeconomic differences on regional carbon emissions and derived informative conclusions to help understand the drivers of carbon-emission changes in China.

However, a comprehensive assessment of regional climate-mitigation performance is still necessary to highlight the leaders and laggards in China's carbon-emission reduction during the carbon-reducing period from 2013 to 2016. Illustration of the leading and lagging provinces, and indication of the crucial factors driving regional performance can promote interregional cooperation and mutual learning[17]. As a global issue, the mitigation of climate-change risks requires regional cooperation and joint effort. One single region would be reluctant to take action in climate mitigation without effective measures in the surrounding areas due to the great externality of this issue. Therefore, evaluating regional efforts through a "naming and shaming" process could pinpoint the critical factors in carbon reduction at a provincial level and help to guide future policy packages toward peak emissions and carbon neutrality. The poor-performed provinces should be pointed out to get the urge for more efficient climate actions and additionally, the effective policies should be highlighted to facilitate the potential of promotion.

This study aims to evaluate regional performance in climate-change mitigation, especially in the carbon reducing period, and explore different regions' motivations and obstructions. The regional assessment is conducted using the climate-change mitigation index (CCMI)[15], which evaluates mitigation performance from four perspectives: emissions, efficiency, nonfossil fuel, and climate policy. The indicator "emissions" evaluates the current emission levels and recent emission changes, "efficiency" measures energy intensity and carbon intensity and their changes, "nonfossil energy" is the share of nonfossil energy to the total energy consumption, and the indicator "climate policy" compares provincial climate targets to reduce energy intensity and the actual performance. To explore the regional performance in different phases, this study applies CCMI to three-year windows

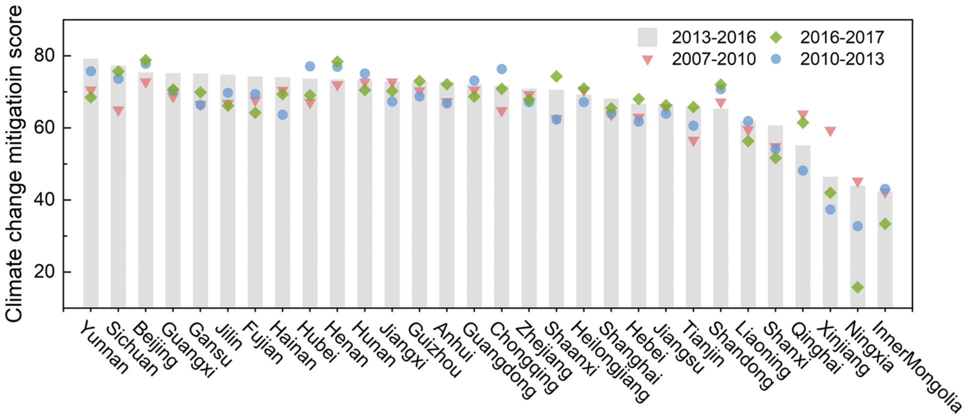

Fig. 1 Provincial climate-change mitigation performance from 2007 to 2017. The provinces are sorted according to the climate change mitigation index scores for the 2013–2016 period.

from 2007 to 2017 (except 2016–2017 due to data availability). The period is divided into four phases according to changes in national carbon emissions: a recovery period of financial crisis in 2007–2010, a period of stable growth in 2010–2013, a period of decrease in 2013–2016, and a rebound period in 2016–2017. The results indicate that achievements in industrial transition and nonfossil fuel development determined the leading provinces during the period of decrease in 2013–2016. Next, a fuzzy-set qualitative comparison analysis (fsQCA) is employed to explore the necessary and sufficient conditions for better performance in regional climate-mitigation actions. Four conditions that are assumed to correlate with regional climate mitigation motivations were employed: fossil fuel dependence, economic structure, resource endowment, and government budget. The recommended solution for a future emission peak and ultimate carbon neutrality in China is to promote the transformation of the industrial structure and the energy mix. In addition, the path of energy outsourcing to reduce carbon emissions is a warning for policymakers. Consumption-based emission accounting and interregional cooperation are suggested to motivate developed regions to take more responsibility for climate-change mitigation.

Results

Regional performance in climate-change mitigation. Regional performance across the assessment years varied greatly, which means that regional roles in affecting national climate-change mitigation differ between the years (Fig. 1). Generally, the four provinces and regions with the worst performance across recent years were Ningxia, Inner Mongolia, Xinjiang, and Shanxi. Remarkably, three of these regions are in northwestern China (see Supplementary Table 1), which reflects the geographical properties and structural differences between the diverse areas of China. For those with high performance, few provinces were able to maintain their high rankings during the assessment period, except for Beijing. The capital city of China, Beijing, was distinguished because it ranked 1st in 2007–2010 and 2016–2017 and 3rd in the other two periods. In general, Yunnan, and Sichuan achieved higher CCMI scores in recent years, but their performance was not stable.

Regional performances in the decreasing phase between 2013 and 2016 were the best across the decade. The average CCMI score in the period is 68.1, which is the highest of the four phases. The overall enhancement of climate-change mitigation efforts in all regions played a very important role in decreasing national carbon emissions. Beijing and several southwestern provinces (Yunnan, Sichuan, and Guangxi) made substantial contributions to national carbon-emission reduction as reflected in the CCMI scores in 2013–2016.

Regional performance in the four areas of climate-change mitigation. The regional performance in the field of “emissions” shows consistency with energy consumption, especially from the heavy industry and energy-production sectors. Several provinces demonstrate a leading role in controlling carbon emissions, accompanied by a low level of energy consumption per capita. For instance, Beijing, Yunnan, Guangxi, and Hunan show excellent performance in the area of carbon emissions for the whole period (Fig. 2a). Beijing has ranked in the top 2 since 2013 because it has achieved a continuing decrease in carbon emissions (Fig. 3). From 2007 to 2017, carbon emissions from industry and from electricity and heat production decreased by 84.7% and 24.8%, respectively, while the total carbon emissions in the region gradually declined by 17.4%. Although Guangxi’s contribution to overall climate mitigation was relatively modest in recent years (ranked 10th and 11th, except for 2013–2016), its energy consumption and carbon emissions per capita remained very low, i.e., 3.3–4.0 t CO_2 emissions and 1.57–1.87 t standard coal consumed per capita each year. Such advantages helped Guangxi achieve near-perfect scores in the corresponding indices. On the other hand, four provinces, characterized by rich-resource endowment, trailed the others by a large margin in emissions: Ningxia, Inner Mongolia, Xinjiang, and Shanxi. In Ningxia, carbon emissions and energy consumption from electricity and heat production and from industry increased dramatically in 2017, leading to 9.51 tons of standard coal equivalent consumed per capita and 25.7 tons of carbon emitted per capita. Ningxia thus received a zero in the two indices. As one of the main sources of electricity production and the energy industry, Inner Mongolia holds a considerable proportion of energy consumption and carbon emissions in China. The average energy consumption per capita increased from 6.81 to 7.87 tons of standard coal equivalent, and carbon emissions ranged from 0.19 to 0.25 Mt in the past decade, which led the province to obtain scores below 25. The energy self-sufficiency (the ratio of produced energy to consumed energy) of Shanxi, Xinjiang, and Inner Mongolia was above one in 2017. In addition, carbon emissions in most provinces were from industry, electricity, and heat production (Fig. 3). Specifically, the energy production and heavy-industry sectors accounted for a large proportion of the total carbon emissions[20,21].

Consistent with the overall CCMI performance, regional efforts in carbon emissions were extensively improved from 2013 to 2016 due to structural changes in the energy mix. In addition to Yunnan, Beijing, and Guangxi, Sichuan and Hainan showed excellent performance in carbon control. The reduction in carbon emissions in Sichuan was mainly from coal mining and dressing and from electricity and heat production, being 8.9 Mt of CO_2 and 30.25 Mt of CO_2, respectively. In addition, Sichuan’s efforts to decarbonize

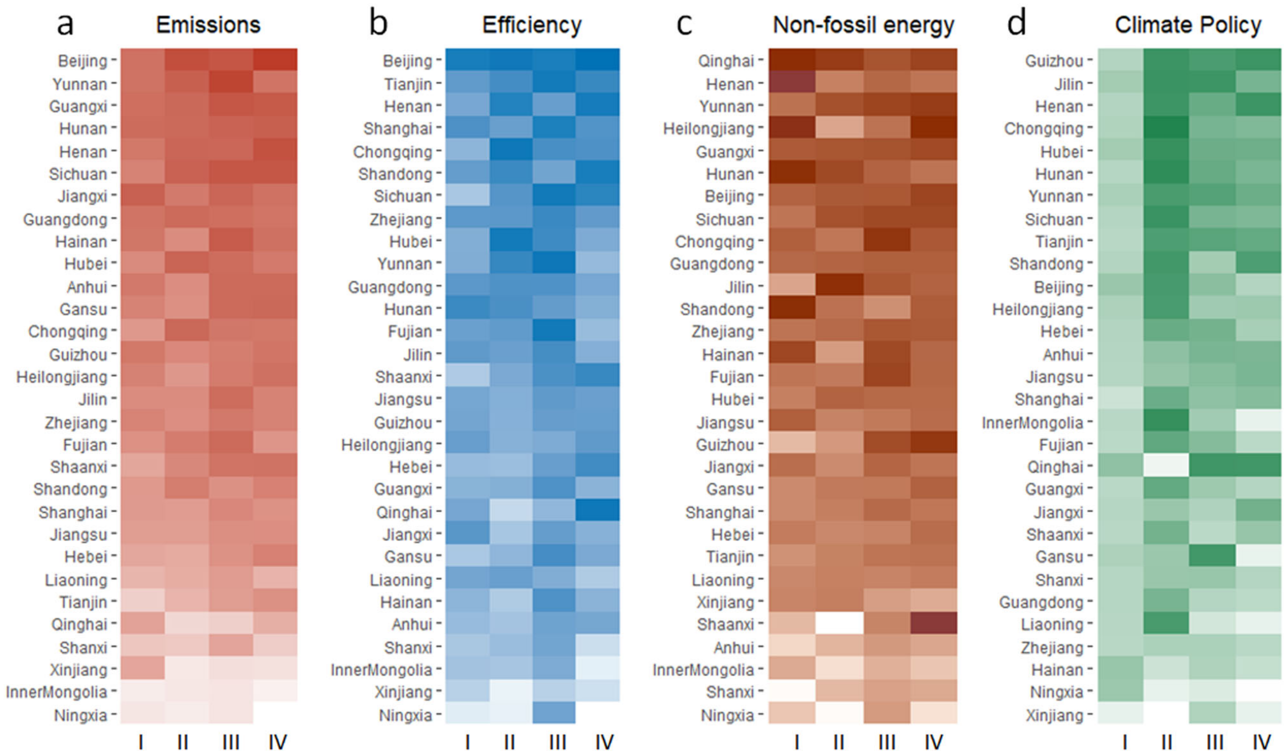

Fig. 2 Provincial climate change mitigation performance in the four fields from 2007 to 2017. I, II, III, and IV represent the periods of 2007–2010, 2010–2013, 2013–2016, and 2016–2017, respectively. Darker colors mean better performance, and lighter colors mean worse performance. **a** Climate change mitigation performance in emissions. **b** Climate-change mitigation performance in efficiency. **c** Climate-change mitigation performance in nonfossil fuel energy. **d** Climate-change mitigation performance in climate policy.

electricity production were remarkable. Primary electricity production in Sichuan was 202.3-billion kilowatt hours (Kw·h) in 2013 and increased by nearly half, to 302.1 billion kW·h in 2016. The carbon-emission reduction in Shanxi Province in 2013–2016 was the largest among all the regions; up to 39.2 Mt of carbon emissions were cut off in the province, accounting for 7% of the total national carbon reduction in the period. Carbon emissions from three sectors declined substantially in Shanxi, namely, 6.67 Mt in petroleum processing and coking, 4.06 Mt in coal mining and dressing, and 22.42 Mt in electricity and heat production. Unfortunately, most regions experienced a carbon-emission rebound in 2017. For example, the carbon emissions of Shanxi Province in 2017 rose to the same level as in 2013, 488 Mt of CO_2. In Yunnan, carbon emissions declined gradually by 12.7% from 2013 to 2016 but increased by 8.3% to 195 Mt of CO_2 in 2017. In line with the energy-structure changes at the provincial level, the national carbon-emission reduction from 2013 to 2016 was mainly from emissions embedded in raw coal use, while carbon emissions from oil and gas use continued to increase[9] (see Supplementary Fig. 2).

The results of the regional assessment for the "efficiency" indicator are correlated with economic development, which is quite different from the "emissions" results and the overall CCMI assessment (Fig. 2b). The three provinces with the highest gross domestic product (GDP) per capita were preeminent in improving energy efficiency, namely, Beijing, Tianjin, and Shanghai. Given adequate economic support and technological impact, the developed regions were capable of improving energy efficiency and thus showed excellent performance in this field. For instance, Beijing ranked 1st, 2nd, 5th, and 1st for its efficiency score in the four assessment periods. CO_2 emissions per ton of total energy consumption decreased from 1.48 tons to 1.19 tons, and the total energy consumption per unit of GDP of Beijing declined dramatically by 37.4% during this decade. Beijing was evaluated as a perfect model in terms of its low-energy density in 2017. Tianjin and Shanghai's efforts to improve energy efficiency were noteworthy, although they did rather moderate jobs in controlling their overall carbon emissions. Energy consumed per unit of GDP was reduced by 42.0% and 35.3% in Tianjin and Shanghai during 2007–2017, respectively. These provinces benefit from the structural transition in industrial development and have decoupled their economic development from coal use[19].

The less-developed regions in the northwest, especially Ningxia, Xinjiang, and Inner Mongolia, showed concerning performance in energy efficiency. Economic development in these provinces highly relies on fossil fuel consumption and carbon-intense industries. The energy sector represents a large proportion of total carbon emissions. In addition, economic backwardness in these regions impedes technological updates and thus weakens their capacity to improve energy efficiency. For example, approximately 73.2% of the total carbon emissions in Ningxia were from the energy sector in 2017. Simultaneously, Ningxia consumed 2.65 tons of standard coal per thousand yuan of GDP and emitted 2.70 tons of CO_2 per ton of energy consumed. The carbon intensity and energy intensity in Ningxia increased by 10.1% and 7.6% from 2016 to 2017, respectively, which led to zero scores for Ningxia's performance in efficiency improvement. The situations are similar in Xinjiang and Inner Mongolia, where the energy sector represents 63.1% and 73.5% of the total carbon emissions, respectively. Development in tertiary industry is important for these provinces to reduce the negative impact from the energy sector. In addition, regional cooperation, the promotion of regional balance, and technological support from developed regions are necessary for carbon-emission reduction at a national level.

The regions with advantages in "nonfossil energy" endowment and greater efforts toward an energy transition performed better in this field. In general, regional performance in nonfossil fuel

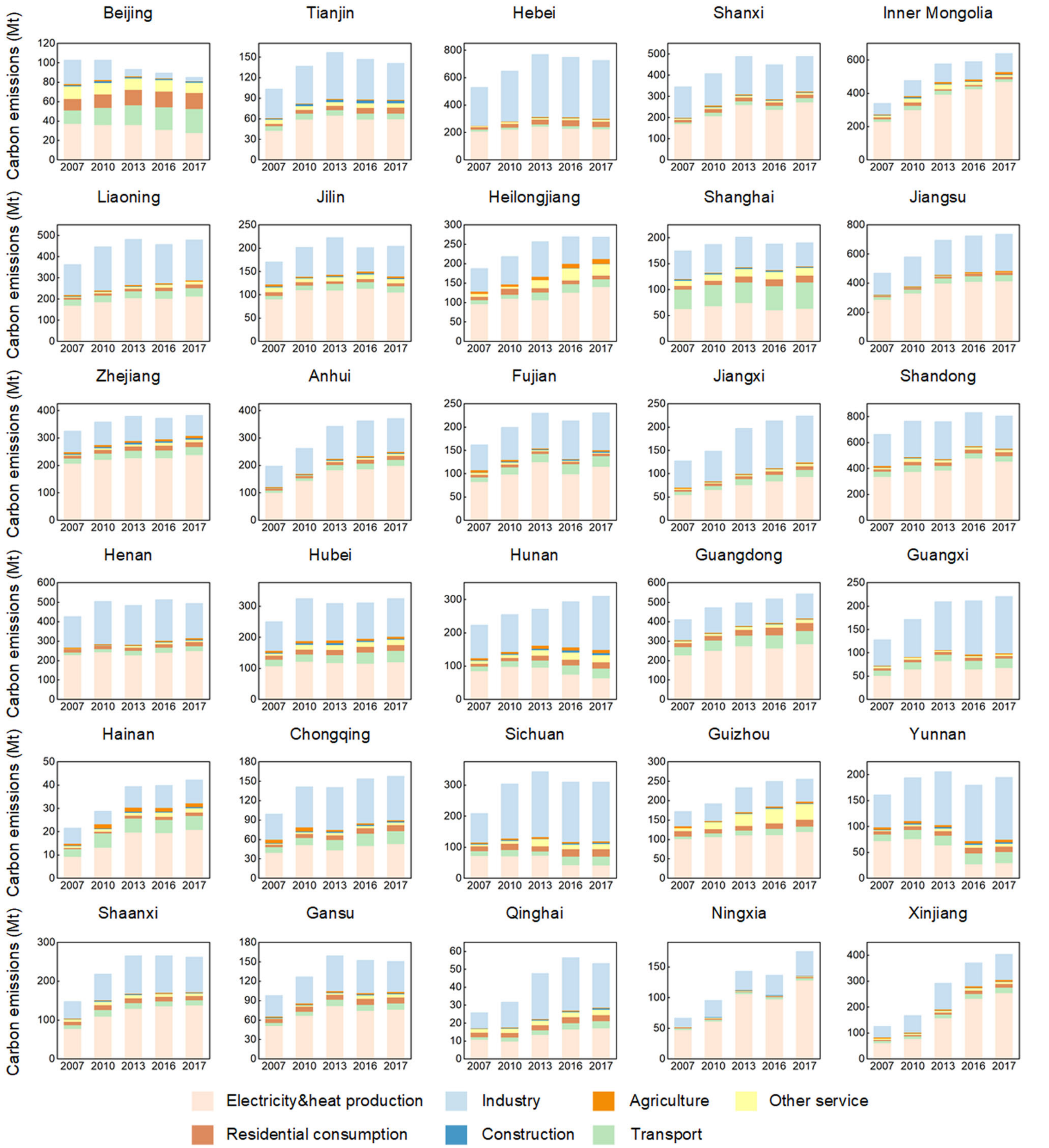

Fig. 3 Sectoral carbon emissions in the 30 provinces from 2007 to 2017. Pink, light blue, orange, yellow, brown, blue, and green represent carbon emissions in electricity and heat production, industry, agriculture, other services, residential consumption, construction, and transport sectors, respectively.

development was not consistent (Fig. 2c), which may reflect inconsistent effort in nonfossil fuel production and application in the regions. However, several provinces showed aggressive ambitions in nonfossil fuel development. Located in the northwest on a plateau, Qinghai is rich in solar power and hydropower. The nonfossil fuel supply in Qinghai is among the highest in China, and approximately 16.5% of the total energy consumption in Qinghai was from nonfossil fuels (according to calorific value calculation) in 2017. As a province in northwestern China, Qinghai can clearly be set as a model for other regions in the northwest for its ability to take advantage of the natural conditions and improve its nonfossil fuel supply. From 2013 to 2016, the proportion of nonfossil fuel supply to the total energy consumption in Chongqing and Fujian increased considerably, by 76.4% and 81.2%, respectively.

The regions with abundant fossil resources faced great obstructions in developing nonfossil fuel energy. As a typical energy-exporting province, Inner Mongolia did very poorly in promoting the local supply of nonfossil fuel. The production of nonfossil fuel is not low in Inner Mongolia, namely, 68.46-billion

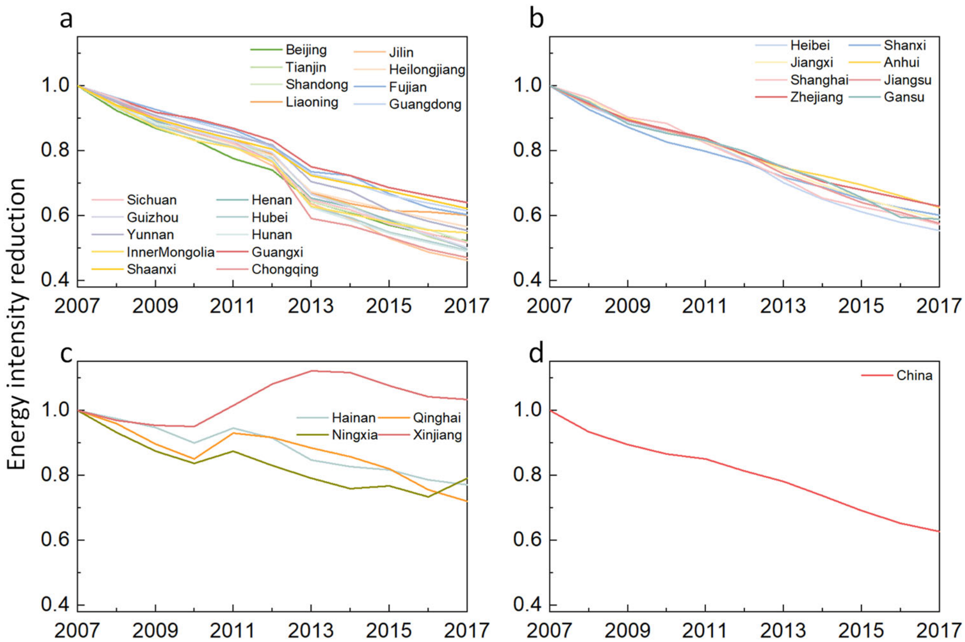

Fig. 4 Energy-intensity reduction during 2007–2017. Energy intensity in 2007 = 1. **a** Energy-intensity reduction experienced an acceleration in some provinces in 2013. **b** Energy intensity has been reduced continuously during 2007–2017 in some provinces. **c** Energy intensity increased in some periods in four provinces, namely, Hainan, Qinghai, Ningxia, and Xinjiang. **d** Energy intensity saw consistent reduction in China.

kW·h of primary electricity in 2017, but the region exported a large volume of electricity to other provinces and abroad, leading to a negative nonfossil fuel supply. It is clear that energy exporters suffer more stress in climate mitigation, while energy importers freely ride, in part, on the exporter. Regional cooperation is urgently needed to motivate both the supply side and the consumption side to invest effort in energy transition.

The regional performance in "climate policy" was quite different from performance in the previous indicators. Unlike the other indicators, where the highest scores were prevalent in 2013–2016, the greatest accomplishment in the four periods of energy-intensity reduction tasks occurred in 2010–2013 (Fig. 2d). From 2010 to 2013, the energy intensity of the 30 regions decreased by 6.2% per year. The dramatic rate of decline for this period, especially for 2013, was the highest over recent years (Fig. 4) and was due to a reduction in total energy consumption in 2013[22].

Most regions delivered a positive response to the national climate policy by casting off the energy dependence of economic development. Guizhou, Jilin, and Henan performed best in this field. From 2013 to 2016, energy consumption per unit of GDP in Jilin showed a rapid decline of 23.4%, which was the highest in China. In addition, Jilin showed the highest energy-efficiency improvement in the whole period from 2007 to 2013, with energy consumption per unit of GDP declining by 53.7%. The energy intensity in Qinghai and Gansu from 2013 to 2016 also declined substantially, by 14.5% and 20.5%, respectively.

By contrast, Xinjiang failed to optimize its economic structure and even showed heavier reliance on energy consumption. Before 2013, the energy intensity of Xinjiang increased by 12.2%, but it started to decline in 2013. Overall, energy consumption per unit of GDP in Xinjiang increased by 3.3% from 2007 to 2017.

Leaders in national carbon-emission reduction. The preliminary process of industrial and energy transition distinguished Beijing and its relatively stable achievements in CCMI. The continuously decreasing energy consumption and carbon emissions demonstrate Beijing's efforts in controlling emissions and enhancing energy efficiency. Beijing's carbon emissions per capita were 3.92 tons in 2017, among the lowest in China. Reduced carbon emissions in industry and agriculture also awarded Beijing 100 points in the corresponding indicators. Beijing took advantage of structural changes in its industry development[15]. The secondary industry represented 32.7% of Beijing's GDP in 2000. Given continuing efforts toward structural adjustment and investment in tertiary industry, the proportion of the secondary industry to GDP in Beijing shrunk to 19.0% by 2017. In general, Beijing represents the forefront of industrial transformation and upgrading and should lead other regions to achieve more resilient and sustainable economic development[17].

Taking advantage of the abundant nonfossil fuel resources, the southwestern provinces' efforts in climate mitigation were also impressive. Yunnan and Sichuan were leaders in the southwest, followed by Guizhou and Guangxi. Chongqing did a relatively modest job but still exceeded most of the other regions. The advantages of Yunnan and Guangxi were the low level of carbon emissions and increasing nonfossil fuel supply. From 2013 to 2016, carbon emissions from electricity and heat supply dropped by 19.2% in Guangxi, which helped the region obtain 100 points in the indicator. In addition, nonfossil fuel accounted for 14.3 and 16.1% of the total energy consumption in Guangxi and Yunnan, respectively. Guizhou, Sichuan, and Chongqing were outstanding in their performance improving energy and carbon efficiency. From 2010 to 2017, energy intensity in Guizhou decreased at a rate of 6.3–7.5%, more than twice the targets. Enjoying benefits from their unique geographical conditions, the southwestern provinces are leading China in nonfossil fuel utilization. For example, Sichuan is motivated to address climate problems in conjunction with the development of nonfossil electricity. Sichuan is one of the most important clean energy bases in China[4], its theoretical reserve for hydropower is 143 GW, with 120 GW that can be exploited and utilized[23]. In 2017, the primary electricity production of Sichuan was 321.6-billion kW·h. Although Sichuan is the 8th largest consumer of both total energy and electricity in China, it has the optimal energy consumption structure compared with the northern and eastern

Table 1 The two solutions for climate mitigation motivation.

	Solution 1	Solution 2
Conditions	~Fossil fuel dependence[a] ~Energy Self-sufficiency	~Fossil fuel dependence[a] ~Industry share
Better performance (greater than 0.5 membership)	Beijing Guangxi Fujian Hubei Jilin Jiangxi Hainan	Beijing Yunnan Sichuan Hunan Hainan Guangdong
Worse performance (less than 0.3 membership)	Tianjin Shanxi Inner Mongolia Heilongjiang Ningxia Xinjiang	Hebei Inner Mongolia Jiangsu Shandong Shaanxi Ningxia

Notes: ~absence of the condition.
[a]combination of conditions.

parts of China[4,24]. Clean energy consumption in Sichuan accounts for approximately 40% of its total energy consumed. In addition, the five provinces in southwestern China produced primary electricity of 777.6-billion kW·h in 2017, which accounted for 41.8% of the total national primary electricity production.

Motivation for regional climate actions. Two solutions were derived for CCMI performance. Solution 1 emphasizes the impact of fossil fuel dependence and resource self-sufficiency on climate-mitigation actions. Solution 2 focuses on economic structure, represented by the share of secondary industry, and fossil fuel dependence. The two solutions imply that reducing fossil fuel dependence is the exclusive pathway for climate mitigation in China. Rich resource endowment or industry reliance also affects regional motivation and capacity for climate goals. Economic and financial strength represented by government budget per capita has little impact on CCMI scores.

In solution 1, regions that imported energy from other provinces and held a low fossil fuel share showed better performance in climate-change mitigation (Table 1). For example, nonfossil fuel accounted for 12.3% of Beijing's total energy consumption in 2016, which was among the highest in China. However, approximately 95% of its total energy consumption and 58% of the electricity consumption were from exports. The situation was similar in Jilin. This province took advantage of an inadequate resource endowment to compensate for the shortcomings of relying on secondary industry development. In contrast, the main energy exporters suffered extremely from supply-side stress. For example, the northwestern provinces benefited from economic development in the energy sector, while they had to assume responsibility for eliminating environmental impacts. As mentioned above, Inner Mongolia, Ningxia, and Shanxi showed poor performance in almost all fields. Along with their resource endowments, these regions also serve as the power-production base for China. Approximately 23% of the total thermal power production in Shanxi and Inner Mongolia was exported to other provinces in 2016. The path to reducing carbon emissions by importing energy and outsourcing environmental responsibility is a signal that deserves attention.

In solution 2, efforts toward industrial transition and the decoupling of economic development from fossil fuel consumption are highlighted in climate-mitigation performance. Beijing also followed solution 2 for decarbonization. With industry accounting for less than 20% of GDP, carbon emissions in Beijing continued to decrease in 2007–2017 (Fig. 3). Although the energy self-sufficiency of Yunnan was very high, the province compressed its industry share, limited fossil fuel utilization, and thus delivered better climate-mitigation actions through Solution 2. In 2016, the nonfossil fuel consumption in Yunnan was 14.7%, which helped the province disengage itself from the fossil fuel-dependent group. In addition, secondary industry accounted for 38.5% of Yunnan's GDP, which is relatively low compared with other regions. This explains why Yunnan was more motivated to engage in climate-mitigation tasks.

Several provinces fell into the group that cannot be explained by either solution, reflecting a mismatch between insufficient climate actions and socioeconomic conditions. Membership in this group implies that the outlier provinces are taking inadequate responsibility for climate-change mitigation. For example, Shanghai and Jiangsu failed to be recognized for sufficient climate-change mitigation efforts, with memberships of 0.30 and 0.23, respectively. However, the two provinces are among the most developed provinces in China. Located in the eastern coastal area, economic development in these two provinces is highly decoupled from resource endowment, with 93.7% of Jiangsu's total energy consumption being imported from other regions and more than 99% of Shanghai's. Furthermore, secondary industry represented only 19.3% of GDP in Shanghai in 2016 and 44.7% in Jiangsu. The main problems for these two provinces may stem from their fossil fuel dependency, with 93% and 94.8% of the total energy consumed being from fossil fuel in Shanghai and Jiangsu, respectively. Their memberships in the fossil fuel-dependent group were 0.48 and 0.66 for the provinces, but this is still insufficient to explain their poor CCMI performance. Thus, they are considered outliers of both solutions, and urgent action is necessary to motivate them to take more responsibility.

Both individual and overall solution consistency exceed the threshold of 0.8 (see Supplementary Table 2). The overall solution consistency implies that the share of a solution configuration will result in a high CCMI score of 84%. In addition, the overall solution coverage is 0.71, which is acceptable (>0.6). The coverage means that the solution can be exactly matched with 71% of the empirical cases. This suggests that the derived solutions are adequate to explain regional climate performance.

Discussion

Both solutions highlight the importance of the independent development of fossil energy. In conjunction with this, a low level of energy self-sufficiency and limited industry share of GDP are alternative conditions for climate-mitigation actions. The solutions provide explanations for the regional motivation behind climate-mitigation actions and pathways for those regions with poor CCMI performance.

The recommended pathway for China to reach its targets for a future carbon-emission peak and ultimate carbon neutrality is reducing fossil fuel consumption and improving development in tertiary industry. A lower level of fossil fuel dependence is the core condition to motivate regional efforts in climate-mitigation actions. Fossil fuel dependence brings higher costs for an energy transition and creates many obstacles to climate mitigation[25]. Pressure from fossil fuel owners impedes the effect of future climate policies[26]. In Australia, the current regulatory model of the national electricity market favors the centralized generation and distribution of large fossil fuel power plants and impedes the transition to multiple decentralized renewable energy generation sources[27]. Along with nonfossil fuel utilization, an optimal industrial structure is also important to motivate climate-mitigation actions. Many studies have demonstrated that a structural transition in industry is the main driver of carbon-emission changes in China[2,9,17,28,29] (see Supplementary Fig. 3). A transformation increasing the proportion of tertiary industry is highlighted as one of the main pathways for China to achieve resilient and sustainable development and reduce its carbon emissions. In the past, China focused its investment on heavy industry and infrastructure construction, creating essential risks for the environment and economic system. Since the start of the new normal phase, China has sought to deliver high-quality economic growth under a sustainable mode. The top–down reform in energy consumption and economic structure has helped many provinces reduce their carbon emissions. For example, secondary industry accounted for 51.0% of Sichuan's GDP in 2013, and this proportion shrank to 40.8% in 2016. Although boosting the tertiary industry is the consent for China's economic transition, the secondary industry is still critical in supporting the economic growth in the next decades. Decarbonizing the remaining share of the secondary industry is still vital for sustainability. Reducing carbon emissions and promoting technological upgrade is in the energy- and carbon-intensive industries, especially the metal and energy sectors (see Supplementary Fig. 4). The results of the robustness test using the indicator of industrial-energy consumption share show that reducing energy intensity of the secondary industry helps to achieve better climate-change mitigation performance (see Supplementary Information for the robustness test). This is recommended for the remaining share of the secondary industry.

However, the energy-outsourcing approach to reducing carbon emissions by sustainably decreasing local energy self-sufficiency, revealed in solution 1, is a signal that policymakers should be alert to. The provinces with advantages in resource endowment, especially in Northwest China, should focus on reducing fossil fuel dependency (Table 1). Interregional cooperation is urgently needed to solve this problem. For Ningxia and Inner Mongolia, a large share of industry development and a high level of energy exports impedes their implementation of climate-mitigation measurements. The development of secondary industry accounted for approximately 47% of the whole economic system in the two regions in 2016. In addition, 98.1% of the total energy consumption in Ningxia was from local supply. The situation is even worse in Inner Mongolia, as this area is one of the main sources of energy production in China. Energy self-sufficiency was 329.4% for Inner Mongolia in 2016, indicating that high energy exports support the local economy. As energy exporters, these provinces experience much more stress because they share the environmental responsibility of energy importers. The transformation of both producers and consumers is critical for the national decarbonization process. Regional cooperation should be boosted to promote technological updates to solve the problem. Nonetheless, developed provinces showed insufficient actions in industrial upgrades and nonfossil fuel development. The provinces on the eastern coast should play a leading role in climate mitigation because they have strong economic support and social development. However, Zhejiang ranked 17th in the CCMI score, followed by Shanghai at 20th and Jiangsu at 22nd. The poor performance in emissions led to their low CCMI scores. Additionally, their efforts in meeting climate targets and utilizing nonfossil fuels were inadequate. In the future, solution 2 is recommended to reduce fossil fuel dependence and optimize the economic structure by decreasing the share of secondary industry. For Shanghai, most of its energy consumption was from imports. The fsQCA results demonstrated that Shanghai should take advantage of its economic structure and improve its nonfossil energy supply. In addition, the approach of importing energy in developed provinces transfers part of the environmental responsibility to the exporters, but these developed provinces are more capable of economic support and technology upgrading. Thus, it is recommended that developed regions take more responsibility for climate-change mitigation and assist energy exporters with environmental issues.

The government budget is not listed as a necessary condition for CCMI performance. The results show that performance in climate-change mitigation did not correlate with the government budget. For example, the government budget per capita of Tianjin was 2.36 thousand yuan in 2016, which made it a partial member of the adequate budget group at the 0.98 level. However, the CCMI for Tianjin was 65.85 in 2013–2016. In contrast, Henan gained 73.49 in its CCMI, with only 0.69 thousand yuan per capita for its budget. This is plausible, as similar results have also been found in other studies. For example, it was found that high allocations of the regional government budget earmarked for climate mitigation did not deliver the expected outputs and outcomes[30]. The inconsistency between budget and climate mitigation may stem from insufficient fund allocation into climate affairs[27] or inappropriate climate programs without a well-tailored design[31].

Certain limitations exist in this study. First, although the index development is based on a series of widespread index and literature, it is undeniable that indicator selection remains subjective to some degree. For example, only one indicator is measured for climate policy. In the future, more detailed and comprehensive assessment can be involved to measure the effectiveness of regional climate policy. Second, changes in the weightings of the CCMI indicators will bring uncertainty to the result. When coping with the relationship of the indicators and the four CCMI fields, it should be cautiously interpreted. Third, the accuracy of carbon-emission accounting is important to the result. Data uncertainty caused by emission factors or oxidation efficiency used is inevitable. These limitations in this study may be addressed by more reliable and comprehensive data in the future work.

For policy implications, the transition in industrial structure and improvements in energy efficiency contributed substantially to motivating regional climate-mitigation actions. In this study, the regions with low carbon emissions from secondary industry and well-controlled energy intensity in the emission-reduction period were considered to be leaders. Reducing reliance on carbon-intense industries and decoupling economic growth from fossil fuel consumption is critical for decarbonization in China. In addition, the development of nonfossil fuels is another factor that can help provinces improve their climate-mitigation performance. The local governments should take advantage of their natural conditions to develop nonfossil fuel production and promote structural changes in the energy system. The central government's technology and policy support in the nonfossil fuel development projects could be important for these provinces. In conclusion, a transition in the economic system that decreased the share of secondary industry and optimization of the energy mix at the regional level were the main drivers of national carbon-emission reduction from 2013 to 2016. This is also the recommended pathway for China to reach its carbon-emission peak and carbon neutrality in the future.

The energy-outsourcing mechanism revealed in this study serves as a warning for policymakers. Energy exporters rely heavily on energy generation and secondary industry. However, these regions have a rather limited GDP share, leading to constrained capacity for technological progress and climate-adaptation measures. In contrast, developed regions were able to improve energy efficiency because of their enhanced economic system, but they failed to play a leading role in climate-change mitigation. These provinces had poor resource endowment and obtained most of their energy from other regions. The developed regions shifted their environmental cost and pressure for mitigation due to fossil fuel dependency to the energy exporters

Table 2 Details of the indicators in the climate change mitigation index.

Categories and weighting		Indicators and weighting		Description
Emissions 60%	Emissions level 30%	Energy consumption per capita	15%	Total energy consumption includes coal, oil, gas and primary electricity.
		CO_2 emissions per capita	15%	
	Emission changes 30%	CO_2 emissions changes from energy sector	10%	The energy sector includes production and supply of electric power, steam, hot water, gas, and tap water.
		CO_2 emissions changes from industry	9%	
		CO_2 emissions changes from transport	3%	The transport sector includes transportation, storage, post and telecommunication services
		CO_2 emissions changes from construction	2%	
		CO_2 emissions changes from services	2%	The service sector includes wholesale, retail trade, catering and other services.
		CO_2 emissions changes from residential consumption	2%	The residential consumption includes urban and rural consumption.
		CO_2 emissions changes from agriculture	2%	The agriculture sector includes farming, forestry, animal husbandry, fishery, and water conservancy
Efficiency 20%		CO_2 emissions per unit of total energy consumption	2%	Carbon intensity of the region's energy
		Changes in CO_2 emissions per unit of total energy consumption	8%	
		Total energy consumption per GDP	2%	Energy intensity of the region's economic development
		Changes in total energy consumption per GDP	8%	
Nonfossil fuel 10%		Share of nonfossil fuel in total energy consumption	2%	Nonfossil fuel consists of nuclear power, renewable energy and heat and electricity imported from other regions or countries.
		Changes in energy supply from nonfossil fuel	8%	
Climate policy 10%		Target-performance comparison	10%	The comparison of target and performance is the proportion of actual reduced energy intensity to the province-specified target set by the central government in its five-year plans.

through outsourcing. This leads to overload of environmental stress for the less-developed provinces and designing a more effective system for decarbonization-responsibility allocation is necessary. This implies that although the performance-assessment results show that the energy-exporting provinces are major emitters, it is not appropriate to simply attribute it to insufficient efforts in climate-change mitigation of the exporters. The widely accepted principle in the United Nations Framework Convention on Climate Change, Common but Differentiated Responsibilities, may have enlightenment for the climate-responsibility allocation mechanisms in China[32]. "Common" suggestions that all nations should "cooperate in a spirit of global partnership", while the responsibilities should be "differentiated". The Common but Differentiated Responsibilities principle implies that not all countries need to contribute equally[33]. The rich countries usually carry a larger share of carbon-abatement burdens than the poor in climate-change mitigation. Following the Common but Differentiated Responsibilities principle, all provinces in China should take common responsibility for climate issues but the wide variations in the level of economic development differences between the regions should also be recognized. The region's contributions in carbon emissions, as well as the capacities, should be accounted for in the responsibility allocation. To facilitate regional equality, rich and carbon-importing provinces should take more efforts in carbon abatement[34]. The application of consumption-based carbon accounting is suggested to internalize negative externalities and solve the problem of carbon leakage[35]. Additionally, interregional cooperation between the provincial governments is urgently needed. China's national carbon emissions trading market has been opened since July 2021, which is a good platform for promoting interregional cooperation. The developed regions should take more responsibility and support technological progress in energy-exporting and less-developed regions.

Methods

Regional assessment: a climate-change mitigation index. The calculation of CCMI scores was based on the method proposed by Mi et al.[15], assessing climate-change mitigation performance according to four fields: emissions, efficiency, nonfossil fuels, and climate policy (see Supplementary Information for background of CCMI). These four fields account for 60%, 20%, 10, and 10% of CCMI, respectively, and they were measured using sixteen indicators. Details are provided in Table 2, and there are several changes compared with the original method in the study of Mi et al.[15].

Specifically, the following are some details of the calculation of CCMI scores:

1. For the changes in emissions, the national economic systems are divided into seven sectors: electricity and heat production, industry, transport, construction, other services, agriculture, and residential consumption.
2. The weights of the seven indicators in emission changes are determined by the sector's share of total carbon emissions.
3. According to current allocation system of emission-reduction responsibility in China, production-based emissions are used in CCMI. Thus, heat and electricity imported from other regions or countries is treated as nonfossil fuel because the export regions are responsible for the corresponding carbon emissions.
4. The "changes" in an indicator mean the annual change ratio of the current period value to the previous period value. Formula (1) shows the calculation:

$$a_{\mathrm{r,t}} = \frac{A_{\mathrm{r,t}} - A_{\mathrm{r,t-1}}}{y_t \times A_{\mathrm{r,t-1}}} \tag{1}$$

where $a_{\mathrm{r,t}}$ is the development of indicator A in region r during period t, $A_{\mathrm{r,t}}$ is the value of indicator A in region r at the end of period t, $A_{\mathrm{r,t-1}}$ is the value of indicator A in region r at the start of period t, and y is the number of years during period t.

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method was conducted based on a temporal comparison of the indicators across the four periods. First, each indicator was normalized according to CCMI-assessment procedures[15]. The normalized indicators were all benefit-type indicators, which means the best performance among all the regions in the four periods is awarded 100 points and the worst is awarded 0. Then, the best distance and worst distance between region r and the best/worst performance were calculated to derive the CCMI scores according to formulas (2–4):

$$d_r^- = \sqrt{\sum_{i=1}^{n} \omega_i^2 (N_{\mathrm{i,r}} - N_i^{\min})^2} \tag{2}$$

$$d_r^+ = \sqrt{\sum_{i=1}^{n} \omega_i^2 (N_i^{\max} - N_{\mathrm{i,r}})^2} \tag{3}$$

$$I_{\mathrm{CCMI,r}} = d_r^- / (d_r^- + d_r^+) \tag{4}$$

where d_r^- is the worst distance, d_r^+ is the best distance, $I_{\mathrm{CCMI,r}}$ is the CCMI score of region r, ω_i is the weighting of indicator i, $N_{\mathrm{i,r}}$ is the normalized figure of indicator i in region r, and $N_i^{\min}$ and $N_i^{\max}$ are the minimum and maximum of the normalized indicator i across the four periods.

In this manner, the CCMI score measures comparisons between the regions' performance and the best/worst performance in the four periods. Thus, the CCMI scores of different periods can be analyzed. Regarding the weightings of the indicators, the robustness test shows that changing the weightings of the indicators will not affect the main conclusions in this study. The top- and bottom-performed provinces remain consistent, while the rankings of the middle-level provinces slightly change (see Supplementary Fig. 5 and Supplementary Table 3).

Climate motivation: a fuzzy-set qualitative comparison analysis. The fsQCA is a set-theoretic method for causal relation inference utilized to find the pathways to motivate regional climate actions. Ragin designed a method to analyze complex causal patterns to explain an outcome by examining diverse variable combination patterns ("configurations")[36,37]. A necessary condition implies that it is present in all instances of the outcome, whereas a sufficient condition means that the presentation of the condition certainly leads to the presentation of the outcome[38]. For social studies, necessary conditions rarely exist and sufficiency assessment is important. Every possible configuration is tested to estimate the sufficiency to lead to an expected result (better climate mitigation performance in this study). Based on this, the fsQCA results show how causal conditions contribute to a result and how combinations of conditions produce the same result[39] (see the supplementary information for details about the causality in fsQCA). The fsQCA method is able to analyze the effects of sets of several variables, rather than focuses on the average effect of single variables, and it can also address relationships where multi-collinearity exists[40]. Therefore, fsQCA is conducted to study interactions between the assumed conditions that drive regional performance in climate-change mitigation actions.

All causal variables and the outcome variable were assigned numbers ranging from 0 to 1 that reflect membership of a condition or outcome. For example, 0 means the absence of a defined set, whereas 1 means it is present. Then, all the conditions were tested individually to determine if a necessary condition existed. Subsequentially, all the condition combinations were tested to explore the solutions that led to the outcome. Two main values were derived to indicate the explanatory power of the results: consistency and coverage.

The membership and outcome of region r in the set of solution i is calculated as follows (solution i is the combination of conditions 1,2,…j):

$$s_{i,r} = \min_j c_{j,r} \tag{5}$$

$$otcm_{i,r} = \min(s_{i,r}, otcm_{\mathrm{emp},r}) \tag{6}$$

where $c_{j,r}$ is the membership of region r in the set of condition j, $s_{i,r}$ is the membership of region r in the set of solution i, $otcm_{i,r}$ is the membership of region r in the outcome set of solution i, and $otcm_{emp,r}$ is the membership of region r in the set of empirical outcomes (determined by CCMI scores).

The consistency of solution i is

$$consistency_i = \sum_{r=1}^{30} otcm_{i,r} / \sum_{r=1}^{30} s_{i,r} \tag{7}$$

$$coverage_i = \sum_{r=1}^{30} otcm_{i,r} / \sum_{r=1}^{30} otcm_{emp,r} \tag{8}$$

Then, the membership and outcome of region r in the set of the overall solution (consisting of solutions 1, 2, …i) is obtained as follows:

$$S_r = \max_i s_{\mathrm{i,r}} \tag{9}$$

$$\mathrm{otcm}_r = \max_i otcm_{\mathrm{i,r}} \tag{10}$$

The consistency and coverage of the overall solution is

$$\text{Consistency} = \sum_{r=1}^{30} otcm_r / \sum_{r=1}^{30} S_r \tag{11}$$

$$\text{Coverage} = \sum_{r=1}^{30} otcm_r / \sum_{r=1}^{30} otcm_{\mathrm{emp,r}} \tag{12}$$

Generally, the consistency and coverage of the overall solution should exceed 0.8 and 0.6, respectively.

Four conditions that are assumed to correlate with regional climate mitigation motivations were employed in this study: fossil fuel dependence, economic structure, resource endowment and government budget. Four indices were selected because for a medium-*n* analysis of twenty to forty cases, it is suitable to employ four conditions[41]. The CCMI scores for 2013–2016 were analyzed, since this period is the focal point of this study, and the amount of data in a single period is suitable for fsQCA[37]. The four conditions employed in this study are as follows.

Fossil fuel dependency was employed to explain regional climate performance. Economic dependence on fossil fuel has been proven to substantially affect climate and energy policies[26,27,42]. Here, fossil fuel dependency is calculated by the share of fossil fuel consumption to the total energy consumption.

Resource endowment is another important driver of local energy-transition strategies and thus affects climate-change actions[15,43,44]. In this study, energy self-sufficiency was employed as a proxy of resource endowment. Energy self-sufficiency is the ratio of total primary energy production to total energy supply.

The industrial structure is a critical factor in the balance of economic development and energy consumption. An effective industrial structure adjustment can bring considerable potential for energy conservation and carbon reduction[15]. However, relying on high-emitting industries creates obstructions to decarbonization[2]. Thus, the effect of industrial structure, represented by the proportion of secondary industry to GDP, on regional CCMI performance was tested in this study.

The government's fiscal expenditure plays an important role in controlling carbon emissions[45,46]. Public budget on environment, education, and technology has a positive effect on carbon-emission reduction by eliminating environmental damage, increasing residents' awareness of energy saving, and promoting the progress of energy technology. It is suggested that subnational governments have limited capacity to include climate mitigation or adaption actions in their budgets[1]. Thus, the government budget per capita was employed to measure the economic development of a region and the capacity of its government to implement climate policies.

In this study, no condition was necessary according to the necessity test; thus, combinations of the conditions were tested. A robustness test was performed to verify the results by changing the time window and the major factors. In addition, a pooled ordinary least-squares analysis was performed to enhance the results. The results were proved to be robust (see Supplementary Table 4). Parsimonious solutions are analyzed in this paper, and hence, all the conditions are core conditions.

Data availability

Population, GDP, and government budget data are from China's Statistical Yearbook, published by the National Bureau of Statistics of China (http://www.stats.gov.cn/english/Statisticaldata/AnnualData). Energy-related data are from China's National Energy Statistical Yearbook (https://data.stats.gov.cn/english). Regional and sectoral carbon emissions are from the China Emission Accounts and Datasets (www.ceads.net)[20,21]. The energy-intensity reduction targets are from the national 11th, 12th, and 13th five-year plans (http://www.gov.cn/zhengce/content/2008-03/28/content_2834.htm; http://www.gov.cn/zhengce/content/2011-09/07/content_1384.htm; http://www.gov.cn/zhengce/content/2017-01/05/content_5156789.htm). The 30 provinces involved in this study are divided into eight Chinese regions[17,18] (see Supplementary Table 1). Supplementary Data 1 presents the data for CCMI calculations.

Code availability

All computer codes generated during this study are available from the corresponding authors on reasonable request.

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Author contributions

Z.M. conceived the study. X.S. performed the analysis. Both authors interpreted the data and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Z.M. or X.S.

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