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Original Research

Aligning regional carbon neutrality pathways with national climate goals: An integrated analytical framework

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A B S T R A C T

Under national carbon neutrality targets, energy-producing regions hold significant responsibilities for reducing emissions. Given the diverse economic, industrial, and resource profiles of these regions, tailored strategies are essential for designing regional emission pathways. Currently, a systematic analysis that simultaneously integrates broader national climate objectives and regional heterogeneity is lacking, hindering the formulation of localized roadmaps. To address this gap, we propose an integrated analytical framework combing top-down and bottom-up approaches. It considers macro-level constraints (socio-economic development) and micro-level feasibility (renewable energy potential and forest carbon sinks), incorporating diverse regional characteristics such as resource endowment, energy consumption patterns, and industrial structures. We apply this approach to an energy-producing region in central China. Our analysis highlights the need for a clean energy transition that maintains energy security and meets growing electricity demands. By 2060, wind and solar power are projected to account for 87% of electricity generation, representing a substantial shift from the current fossil-fuel-dependent structure. Significant reductions in greenhouse gas emissions can be achieved by optimizing the energy structure, enforcing production controls, and deploying advanced technologies across industry, transportation, and buildings. Additionally, enhancing carbon removal strategies will further support emission reduction targets. This framework demonstrates the feasibility of achieving climate objectives in fossil-fuel-dependent regions, providing strategic guidance for integrating regional traits into national decarbonization plans.

1. Introduction

Due to the acceleration of industrialization and the widespread utilization of fossil fuels, global warming is intensifying. As of 2022, human-induced warming has reached 1.26 °C, highlighting the

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urgency of addressing climate change [1]. This increase in temperature raises the possibility of surpassing the Paris Agreement's [2] objective of keeping levels to well below 2 °C and pursuing a target of 1.5 °C [3]. As the largest emitter in the world [4], China has made an ambitious commitment to reach peak carbon dioxide (CO_2) emissions before 2030 and achieve carbon neutrality before 2060 [5]. Provinces in China have actively responded to this call and have made individual pledges [6,7]. As sub-national economies with distinct economic and resource profiles, provinces have the authority to formulate their net-zero policies and renewable energy development plans, positioning them as primary implementers of climate policies and key drivers of environmental action [8−10]. Additionally, regional differences in development, such as varying levels of clean production technology and energy demands, significantly influence the transformation pathways of their economies [11,12]. Therefore, it is necessary to formulate detailed techno-economic pathways to set and achieve provincial-level carbon peak and net-zero emission targets.

Transitioning the energy system is a crucial measure in mitigating climate change. Achieving carbon neutrality involves implementing zero-carbon power systems, low-carbon end-use energy technologies, and negative emission technologies. China's power sector accounts for 46% of total greenhouse gases (GHGs) [13], making zero-carbon energy essential for reducing emissions. Furthermore, mitigation in all end-use sectors relies on emissions reductions in the power sector, for instance, electrification in the transport and industrial sectors, as well as heating and clean cooking in the residential sector. China has set a national target of increasing the share of non-fossil energy consumption to around 25% by 2030 and over 80% by 2060 [14,15]. To achieve this goal, thermal power produced from fossil fuels will be reduced by the widespread adoption of renewable energy, including orderly phaseout or biomass co-firing [16].

Sub-national economies are facing severe challenges, especially for those highly dependent on fossil fuels. For instance, an inherent contradiction exists between achieving emission reduction while maintaining domestic energy security. The transition to renewable energy raises the demand for grid planning and modernization. Coal-fired power plants remain essential for grid stability during this transition [17]. In addition, balancing emission reduction and the effective use of coal resources to promote economic development is challenging. In terms of utilizing coal as a raw material, traditional coal-based chemical industries focus on primary low-value products such as fertilizers, methanol, and polyvinyl chloride [18]. However, industrial by-products such as coke are rich in hydrogen resources, which is conducive to reducing emissions through large-scale and cost-advantaged industrial hydrogen production [19,20]. Previous projects, such as Transition in Coal Intensive Regions (TRACER) [21], which support the European Union's coal-mining regions in developing strategies for transitioning to sustainable energy systems, highlight the importance of phasing out [22] and adopting a new energy mix. Therefore, it is necessary to undertake a detailed modeling and characterization of the energy system and its associated industries to conduct pathway simulation and optimization.

Several scholars have explored pathway designs for carbon peak and carbon neutrality. In terms of research objects, traditional pathway planning mainly focuses on the national level as a whole [23] or specific industries [24,25]. Recent literature highlights the need for bespoke strategies that accounts for local resource endowments and economic structures [26] and offers insights into decarbonization pathways for coal-dependent regions [27], the importance of fossil fuel phase-out [22], and the critical role of renewable energy [28]. Few studies outline the trajectory from a sub-national standpoint [29−34], and there has been little research proposing pathways tailored to local conditions in each province. An increasing amount of studies have focused on the provincial transition of the power system since China implemented mandatory energy-saving goals in 2006. Studies on Shanxi Province, for instance, have analyzed CO_2 emission characteristics and drivers and created scenario simulations of future energy structure and emission trajectories [35,36]. However, few investigations have systematically addressed changes in the energy system [37] or carried out comprehensive simulations encompassing all economic aspects. In terms of research methodology, studies at the provincial level often fail to implement systematic models to simulate wind and solar potential, carbon sinks, localized energy structure design, and power system matching relationships. These gaps in the research in this area hinder its ability to support localized pathway design, and the conclusions are too unreliable to serve as references for energy-rich provinces.

This study aims to evaluate the full-spectrum of characteristics of provincial carbon pathways by employing an integrated framework based on the Chinese Academy of Environmental Planning Carbon Pathways (CAEP−CP) model [38]. Through scenario analysis, a comprehensive understanding of carbon peak and neutrality trajectories under projected socio-economic conditions will be achieved. As a major province heavily reliant on fossil fuels, Shanxi is expected to face more challenges in reducing emissions than other provinces in China (Supplementary Material Fig. S1). Its dependency on coal for heavy industry leads to significant structural obstacles to achieve significant carbon peak targets. Additionally, as a vital electricity exporter that relies on coal power, this province bears the responsibility for energy security, further exacerbating the difficulty of it peaking on schedule. By taking Shanxi as a case study, this paper demonstrates the feasibility of achieving regional climate goals based on real energy supply and demand dynamics in energy-intensive provinces. Additionally, it provides innovative methods of formulating more effective carbon neutrality roadmaps and policies, particularly for those regions that face significant dependence on fossil fuels.

2. Material and methods

The framework for projecting the carbon neutrality pathway in Shanxi Province included emission accounting, pathway projection, and uncertainty analysis of key parameters (Fig. 1). We started with emission accounting for the status quo. We used the CAEP−CP model [38] to project further pathways in all sectors. This model is a comprehensive analysis framework that simulates carbon emission scenarios under various policies and strategies, setting it apart from other integrated assessment models like Global Change Analysis Model (GCAM) [39] and The Integrated MARKAL-EFOM-1 System (TIMES) [40], which cannot achieve detailed industry-specific technological paths and close integration with energy flows. The CAEP−CP model integrates top-down and bottom-up strategies to optimize emission reduction costs, including MESSAGEix-CAEP [41]: a crucial component that evaluates sectoral decarbonization pathways and their cost-effectiveness by analyzing energy and material flows. Finally, we identified key parameters for the CAEP−CP model and ran an uncertainty analysis.

2.1. Emission accounting

According to the Kyoto Protocol, GHGs predominantly consist of six types: CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. The contribution of GHGs to global warming is measured by global warming potential (GWP), which is expressed as carbon dioxide equivalent (CO_2eq). This

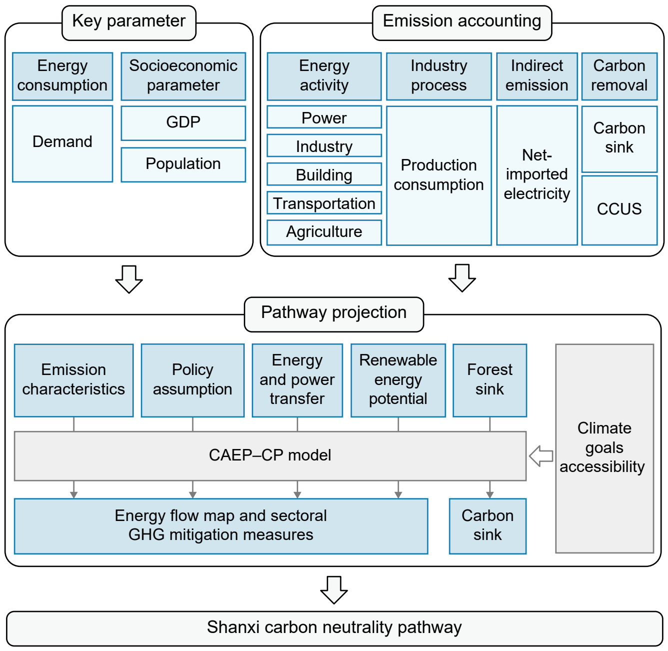

Fig. 1. The research framework for projecting the carbon neutrality pathway. GDP: gross domestic product; CCUS: carbon capture, utilization, and storage; CAEP–CP: Chinese Academy of Environmental Planning Carbon Pathways; GHG: greenhouse gas.

paper calculated GHG emissions in Shanxi Province using the emission factor method taken from the Intergovernmental Panel on Climate Change (IPCC) guideline [42]. This includes fossil fuel combustion, industrial processes, indirect emissions, and carbon removal.

$$GHG = GHG_{\text{Fossil fuel combustion}} + GHG_{\text{Industrial processes}} + GHG_{\text{Indirect}} + GHG_{\text{Carbon removal}} \quad (1)$$

where $GHG_{\text{Fossil fuel combustion}}$ is the GHG emissions from urban fossil energy consumption; $GHG_{\text{Industrial processes}}$ is the GHG emissions resulting from chemical reactions in industrial production processes, including GHG emissions from cement, glass, ammonia, soda ash, ferroalloys, aluminum, magnesium, and lead-zinc smelting processes. GHG_{Indirect} is the indirect GHG emissions. $GHG_{\text{Carbon removal}}$ includes carbon sink, i.e., CO_2 absorbed by forests as they grow, and carbon dioxide capture, utilization, and storage (CCUS).

$$GHG_{\text{Fossil fuel combustion}} = \sum_{i,j} (AD_{i,j} \times EF_i) \quad (2)$$

where i is different energy sources, such as coal, refined oil, natural gas; j refers to different sectors, mainly power, industry, building, and transportation; $AD_{i,j}$ is the consumption of energy i in sector j. EF_i is the GHG emission factor of energy i.

$$GHG_{\text{Indirect}} = AD_{\text{net-import}} \times EF_e \quad (3)$$

where $AD_{\text{net-import}}$ represents the net-imported electricity (MWh), and EF_e means the emission factor of electricity (ton CO_2 MWh^{-1}), derived from China's national greenhouse gas inventory.

2.2. Emission pathway projection

In the future scenario projection of Shanxi's carbon-neutral pathway, key socio-economic parameters included gross domestic product, population size, urbanization rate, and electricity consumption (Table 1, Supplementary Material Text S1). Areas of policy for both China and Shanxi Province included industrial development, import and export, and product and service substitution. Based on the above, we predicted future product output, electricity generation (for the electricity sector), passenger and freight volume (for the transportation sector), building scale (for the construction sector), coal mining volume, etc. We predicted changes in carbon emission intensity per unit of product based on how the application of advanced technology would progress. We calculated future GHG emissions for each sector using activity levels and emission factors. The above assumptions allowed us to predict the activity level or emission factor for each sector, facilitating the calculation of their future carbon emissions.

The research investigated two distinct future emission scenarios: a business-as-usual (BAU) and a low-carbon scenario. These differed from sector to sector regarding energy efficiency, activity levels, energy structure, and resource potential. Compared with BAU, the low-carbon scenario incorporated even more ambitious measures, including the faster development of renewable energy, a higher proportion of electric vehicles, and more substantial energy-saving reforms and electrifications.

In the electricity sector, we referred to the 14th Five Year Plan for National Economic and Social Development and the Long Range Objectives for 2035 in Shanxi Province [44], the Implementation Plan for Carbon Peak in Shanxi Province [6], and the Working guidance for carbon dioxide peaking and carbon neutrality in full and faithful implementation of the new development philosophy [14]. We forecasted electricity consumption demand based on socio-economic development expected from these policies. We used non-fossil energy generation capacity as a constraint to determine fossil fuel-based electricity generation requirements. We referred to the Implementation Plan for nationwide retrofitting and upgrading of coal-fired power units [46] and assumed that coal-fired power units would be upgraded. Under the BAU scenario, fossil fuel-based electricity generation would be 0.42 trillion kilowatt hours (kWh) and 0.11 trillion kWh, respectively, in 2030 and 2060. The carbon emission per unit of coal-fired electricity generation would be 345.9 and 331.2 g CO_2 kWh^{-1} in 2030 and 2060, respectively. Under the low-carbon scenario, we assumed a further increase in renewable energy generation would lead to a decrease in coal-fired power demand. Thus, fossil fuel-based electricity generation would drop to 0.35 trillion kWh and 0.06 trillion kWh, respectively, in 2030 and 2060. In the low-carbon scenario, the carbon emission factor per unit of coal-fired electricity generation would remain the same in 2025 and 2030, becoming 276 g CO_2 kWh^{-1} in 2060.

In the industrial sector, we referred to the Shanxi Province Industrial Sector Carbon Peak Implementation Plan [47], Shanxi Province Steel Industry Transformation and Upgrading 2023 Action Plan [48], and Shanxi Province Building Materials Industry Transformation and Improvement 2023 Action Plan [49], etc. We focused on the steel, cement, and coking industries, which account for more than 80% of total industrial sector emissions. We forecasted major industrial product output based on socioeconomic development and the expectations of the upstream and downstream industrial chains. With further information on technology iteration, energy consumption of production processes, and the scale of raw material substitution, we projected carbon emission intensity declines. Under the BAU scenario, the output of crude steel, cement, and coke would be 66, 34, and 98 million tons (Mt), respectively, in 2030 (27, 8, and 22 Mt in 2060). Assuming that the proportion of short-process steelmaking would reach more than 10% by 2030, we projected that the carbon emission per unit of crude steel would be 1680 kg CO_2 t^{-1} in 2030 (816 kg CO_2 t^{-1} in 2060). Predicting that

Table 1
Socio-economic key parameters for future scenario projection.

Parameters	2020	2025	2030	2035	2040	2050	2060	Reference
Population (million)	34.9	35.7	35.8	35.5	35	33.7	31.3	[43]
Gross domestic product (GDP; trillion)	1.8	2.6	3.7	4.9	5.8	6.6	7.2	[44]
Per capita GDP (thousand CNY)	50.6	72.7	102.7	137.8	166.1	196.2	228.5	[44]
Urbanization rate (%)	63	68	70	72	74	77	77	[44]
Electricity consumption (10 billion kWh)	23.4	29.3	35.3	40.0	43.7	48.3	48.5	[45]

the proportion of cement clinker energy efficiency above the benchmark level would reach 30%, we projected that the carbon emission per unit clinker would be 293.9 kg CO_2 t^{-1} in 2030 (242.4 kg CO_2 t^{-1} in 2060). Taking the proportion of advanced coke oven production capacity to reach over 95% by 2030, the projected carbon emission factor of coke is 510 kg CO_2 t^{-1} in 2030 (417 kg CO_2 t^{-1} in 2060). Under the low-carbon scenario, further production capacity reduction and the application of advanced technologies are considered. In 2030, the output of crude steel, cement, and coke would be 61, 33, and 89 Mt, respectively (18, 7, and 14 Mt in 2060). Incorporating an acceleration in the use of electric furnace steel and the development of hydrogen metallurgy, the carbon emission factor of crude steel will be 1603 kg CO_2 t^{-1} in 2030 (800 kg CO_2 t^{-1} in 2060). Further improvement in energy efficiency after 2025 would mean a carbon emission factor per unit clinker of 291 kg CO_2 t^{-1} in 2030 (240 kg CO_2 t^{-1} in 2060). If the energy consumption of all coke ovens increases further after 2025, its carbon emission factor will be 492 kg CO_2 t^{-1} in 2030 (408 kg CO_2 t^{-1} in 2060). Emissions from other industries would remain unchanged compared with the BAU scenario.

In the transportation sector, we referred to the Shanxi Province 14th Five-Year Plan for the Development of a Modern Comprehensive Transportation System [50] and the Shanxi Province Statistical Yearbook 2022 [51]. We based our predictions about vehicle demand growth on macroeconomic development and transportation need forecasts. Our projections on future vehicle composition and fuel consumption patterns were garnered from the evolution of the electric vehicle industry and alternative fuels. Under the BAU scenario, the number of vehicles would be expected to grow at an average annual rate of 5%, identical to the historical trend. Renewable energy vehicles would account for 30% of new vehicles in 2030 and over 90% in 2060. Under the low-carbon scenario, growth in the number of renewable energy vehicles would accelerate, thus their proportion would increase to 40% and 100% in 2030 and 2060, respectively.

In the building sector, we referred to the Shanxi Province Implementation Plan for Carbon Peak in the Urban and Rural Construction Sector [52], the 14th Five-Year Plan for the Development of the Construction Industry [53], the 14th Five-Year Plan for the Development of Building Energy Saving and Green Buildings [54], etc. We estimated future building scales based on population and urbanization rate trends and projected the evolution of the energy structure and energy intensity in future buildings. Using other developed countries as a reference, Shanxi's future urban residence per capita was expected to be around 40 square meters. Under the BAU scenario, the electrification rate of new buildings would reach 90% in 2030; the electrification rate of existing buildings would reach 55% in 2030 and more than 80% in 2060. Under the low-carbon scenario, the energy consumption structure would be further optimized. The electrification rate of existing buildings will reach 60% in 2030 and up to 100% in 2060.

Changes in carbon emissions in the agricultural sector are predicted based on the implementation of the Implementation Plan for Agricultural and Rural Carbon Reduction and Fixation [55], which includes a reduction in chemical fertilizer usage and an increase in low-carbon innovations in animal husbandry. These technological applications are expected to reduce GHG intensity in the agricultural sector.

Methane is the major component of non-CO_2 GHGs and is associated with coal mining. We referred to the requirements outlined in the Guidelines of the Communist Party of China Central Committee and the State Council on Fully Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality [14] regarding the goal of achieving a non-fossil energy consumption share of over 80% by 2060. Additionally, we referred to the 14th Five-Year Plan for the Development of the Coal Industry in Shanxi Province [56]. Under the BAU scenario, Shanxi's coal mining volume would be 1.14 and 0.20 billion tons, and the coal mine gas utilization rate would be 50% and 60% in 2030 and 2060, respectively. Under the low-carbon scenario, considering a further decline in coal demand caused by developments in renewable energy, coal mining volume in 2030 and 2060 would be 1.04 and 0.18 billion tons, respectively, and the coal mine gas utilization rate would reach 75% in 2060.

The carbon sink was mainly evaluated based on the guidelines in the report on Ecological Function Zoning of Shanxi Province [57]. Carbon removal of CCUS is determined based on the estimations set out in the Annual Report on Carbon Dioxide Capture, Utilization and Storage in China (2021) [58].

2.3. Data sources

Activity level data were derived from statistical yearbooks and documents. The main statistical sources were the Shanxi Statistical [51] and the China Energy Statistical Yearbooks [59]. The main documents used for this analysis include the Outline of the 14th Five Year Plan for National Economic and Social Development and the Long Range Objectives for 2035 in Shanxi Province [44], Shanxi Province 14th Five Year Plan for Green Transportation Development [60], Shanxi Province 14th Five Year Plan for the Development of a Modern Comprehensive Transportation System [50], Shanxi Province 14th Five Year Plan for Future Industrial Development [61], and Shanxi Province 14th Five Year Plan for Energy Conservation and Emission Reduction [62]. Sectoral energy consumption data (electricity, coal, gasoline, diesel, fuel oil, liquefied petroleum gas, natural gas, crude oil, etc.), forest resource data, and future development trends were obtained from departmental surveys: the Shanxi Bureau of Development and Reform, Department of Natural Resources, Department of Housing and Construction, Department of Agriculture and Rural Affairs, Department of Forestry, Department of Statistics, Department of Transportation, Department of Industry and Information Technology.

Emission factor data from fossil energy combustion are from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [42], and grid emission factors are derived from the Ministry of Ecology and Environment [63]. The GWP values came from the 100-year value proposed in the Sixth Assessment Report of the IPCC [64].

2.4. Uncertainty analysis

The uncertainty of GHG emissions was mainly derived from applied activity data and emission factors. By referring to IPCC guidelines [42], we quantified the uncertainty of activity levels and emission factors to determine the probability distributions using the Monte Carlo simulation method, ranging from 15% to 25% for different sectors (power, industry, transportation, building, non-CO_2, etc.). The above is determined based on the completeness of officially published energy data. Referring to our previous study [65], equation (1) was used in the simulation process. Each emission factor and each activity level were simulated 10,000 times based on their probability distribution, and the simulated results of the total emissions were obtained by random sum and multiplication of the simulated emission factors and activity level.

3. Results

3.1. Greenhouse gas emissions in Shanxi Province

GHG emissions in Shanxi Province were 802 Mt CO_2eq in 2020 (90% confidence interval: 708−894 Mt CO_2eq), in which CO_2 emissions were the main contributors (611 Mt CO_2eq, accounting for 76%), which was much higher than the contribution of non-CO_2 emissions. Our findings reveal that energy-related activities primarily contributed to CO_2 emissions, accounting for 89%. Within energy-related emissions, coal combustion constituted a significant portion (82%) (Fig. 2). In 2020, Shanxi ranked first in coal production among all provinces in China. The key factor is that Shanxi's heavy industry mainly relied on coal, leading to coal consumption accounting for over 80% of primary energy usage (Fig. 3a). Secondly, as a crucial energy supply base and electricity outputter, the rising electricity demand has led to a sharp increase in coal mining and consumption in the province. Industrial processes accounted for 11% of CO_2 emissions, mainly from the cement, lime, and steel industries, accounting for 3.6%, 3.5%, and 2.1% of CO_2 emissions, respectively. For non-CO_2 emissions, the primary source was methane emissions from coal mining, accounting for about 94% of non-CO_2 emissions (191 Mt CO_2eq) (Fig. 2).

For spatial distribution, our results show emission characteristics of agglomeration, with Datong as the agglomeration center in the north, Taiyuan and Lvliang in the central area, and Jincheng and Yuncheng in the south (Fig. 4a). The predominance of coal mining, coal power, steel, and coking industries results in relatively high emissions in these areas.

In terms of contributions by sector, the electricity and industry sectors are the prevalent carbon-emitters in Shanxi Province, with 285 Mt CO_2eq (47% of total CO_2 emissions) and 220 Mt CO_2eq (36%), respectively (Fig. 2). The reliance on thermal power (85%) is a crucial factor contributing to this (Fig. 3a). Steel and coke are pivotal industries in Shanxi, with the province ranking fifth in steel output and first in coke output nationally. The two industries consume nearly 80% of the coal in the industrial sector (Fig. 3a) and emerge as the primary emitters, contributing 113 and 55 Mt CO_2eq, respectively. Transportation is the third largest emission sector with 18 Mt CO_2eq. As a resource-exporting province, road transportation dominated by diesel vehicles leads to high emissions. The residential building sector, service building, and agriculture have relatively low carbon emissions, amounting to 10.8, 7.5, and 3.5 Mt CO_2eq, respectively, accounting for only about 4% of total emissions (Fig. 2). The proportion of low emissions is primarily attributed to electricity-based energy structures.

Currently, carbon removal in Shanxi Province is dominated by carbon sinks (33 Mt) (Fig. 2), and carbon storage mainly comes from arbor forest land (Fig. 4b). In 2020, Shanxi's total forest land carbon storage was 4.14 billion tons, of which arbor forest accounted for 62.1%, shrub land 22.7%, other forests 13.8%, bamboo forest 0.01%, and other biomass carbon reserves 1.3%. The spatial distribution of carbon density (carbon storage per unit area) in Shanxi Province generally exhibits an increasing trend from north to south and west to east.

3.2. Pathway toward carbon peak and neutrality in Shanxi Province

Shanxi Province exhibits a similar trend of GHG emissions with a gradual increase and peak followed by a consistent decrease under both BAU and low-carbon scenarios. Yet, the two scenarios differ significantly in terms of the timing of carbon peak and the feasibility of carbon neutrality. Various factors contribute to these differences, including energy structure transformation, low-carbon technology innovation, and production capacity control.

Under the BAU scenario, Shanxi Province will fail to reach a carbon peak before 2030, mainly due to the rapid growth of emissions from the electricity sector, transportation sector, and non-CO_2 emissions. Shanxi Province's CO_2 emissions will peak in 2032, reaching 696 Mt (14% higher than the 2020 level, 90% confidence interval: 620−771 Mt CO_2eq, Fig. 5a). The emission peaks for the electricity and transportation sectors would both be later than for the overall economy. In the electricity sector, carbon emissions are projected to peak in 2035, reaching 395 Mt (Supplementary Material Table S1). The main reason is that Shanxi transfers electricity to other regions. In the short term, the renewable energy will struggle to meet the growing national demand for electricity. To ensure energy security, coal-fired power generation capacity is expected to increase further. In the transportation sector, although the volume of bulk cargo such as steel and cement will decrease from 2020 to 2035, the demand for high-value, dispersed, and time-sensitive freight will rise rapidly. The growth of freight demand would result in carbon emissions reaching 26 Mt in 2035, showing an increasing trend year by year. In addition, an increase in coal mining leads to increased methane emissions, which is the main source for the growth of non-CO_2 emissions.

In contrast, the industry and building sectors would be the major contributors to emission reduction before 2035. The carbon emissions of the industrial sector will be reduced to 213 Mt by 2030, a 3% decrease from 2020, and will be reduced to 199 Mt by 2035, showing a downward trend year by year (Supplementary Material Table S1). The reduction in the output of major steel, cement, etc., coupled with the application of low-carbon technologies, such as short process steelmaking in the steel industry,

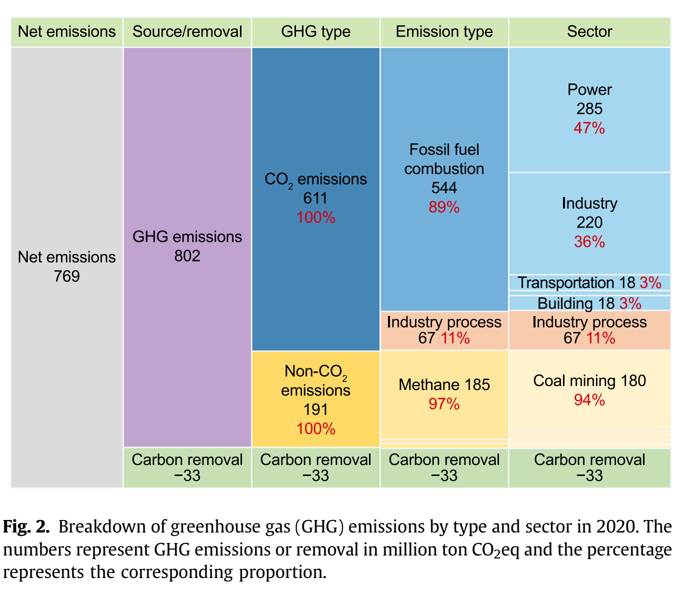

Fig. 2. Breakdown of greenhouse gas (GHG) emissions by type and sector in 2020. The numbers represent GHG emissions or removal in million ton CO_2eq and the percentage represents the corresponding proportion.

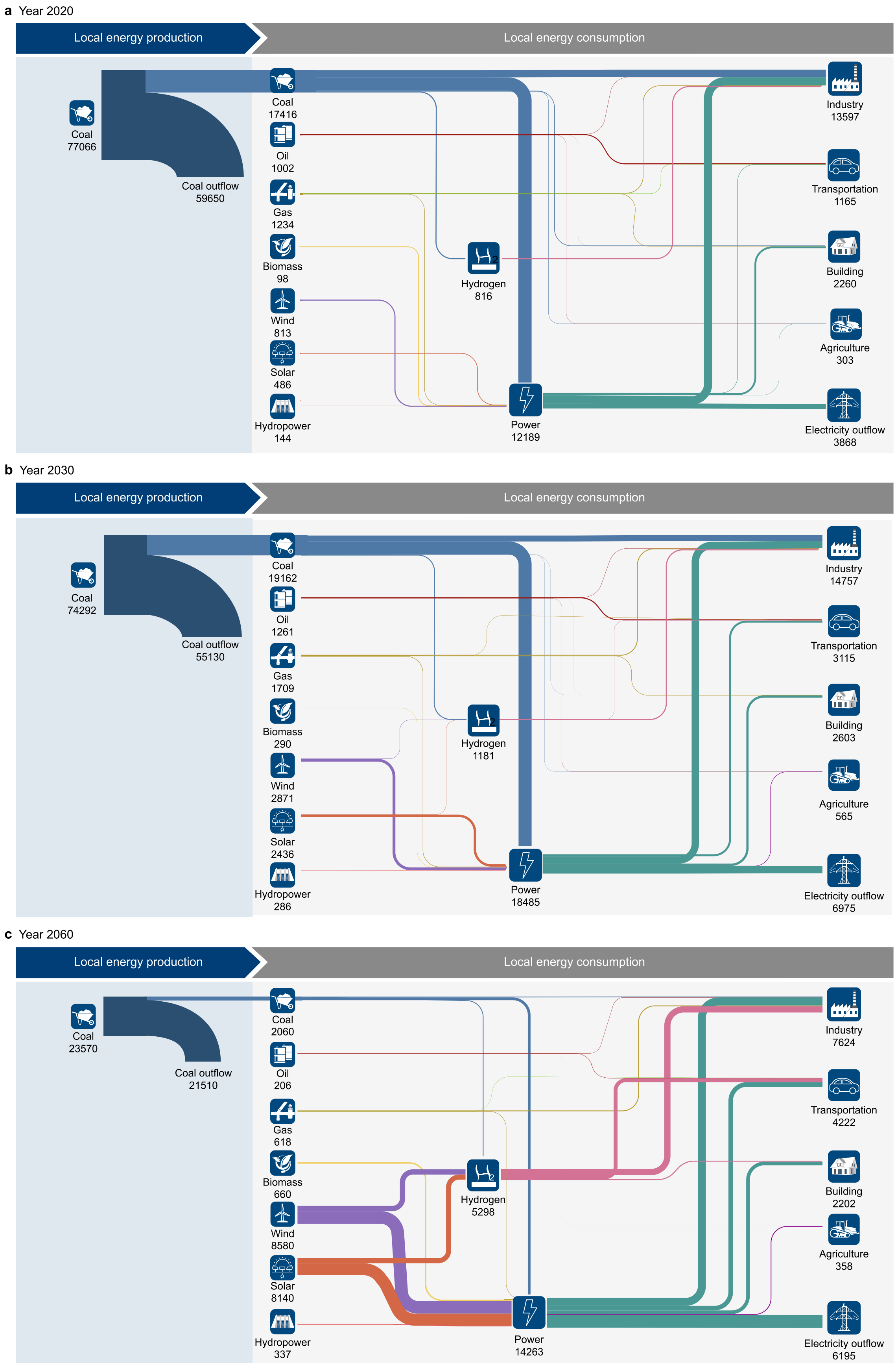

Fig. 3. Energy flow map in the years 2020 (**a**), 2030 (**b**), and 2060 (**c**) under the low-carbon scenario in Shanxi. The numbers represent the energy production or consumption in 10 thousand tons of standard coal equivalent.

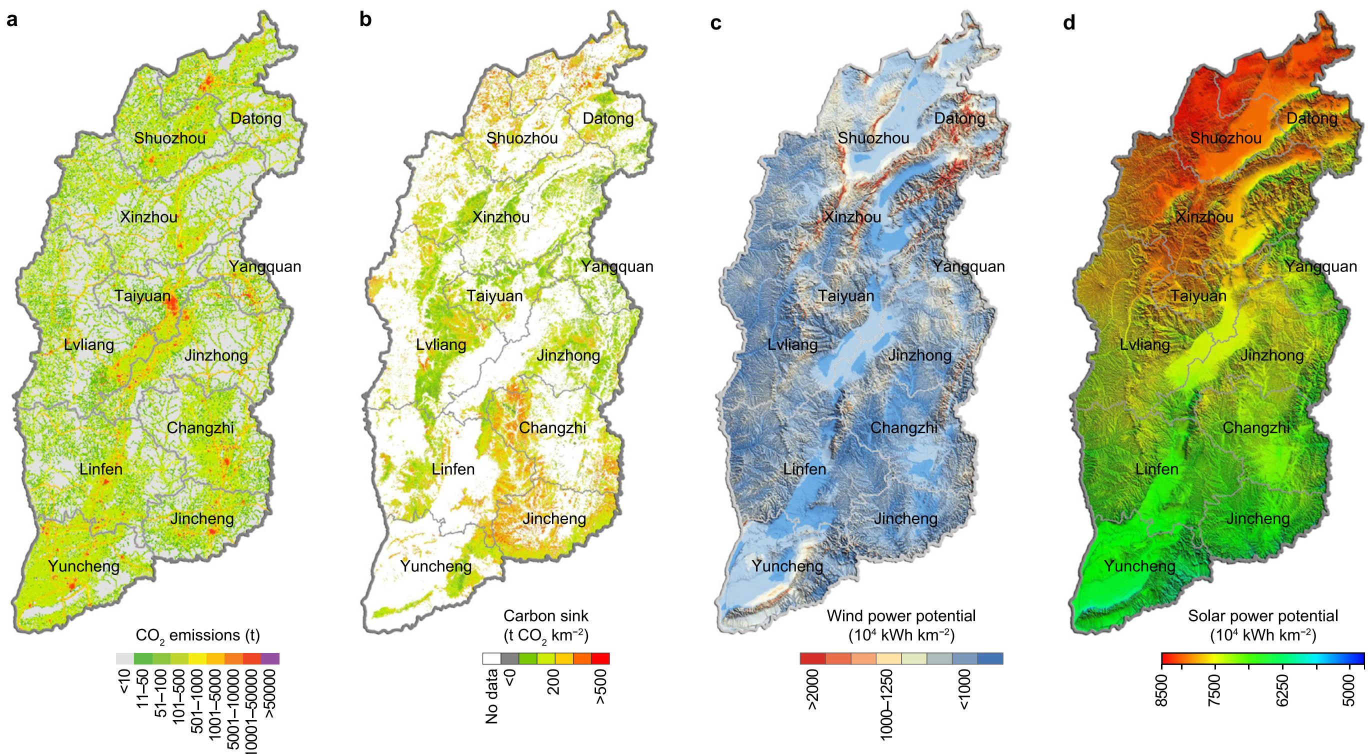

Fig. 4. **a**, Spatial distribution of CO_2 emissions in 2020 in Shanxi. **b**, Carbon sink estimation in Shanxi. **c**–**d**, The new energy potential of wind (**c**) and solar (**d**) power in Shanxi.

alternative fuel and raw material use in the cement industry, will lead to a decrease in industrial emissions. However, the economic and social demand for products in industries such as coal chemical industry will have increased, providing indispensable basic materials for the economic system, during the 2020–2030 period. There will have been a certain increase yearly, resulting in a smaller decrease in CO_2 emissions from the industrial sector. The building sector also shows a downward trend year by year. By 2030, emissions will drop to 11.3 Mt, a decrease of 6.9 Mt (down 38%) from 2020, and to 10.3 Mt in 2035 (Supplementary Material Table S1), mainly due to the increase in the proportion of electric energy utilization in the construction sector.

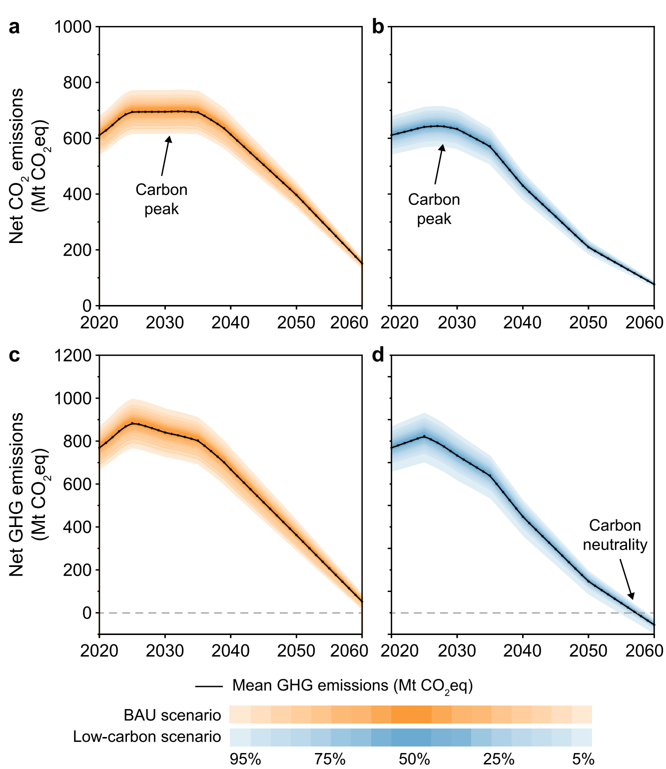

Fig. 5. Net CO_2 (**a**, **b**) and greenhouse gas (GHG; **c**, **d**) emissions projections under Business-as-usual (BAU; **a**, **c**) and low-carbon (**b**, **d**) scenarios.

In 2060, net GHG emissions will still be 52 Mt CO_2eq (90% confidence interval: 18–86 Mt CO_2eq), short of achieving the carbon neutrality goal. In detail, GHG emissions will drop to 177 Mt CO_2eq, and carbon sinks and CCUS removals will account for 125 Mt CO_2eq (Fig. 5c). Due to the large-scale development of clean energy, fossil fuel-based power generation will decrease to 0.10 trillion kWh, causing carbon emissions from the power sector to drop to 96 Mt CO_2eq. In the industrial sector, as the output of steel and other industries drop significantly and energy efficiency levels are improved, carbon emissions from the industrial sector will fall to 39 Mt CO_2eq; with the rapid development of vehicles running on "new" energy, the transportation sector's CO_2 emissions decrease to 4 Mt. In the building sector, electricity will rise to 90% of total energy consumption, and CO_2 emissions drop to close to zero. As a result of reduced coal mining volume, non-CO_2 emissions will drop to 26 Mt.

Increases in forest carbon sinks and the development of CO_2 removal technologies such as CCUS will successively reduce GHG with 58 and 67 Mt CO_2eq in 2060, respectively. Arboreal forests will perform an effective function of increasing sinks, while broad-leaved, artificial coniferous, and natural coniferous forest carbon sink potential may gradually weaken after 2055. Forest carbon sink potential is 46 and 58 Mt, and CO_2 removal with CCUS will increase to 12 and 67 Mt in 2030 and 2060, respectively.

Under the BAU scenario, Shanxi's failure to achieve carbon neutrality would severely impede China's energy transition. Its heavy reliance on coal would delay its decarbonization and jeopardize national targets, including reducing coal consumption to below 20% and increasing non-fossil energy to over 80% by 2060. As a major energy supplier—contributing 13.2% of China's coal consumption, 5.6% of thermal power generation, and exporting 32% of its electricity—Shanxi's inaction would risk carbon neutrality for recipient provinces. Transitioning to a low-carbon pathway is essential to align with national goals, ensure energy security, and mitigate systemic risks.

Under the low-carbon scenario, vigorous renewable energy development would optimize the power structure. Moreover, Shanxi Province would adopt stricter production capacity control and advanced technology applications in the industry sector, further optimize energy consumption structures in the transportation and building sectors, and apply carbon removal technologies on a large scale. The above would prompt Shanxi Province to achieve carbon peak and carbon neutrality goals sooner.

In the near term, the increased proportion of renewable power generation will determine that Shanxi will reach its peak in 2027, with emissions of 643 Mt (90% confidence interval: 573–713 Mt CO_2eq), meeting China's national requirements for peaking before 2030 (Fig. 5b). It is predicted that its energy consumption structure will be further optimized, as the proportion of non-fossil energy consumption increases to more than 17%, and coal consumption drops to less than 70% (Fig. 3b). Under the low-carbon scenario, the power industry will face severe challenges due to an increase in electricity demand resulting from export it. This is causing the region to lag behind the overall provincial peaking schedule. Its CO_2 emissions will peak in 2030 at 348 Mt, marking a 22% rise from levels in 2020 (Supplementary Material Table S1). However, this represents a reduction of 32 Mt, equivalent to an 8% decrease compared to the BAU scenario (Fig. 6). Increased installed power capacity will contribute to the fulfillment of energy needs, reaching 206 GW in 2030, and the proportion of clean energy power generation will increase to 30% (Fig. 3b). Meanwhile, the phaseout of small coal-fired units (below 300 MW) will be further intensified, resulting in a more rapid decrease in carbon emissions. Increasing the peak regulation capacity of coal-fired units and implementing energy storage measures more efficiently are essential for the low-carbon transformation of the power sector. Results show that in 2030, coal-fired power units should collectively possess a peak regulation capacity of no less than 50%. The energy storage system configuration should reach 18 GW (based on a short-term energy storage backup of 8 h).

In addition, in the industrial sector, the reduction in emissions can also be attributed to decreasing demand for major industry products such as steel, cement, and coke, as well as further enhancements of process structures in the steel and coke industries and implementing stricter energy efficiency requirements. In 2030, CO_2 emissions from the industrial sector will reach 191 Mt (29 Mt less than in 2020), which is 21 Mt (10%) less than the BAU scenario (Fig. 6, Supplementary Material Table S1). The transportation sector is the foundational support and assurance for mobility and logistical services. Transportation volume is continuously increasing with the rapid development of the economy and society and the continuous improvement of individual living standards. This escalation is a principal reason for rising CO_2 emissions. However, under the low-carbon scenario, the increased use of railways for transportation and the development of pure electric and hydrogen fuel cell commercial vehicles have become the main contributors to carbon emission reduction. In 2030, CO_2 emissions will increase slightly to 22 Mt (4.5 Mt more than in 2020), still 3.7 Mt less (14%) than the BAU scenario (Fig. 6, Supplementary Material Table S1).

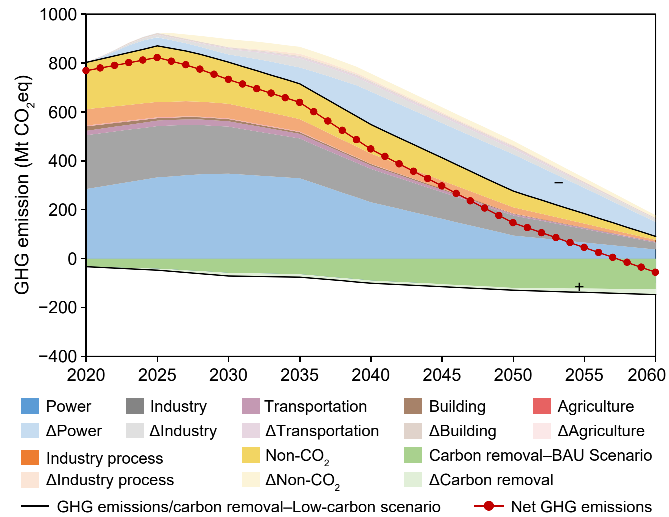

Fig. 6. Greenhouse gas (GHG) emission pathway under low-carbon scenario and the difference between business-as-usual (BAU) and low-carbon scenarios by sector. The minus sign (−) represents the GHG emission reduction, and the plus sign (+) represents carbon removal enhancement under the low-carbon scenario compared to the BAU scenario.

Due to the optimization of the energy structure, consumption of electricity in the building sector further increases (reaching 60%), 3 Mt (29%) less than in the BAU scenario in 2030 (8 Mt, 56% lower than in 2020). Tighter controls in coal mining will reduce non-CO_2 emissions to 170 Mt CO_2eq in 2030, 16% lower than the BAU scenario (Supplementary Material Table S1).

During the period leading toward carbon neutrality, a significant reduction in carbon emissions will rely on the power and industrial sectors, as well as the promotion of carbon removal technologies. Under the low-carbon scenario, the energy consumption structure of Shanxi Province will have been further optimized, incorporating natural wind and solar resources and the development of hydrogen energy by 2060. Non-fossil energy consumption in Shanxi Province will reach 75%, and coal consumption will reach 17% (Fig. 3c). GHG emissions in the region will decrease to 91 Mt CO_2eq, and carbon sink and CCUS will reach 147 Mt CO_2eq by 2060, achieving carbon neutrality by 2060 (90% confidence interval: 2056–2059, Fig. 5d and 6).

Mitigation of the power sector mainly relies on further improvements in the power structure, resulting in GHG emissions decreasing to 37 Mt by 2060, a fall of 59 Mt (61%) compared to the BAU scenario (Fig. 6). According to our estimates, the technical potential of installed capacity for wind in Shanxi Province (Fig. 4c), which factors in meteorology, terrain, land use, and existing technology conditions, is 0.16 Terawatt (TW). The potential of installed solar photovoltaic (PV) capacity in Shanxi Province (Fig. 4d), considering available sunlight (we use the in Global Horizontal Irradiation index in our estimation), geographical environment (terrain conditions, including elevation, slope, and slope to terrain undulation) and PV equipment, is 5.04 TW. In 2060, the proportion of installed capacity and power generation from wind and solar energy will reach 89% and 87% (Fig. 3c). Coal-fired power capacity and electricity generation decrease to 7%. To expand on this, coal-fired power generation will decrease to 50 billion kWh, wind power generation will increase to 321 billion kWh, solar power generation will increase to 296 billion kWh, gas-fired power generation will decrease to 7.2 billion kWh, and hydropower and biomass power generation will increase to 12.3 billion kWh and 24 billion kWh, respectively. Using CCUS technology, coal-fired power units can achieve carbon neutrality before 2058 (Fig. 5d and 6). Regarding energy storage needs, achieving the comprehensive participation of coal-fired units in peak management is imperative. Additionally, emerging energy storage technologies with extended temporal efficacy and larger storage capacity are essential. Examples of such technologies include pumped hydro storage. Estimations show that the medium-to long-term energy storage capacity required should be no less than 95 billion kWh by 2060, and the configuration of the energy storage system for construction is 50 GW (based on short-term energy storage and a backup time of 10 h). The cumulative cost under the low-carbon scenario, including investment, fixed, and variable costs (for detailed parameters, refer to the China Carbon Neutrality Technology Database, http://cntd.cityghg.com/) for the power sector transition is estimated to be CNY 2.0 trillion during the carbon peak period (2020–2030) and CNY 10.4 trillion during the period leading up to carbon neutrality (2020–2060).

Other than the power sector, demands for steel, coke, and cement will further decline in the industrial sector. Together with structural adjustments and the increased application of low-carbon technologies, these transformations lead to a continuing reduction in carbon emissions. By 2060, carbon emissions will have decreased to 27.8 Mt or 11.5 Mt (29%) lower than the BAU scenario (Fig. 6). Due to a 100% increase in new vehicles in the transportation sector, carbon emissions from the transportation sector will decrease to 3.7 Mt by 2060, which is 9% better than the BAU scenario. One result of 100% replacement of electricity for energy in the building sector, CO_2 emissions will be reduced to zero. Decreased coal mining output in the carbon neutral phase and the tightening of methane emission control lead to non-CO_2 emissions being decreased to 14.8 Mt, which is 11.2 Mt lower than the BAU scenario (down 43%) (Supplementary Material Table S1).

For carbon removal, the large-scale application of CCUS technology and precise nurturing of forests collectively enhance the reduction of carbon emissions. Carbon storage is primarily located in the Qinshui–Linfen Basin (Supplementary Material Fig. S2), with a storage capacity of 50–100 Mt. By 2060, carbon offset emissions will have increased to 147 Mt CO_2eq. With the further expansion of CCUS applications in steel and coal-fired power plants, the carbon removal volumes will be 12 and 74 Mt, respectively, in 2030 and 2060 (Fig. 6). In terms of carbon sinks, increased potential of broadleaf forests and mixed forests is the main reason for increases. Carbon sinks are mainly located in the Taihang Mountains, the Lvliang Mountains, and the four major ecological barrier areas. Expanding areas of young and middle-aged forests mean that forest carbon sink potential will be 59 and 73 Mt, respectively, in 2030 and 2060. Shanxi's abundant young forests offer significant carbon sink potential. By improving stand structure and forest management, forest carbon sink will increase 15 Mt more than the BAU scenario by 2060.

4. Discussions and conclusions

Mitigating energy-intensive provinces is crucial to China's achieving carbon neutrality on schedule. This study establishes emission reduction scenarios and conducts empirical analyses of a typical energy-export province—Shanxi. Considering energy supply security, external electricity demand, and national overall peak progress, Shanxi Province should follow a low-carbon scenario to achieve its carbon peak around 2027 and emission neutrality before 2060. The power sector plays a key role in carbon peaking, with renewable electric energy projected to exceed 180 billion kWh and 680 billion kWh in 2030 and 2060, respectively. The industry, transportation, and building sectors can mitigate emissions through product output reductions, improvements in energy efficiency, and the adoption of low-carbon technologies. Methane emissions from coal mining are significant contributors to GHG totals, emphasizing the need to address its reduction through climate action strategies. Compared to the national CO_2 emissions pathway toward carbon neutrality, which is projected to peak around 2028–2029 [66,67] and decline to approximately 1–2 Gt CO_2 by 2060 [66–68], Shanxi's emissions may peak slightly earlier but will require a relatively larger proportion of carbon sinks to be completely offset by 2060.

We propose various suggestions for energy-oriented provinces, including the establishment of a comprehensive policy support system, coordinated promotion of energy supply guarantees and mitigation efforts, construction of renewable energy systems, and the application of carbon removal technologies. Achieving carbon neutrality in China depends on coordinated efforts across government, industry, and society. The government provides top-level guidance on energy planning, coal supply security, and carbon emission regulations. Industries act as key implementers, improving energy efficiency and adopting low-carbon technologies to meet emission targets. Society influences carbon neutrality through consumption patterns and lifestyle changes [69], impacting sectors like transportation and construction. Aligning these stakeholders strengthens the effectiveness of China's carbon neutrality strategies.

A comprehensive top-level policy design is a powerful guarantee for achieving carbon peak and carbon neutrality. As a major province involved in the external transfer of energy, the future development of Shanxi Province will be greatly influenced by changes at the national economic level, requiring support from relevant national policies. To conduct a pathway analysis, we refer to central government policies [15], Shanxi provincial plans [6,44,48,50,52,56], and Shanxi's resources and industry characteristics [51]. We suggest that the local government formulate differentiated scale control policies for new-built coal-fired plants [24] and promote the gradual low-carbon transformation of the power sector. The local government should formulate policies conducive to supporting the investment and construction of renewable energy projects and promote the construction of a new power system with renewable energy as the core [70], particularly in regions with high ecological vulnerability [71]. Additionally, methane emission management plans should be implemented throughout the industry chain, focusing on coal mining control strategies and management systems [72].

Shanxi, as an energy-rich province, plays a critical role in ensuring national energy supplies, which means that regional mitigation pathway planning needs to be coordinated with local conditions and national needs. This aligns closely with the requirement of adhering to a unified national strategy and achieving carbon peaks across different regions in a coordinated manner [15]. Given its role as a major energy source, coal output in Shanxi Province will remain high for a certain time in the future. Considering the limited scale and growth rate of renewable energy, the coal industry has become the key in determining whether Shanxi can reach its scheduled carbon peak. However, carbon emission levels from coal-based electricity are highly unstable due to dynamic adjustments in electricity exports based on national demand. Therefore, it is recommended that Shanxi Province's functions and development needs are considered from a national perspective when planning reduction strategies. For national policymakers, achieving climate goals requires tailored approaches that integrate both traditional and renewable energy sources, ensuring alignment between provincial and national efforts. Policies should also be flexible, adapting to regional development stages for smooth transitions while addressing procedural justice and equity concerns [71,73].

The orderly phaseout of fossil fuels requires the secure and reliable integration of renewable energy sources. Determinant feasible pathways for a secure and stable power system involves considering factors such as national coal and electricity demand, Shanxi's wind and PV potential, the capacity for energy storage facilities, and the increased flexibility of coal-fired units [74]. As China progresses towards its carbon peaking and carbon neutrality goals, the large-scale deployment of renewable energy installations presents the challenge of integrating renewable energy electricity into the power grid. We recommend conducting a scientific assessment of energy storage demand in response to the integration of new energy sources. Moreover, construction of flexible energy sources and energy storage facilities should be accelerated in Shanxi Province [75]. Leveraging local resource advantages and characteristics, establishing a flexible and complementary regulation system to ensure the transition of coal-fired power plants from a major power source to flexible backup function is recommended. Meanwhile, hydrogen energy is a crucial pillar of the energy technology revolution toward carbon neutrality, both in China and globally. Shanxi Province's renewable resources and industrial base offer significant potential for the clean, low-carbon production and large-scale utilization of hydrogen. Advancing hydrogen technologies to ensure its safety, building a robust industry chain, and promoting cross-sector applications will position hydrogen as a key component in supporting Shanxi's energy system [26].

Carbon mitigation technologies in all sectors are crucial for achieving carbon neutrality. Besides electricity, all other sectors must make important contributions to carbon emission reductions. Cutting emissions in the industrial sector largely relies on the implementation of low- and negative-carbon technologies. Conversely, the building, transportation, and other sectors will achieve mitigation primarily through electrification. However, achieving carbon neutrality requires more than mitigation measures. We recommend the vigorous promotion of CCUS in Shanxi's coal power, steel, and other industries by accelerating the deployment of large-scale CCUS industrialization pilot projects [76], as experimental research will confirms its cost, viability, readiness, and ability to scale [77].

Given Shanxi's status as a representative energy-producing province and the significant mitigation challenges it faces, the results of this study hold immense value, offering operational, replicable, and extensible experiences and practices, particularly for subnational governments that rely heavily on fossil fuels. This research strongly recommends future studies into the development of feasible and effective carbon neutrality roadmaps. Nevertheless, this study has limitations that offer opportunities for further improvement. Firstly, although this paper accurately calculates carbon emissions in Shanxi Province and includes many factors in its simulation of a carbon emission pathway, data uncertainty can be reduced. Uncertainties in technology adoption, cost reductions in renewable energy, socio-economic developments, societal preferences, and recent policy changes could impact the feasibility of carbon mitigation pathways [64,78]. Incorporating more detailed spatial and temporal modeling can improve strategy robustness [79]. Secondly, different GHG emission pathways are constrained by technological and economic conditions and have varying impacts on the socio-economic system in the long term [80]. Research could be carried out at a more micro scale level. Carbon emissions, decoupling effects, and mitigation costs could be estimated at a more refined scale to include heterogeneity in the low-carbon development process in Shanxi Province. Therefore, it is imperative to consider both economic development and the cost of innovative technologies. Future research will analyze the role of emission reduction technology in the process of low-carbon development in more detail and then support China and Shanxi Province in formulating energy conservation and emission reduction policies. Even with these limitations, our results are expected to shed light on future pathway planning for provinces in China and other countries.

CRediT authorship contribution statement

Li Zhang: Writing - Original Draft, Visualization, Methodology, Investigation, Data Curation, Conceptualization. **Mingyu Li:** Writing - Original Draft, Investigation, Data Curation. **Zhe Zhang:** Methodology, Data Curation. **Linyan Li:** Writing - Review & Editing. **Jin Yuan:** Data curation. **Shuying Zhu:** Visualization, Investigation. **Huili Wang:** Writing - Original Draft, Visualization, Supervision, Investigation, Data Curation, Conceptualization. **Min Jia:** Writing - Review & Editing. **Jianhui Ruan:** Writing - Review & Editing. **Lingyun Pang:** Visualization. **Yingying Gu:** Visualization. **Shu Ye:** Data curation. **Xiaojun Chen:** Investigation. **Lirong Zhang:** Supervision. **Bofeng Cai:** Methodology, Conceptualization. **Jinnan Wang:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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