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Provincial employment effects of coal mine retirement in China's carbon-neutral transition

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ABSTRACT

China's just transition toward carbon neutrality requires carefully designed coal mine retirement strategies that balance climate objectives with social equity and regional development disparities. In this study, we propose a comprehensive analytical framework combining the RUC-MESSAGEix-China (RMC) integrated assessment model with facility-level coal mine data to evaluate three distinct retirement strategies across China's 19 major coal-producing provinces. The cost-optimal strategy prioritizes economic efficiency, the employment-oriented strategy emphasizes social equity, and the balanced strategy seeks an optimal solution between competing objectives. The results show that while all strategies achieve similar retirement targets by 2060, they follow dramatically different pathways. The balanced strategy emerges as optimal for most provinces like Anhui, preserving cumulatively 1.78 million additional job-years compared to cost-optimal strategies. By 2060, the cost-optimal strategy concentrates all remaining operations in efficient regions like Xinjiang and Inner Mongolia, while the employment-oriented strategy preserves a broader industrial footprint across provinces like Henan, Shanxi, and Liaoning. Furthermore, provincial analysis reveals substantial heterogeneity: high-production, high-GDP provinces like Shanxi benefit from gradual transitions, while resource-constrained regions like Guizhou require targeted support. The carbon capture and storage scenario demonstrates an improved performance on employment, facilitating an extended employment transition period and enhanced job retention. These findings highlight the necessity of differentiated, location-specific just transition policies rather than uniform national approaches, ensuring no region is left behind during China's decarbonization.

1. Introduction

Despite rapid deployment of renewable energy in recent years, coal still dominates China's energy supply, with coal-fired power generation accounting for over half of the country's electricity supply (G. Wang et al., 2022). China's ambitious decarbonization targets, that is, peaking carbon dioxide (CO_2) emissions by 2030 and achieving carbon neutrality by 2060, require systematic energy transitions that directly challenge coal's entrenched position in China's energy landscape (X. Qian et al., 2021). In pursuit of the goals, a just strategy on retiring existing coal mines holds practical significance, as China is the world's largest coal producer and has millions of employments in the coal-mining industry (Gao et al., 2025; W. Li et al., 2015).

Despite amount of studies on phasing-out coal power plants (Cui et al., 2021; Maamoun et al., 2020; Shrimali, 2020) and the implications on employment (Hamilton et al., 2022; Niu et al., 2024), the related research on coal mining industry seems insufficient. In particular, how coal mines retirement causes heterogenous impacts on employment at the provincial level considering enormous regional disparities on coal resource distribution, industrial structure, energy consumption, and other socio-economic development in China. Compared to power plants, coal mining operations face fundamentally different challenges due to their upstream position in the value chain, deeper community integration, and complex closure processes that vary significantly across

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regions (Auger et al., 2021). Coal mine closures often lead to massive unemployment and social instability, challenges that are particularly pronounced in coal-dependent regions (Gong and Lewis, 2024a; Heffron, 2021). Some studies addressed the coal mine retirement issues in scattered provinces or focused on the associated environmental impacts (D. Chen et al., 2022; H. Chen et al., 2023; X. Wang and Lo, 2022). Whereas the impacts on employment, particularly considering the regional heterogeneity, are not sufficiently investigated. Just transition necessitates regionally differentiated strategies that ensures no region or group is left behind during the process, yet there lacks systematic research to assess how economic resilience, employment vulnerability, and transition capacity influence coal mine retirement across provinces (Gong and Lewis, 2024a).

To address this research gap, this study aims to analyze the impacts of provincial coal phase-out pathways on employment in multiple dimensions to explore the corresponding coal mine retirement strategies tailored to specific provincial contexts, thereby promoting China's just transition toward carbon neutrality. By combining China's mine-level data with an integrated energy-economy-environment (3E) model, namely, RUC-MESSAGEix-China (RMC) (School of Applied Economics, Renmin University of China, 2025), this study evaluates three distinct retirement strategies under two scenarios both meeting the dual carbon goals, i.e., a carbon-neutral scenario provides a baseline pathway of coal phase-out, while another carbon-neutral scenario carbon capture and storage (CCS) serving as an alternative case to assess the strategy robustness under a technological route featuring higher penetration of CCS that allows more coal consumption in reaching the goal. The three retirement strategies represent different policy priorities: the cost-optimal strategy emphasizes economic efficiency by retiring high-cost coal mining operations first, the employment-oriented strategy prioritizes social equity by preserving high-employment mines, and the balanced strategy seeks to optimize the trade-off between efficiency and equity concerns. Through a comprehensive analysis of these strategies across China's 19 coal-producing provinces, this study examines regional heterogeneity in the dynamics of coal mine employment to provide empirical insights for differentiated just transition policies.

Our findings indicate that an improved strategy, reflected in the balanced strategy, proves advantageous for most provinces, retaining cumulatively 1.78 million additional job-years relative to efficiency-focused approaches. Provincial outcomes vary markedly: resource-rich and well-developed provinces may benefit from gradual transitions, while resource-constrained regions require targeted support to achieve the goal of a just transition. In the scenario of carbon-neutral with CCS, employment-oriented strategy demonstrates enhanced effectiveness through an extended phase-out period. These results emphasize that equitable decarbonization demands region-specific policy design rather than nationally uniform implementation.

This study contributes to the literature in three aspects. First, by incorporating detailed coal mine data into the analytical framework, we reveal the role of provincial employment patterns in determining appropriate retirement pathways. Second, we make three retirement strategies, prioritizing cost minimization, employment preservation, and balanced objectives respectively, instead of single-criterion optimization prevalent to explicitly examine efficiency and equity trade-offs. Third, through systematic comparative analysis covering China's 19 coal-producing provinces, we identify how variations in regional economic capacity and resource dependence shape strategy performance, thereby providing province-specific strategic insights in China's just transition.

The remainder of this work is organized as follows: Section 2 summarizes existing literature on coal phase-out and the related employment issues in just transition; Sections 3 and 4 introduces the methods, scenario settings and the data; Section 5 demonstrates the results; and Section 6 concludes and discusses policy implications.

2. Literature review

The strategic retirement of coal related infrastructure has emerged as a critical research domain within the broader energy transition literature. Existing research on coal phase-out has primarily focused on the retirement of coal-fired power plants. These studies typically establish retirement priority assessment frameworks based on power plant age, environmental pollution levels, economic efficiency, or multidimensional composite indicators to determine decommissioning sequences (Cui et al., 2021; Yu et al., 2019; Yuan et al., 2018), or concentrate on quantitative analysis of the stranded assets (Auger et al., 2021; Pan et al., 2023). Research on upstream coal mine closure has predominantly approached the issue from environmental and economic perspectives: the environmental perspective primarily analyzes factors such as methane emissions to determine coal mine closure priorities and technical scenarios (D. Chen et al., 2022; Kang et al., 2024; Q. Liu et al., 2024); the economic perspective focuses on inter-provincial variations in coal mine retirement scales, retirement cost accounting, and regional economic impact assessments (Ai-bin et al., 2009; Kang et al., 2024), yet these prevailing economic and environmental frameworks often neglect facility-level social consequences, such as regional employment displacement and broader implications for a just transition.

Research on coal mines and just transition primarily focuses on the political bargaining processes during transition and their impacts on social equity (Gong and Lewis, 2024a; Sovacool et al., 2017; X. Wang and Lo, 2021). However, most studies concentrate on the overall transformation of coal-related industries rather than specifically targeting coal miners, and pay more attention to differences between various interest groups (Carley and Konisky, 2020). Additionally, existing research largely adopts a macro-level perspective to compare coal mine retirement transitions between other countries and China as a whole, lacking differentiated analysis at the provincial level (Michieka et al., 2022). These research orientation overlooks the direct impact of coal mine closures on local employment, while closure decisions actually involve not only cost-benefit considerations but also require striking a delicate balance between avoiding mass unemployment and maintaining social stability (W. Zhang et al., 2023).

Research on the employment impacts of coal phase-out has been conducted across several dimensions. First, macro-level studies typically examine the effects of coal retirement on national economic systems, including fiscal impacts resulting from declining coal revenues and rising electricity costs for consumers in a carbon-constraint scenario with projected net job losses and regional economic decline (Farbotko et al., 2020; Oei et al., 2020). Second, some studies employ Integrated Assessment Models (IAMs) to project employment change in the energy sector across different countries, including China (Pai et al., 2021). Additionally, province-specific research has largely focused on single cases of major coal-producing provinces such as Inner Mongolia, exploring regional employment transition scenarios (X. Wang and Lo, 2022), yet the spatial limitation of these single-province analyses prohibit analyzing the heterogeneous impacts across the country.

Within the just transition framework, existing literature often focuses on policy measures aimed at protecting adversely affected groups, including economic compensation for displaced workers and reemployment support measures (Carley and Konisky, 2020; Michieka et al., 2022). Research on the just transition of coal-fired power plants has received considerable attention, particularly regarding how workers can transition from declining industries to green jobs within the context of energy transformation (R. Wang et al., 2025; Wu et al., 2024). Under this circumstance, a crucial dimension is the study of trade-off mechanisms, which typically encompass the linkage effects between coal sector employment and related industries, and the pursuit of balance between stringent environmental objectives and employment stability(Niu et al., 2024; B. Zhang et al., 2022).

The above literature review shows research gaps in several aspects. First, current coal mine retirement studies predominantly adopt uniform retirement assumptions derived from single dimensions such as environmental factors or economic costs, failing to provide policy-relevant, differentiated retirement strategies based on varying strategic decision objectives. Second, while just transition research explores trade-offs between economic efficiency and social equity, it lacks comprehensive, multi-objective assessment framework explaining how different retirement strategies perform under varying regional contexts and policy priorities. Third, existing studies predominantly employ single-province analyses or aggregated national-level assessments, failing to capture provincial heterogeneity in economic structures and development levels that significantly influence retirement strategy effectiveness. Fourth, although employment considerations are frequently mentioned in just transition literature, research inadequately examines mine-level employment data and how provincial employment characteristics should guide the selection of appropriate retirement strategies. Therefore, this study constructs three coal mine retirement strategies based on cost, employment protection, and comprehensive trade-offs, systematically comparing their differentiated employment impacts across provinces, contributing to both theoretical understanding of coal mine retirement decision mechanisms and scientific evidence for developing tailored coal transition policies and achieving just transition objectives.

3. Methodology

3.1. Methods

The RMC model developed by Renmin University of China, is an integrated 3E model (School of Applied Economics, Renmin University of China, 2025) built upon the worldwide recognized MESSAGEix modelling framework developed by the International Institute for Applied Systems Analysis (IIASA) (Huppmann et al., 2019; IIASA, 2025). The RMC model has a geographic coverage of 31 provincial administrative regions in China, and provides the foundational data on a variety of energy resources, including coal, which serve as the initial constraint for coal mining for each province. Subsequently, the model is used to simulate the two carbon-neutral scenarios, i.e., a baseline case and a case with higher CCS. Based on the results, we implement a systematic retirement strategy for coal mines nationwide by integrating the provincial-level projections from RMC with facility-level data from GCMT-China(Global Energy Monitor, 2022).

For mines labeled as non-operational in the GCMT-China database, we assume production commencement in 2030. We calculate provincial capacity utilization rates by comparing the 2022 provincial coal production targets derived from the constraints with existing total provincial capacity. These utilization rates are then applied to individual mines to calibrate 2022 production levels. For the cost-prioritized retirement strategy, mine-level costs are calculated by multiplying coal production cost by production volumes. To account for production cost variations due to different mining conditions, we apply adjustment coefficients of 1.0, 1.2, and 1.1 to surface, underground, and combined mining operations, respectively (Mohutsiwa and Musingwini, 2015). For the employment-prioritized strategy, employment intensity is measured as the number of workers required per ton of coal production.

We also include methane emission as an environmental variable in the subsequent analysis (G. Liu et al., 2021). Methane is a potent short-lived climate pollutant, possessing a high global warming potential (GWP) significantly greater than that of most other pollutants over a 20-year timescale (Balcombe et al., 2018). Furthermore, coal mine methane (CMM) constitutes a major, quantifiable source of direct operational emissions. The concentrated nature of these resources makes it a critical and measurable factor at the mine level; for instance, the Shanxi, Shaanxi, and Inner Mongolia regions hold 40.6 % of China's coal resources and 54.83 % of CMM (Zhou et al., 2016). Using the GCMT data, we derive methane emission factors for 2022 by dividing each mine's methane emissions by its corresponding production output. These mine-level factors are then aggregated to calculate provincial averages. Assuming constant emission factors over time, future methane emissions are projected by multiplying the model-generated future coal production with the respective emission factors.

Regarding the retirement methodology, when cumulative production capacity from the previous period falls short of provincial constraints, remaining operational mines proportionally increase production to meet targets. Conversely, when cumulative capacity exceeds constraints, mines are retired based on their rankings within each strategy. This approach generates provincial-level coal mine retirement strategies under the strategies with different prioritization, enabling comparative analysis of employment impacts across regions and timeframes.

3.2. Scenarios

Two distinct scenarios implemented by the RMC model to generate the pathways of coal production towards China's carbon neutral target. The carbon-neutral baseline incorporates explicit carbon emission limitations consistent with China's carbon neutrality commitment, with relatively stringent provincial coal production constraints. The carbon-neutral with CCS scenario is characterized by a higher penetration of CCS that allows more coal utilization while achieving emission reduction targets. The modelling horizon is from 2025 to 2060 with a five-year interval. These two scenarios provide corresponding annual coal production projections that serve as aggregate constraints for our subsequent analysis of coal mine retirement scenarios and their employment implications.

Based on the results of the two scenarios from RMC and detailed coal mine data from the Global Coal Mine Tracker (GCMT) for 2022, this study examines three distinct retirements strategies derived from existing research gaps in coal transition scenarios. These three strategies are then operationalized as distinct analytical scenarios to assess their performance under different carbon neutrality scenarios.

The Cost-optimal strategy (COS) prioritizes the retirement of high-cost mining operations to maximize economic efficiency during the transition process. Mine-specific costs are calculated by multiplying each mine's production volume by the regional coal production cost of its corresponding city, with municipal-level cost serving as substitutes where city-level data are unavailable. This market-based approach prioritizes the retirement of mines generating lower net economic value per unit of production, aligning with market-driven transition principles that phase out economically inefficient operations while preserving those demonstrating comprehensive economic efficiency in production costs and coal quality (Shrimali, 2020).

The Employment-oriented strategy (EOS) prioritizes the preservation of high-employment mines by targeting low-employment operations for closure first, reflecting China's longstanding commitment to employment stability and social cohesion. Employment intensity is measured as workforce size per production volume (workers per Mt), identifying mines that provide the greatest employment benefits relative to their output. This policy emphasis on mitigating job displacement and ensuring social stability is underscored by concrete governmental measures, such as the State Council initiate a massive industry consolidation, cutting over 500 million tons of capacity and triggering the introduction of new governmental policies to stabilize affected workers (Gong and Lewis, 2024b), and the State Council further strengthened support for employment stabilization by expanding the scope of social insurance subsidies and encouraging technical schools to recruit relevant unemployed individuals (State Council, 2025).

The Balanced strategy (BAS) integrates both cost and employment considerations through a weighted scoring method. To ensure analytical robustness, cost and employment metrics are first subjected to winsorization at the 5th and 95th percentiles to mitigate the influence of extreme outliers. Subsequently, normalized cost metrics (50 % weight) are combined with inversely normalized employment metrics (50 % weight) to generate composite scores ranging from 0 to 1, with higher-scoring mines prioritized for retirement. The selection of this 50 %–50 % weighting is methodologically justified as it represents the most unbiased approximation of stakeholder neutrality when explicit trade-off preferences are not the immediate focus (Marsh et al., 2017; Yet and Tuncer Şakar, 2020). Furthermore, it directly reflects the dual and equally critical policy objectives of China's energy transition: maintaining coal sector economic efficiency and ensuring social stability through minimizing employment disruption (Y. Qian, 2017). This balanced approach acknowledges the inherent trade-offs between economic efficiency and social equity in energy transitions, seeking to optimize both objectives rather than maximizing either in isolation (Heffron, 2021). To assess the robustness of this weighting scheme, we conduct sensitivity analyses with alternative weight combinations in the supplementary materials.

We use the carbon-neutral baseline as the main scenario to examine three distinct retirement strategies and evaluate their employment implications across provinces. The carbon-neutral with CCS serves as a supplementary case to assess the robustness and comparative advantages of these three retirement strategies under an alternative technological route. This comparative framework design enables systematic evaluation of how each retirement strategy's employment impacts vary across different technological scenarios and prioritization criteria.

4. Data

This study integrates multiple data sources to analyze coal mine retirement strategies under China's carbon neutrality scenarios. The analysis relies on three primary data sources: (1) introduction of RMC integrated assessment model data, (2) detailed coal mine data covering production, employment, and location from GCMT, and (3) supplementary economic indicators from official statistical databases.

4.1. Resource endowments

The RMC model utilizes comprehensive resource data of coal from various sources including national and global databases such as the National Coal Resource Potential Evaluation (China National Administration of Coal Geology, 2016), National Bureau of Statistics, Department of Energy Statistics (2024) and the US Geological Survey (USGS) (Trippi et al., 2015). The model distinguishes between "reserves" (quantities recoverable under existing operational conditions) and "resources" (broader category including quantities not currently extractable but potentially recoverable with future technology or economic conditions). In our study, the remaining coal "resource" of each province serves as the initial, overarching constraint on its cumulative extraction over the modelling horizon.

As of 2022, the national reserve is estimated at around 1890 Gt. The largest endowments are concentrated in Xinjiang and Inner Mongolia, which together hold comparable and dominant shares. Shanxi and Shaanxi follow as the next most resource-rich provinces. Taken together, these four northern regions possess roughly 79 % of the country's total remaining coal resource (Fig. S1).

The projected national pathways of coal extraction, which derived as outputs from the RMC model under various emission limits, show distinct patterns under different scenarios (Fig. S2). Under the baseline carbon-neutral scenario, national coal output peaks at 5.2 Gt in 2030, then declines sharply to only 0.1 Gt by 2060. If CCS is widely deployed in the future, coal production is expected to rise to some extent. In this case, the output is projected to reach a higher peak of nearly 6 Gt per year later in 2035, and the subsequent decline is modest, with 1.8 Gt of annual production remaining by 2060 (Table 1).

4.2. Coal extraction

According to the statistical data on provincial raw coal production from the National Bureau of Statistics for 2015–2022, China's total coal extraction declined markedly in 2015–2016, in response to the capacity-reduction policies, before gradually recovering and surging in 2021–2022. In 2022, national production reached approximately 4.50 Gt, about 20 % above the 2015 level. Similar to resource, coal extraction is highly concentrated in a small number of provinces as well, including Shanxi, Inner Mongolia, Shaanxi, and Xinjiang. Their combined share rose from around 69 % in 2015 to 81 % in 2022, indicating a shift of coal extraction capacity toward northern and northwestern regions with abundant resources (Fig. S3). Among these, Shanxi and Inner Mongolia maintained steady growth, Xinjiang experienced the fastest expansion, while traditional coal-producing provinces such as Shandong and Guizhou saw output declines. Overall, the recent evolution of China's coal production landscape reflects a structural pattern in which dominant provinces have strengthened their position while smaller producers have contracted. Furthermore, to obtain a more granular understanding of China's coal extraction infrastructure, this study employs detailed asset-level information on China's coal mines as of October 2022 from GCMT, which provides a comprehensive source of mine-level operational data in China. The database includes operating coal mines producing 1 million tonne per annum and more, with smaller mines included at discretion.

Table 1
Coal production, mine numbers and workforce size by province in 2022.

Province	Resource (Gt)	Coal Production (Mt/Year)	Mine numbers	Workforce Size
Anhui	23.49	111.77	35	113036
Gansu	54.31	53.52	32	37463
Guangxi	1.63	2.92	1	930
Guizhou	76.33	128.14	95	75686
Hebei	28.41	47.06	23	59406
Heilongjiang	14.68	69.52	28	50152
Henan	46.21	97.73	50	154503
Inner Mongolia	563.79	1174.10	271	137023
Jiangsu	3.16	9.64	5	11552
Jilin	3.1	9.48	5	9234
Liaoning	4.73	31.58	16	40321
Ningxia	63.83	93.55	34	27755
Qinghai	2.03	9.37	3	2430
Shaanxi	138.68	746.05	151	111276
Shandong	18.41	87.53	40	92192
Shanxi	222.44	1307.15	546	590429
Sichuan	11.34	22.24	10	15274
Xinjiang	568.61	412.82	96	35582
Yunnan	22.12	66.59	10	11844

The dataset encompasses operating mines across 19 main coal-producing provinces, capturing key operational characteristics including production capacity, workforce size, geographic location, and operational status. Each mine record includes annual production levels, employment data, and geographic coordinates, providing the granular information necessary for implementing and comparing different retirement strategies. The database includes mines with different operational statuses: Operating, Proposed, Shelved, Mothballed, Closed, and Cancelled, with operating mines forming the primary focus of this analysis.

The data reveal significant provincial variations in coal production, mine distribution, and employment characteristics. Shanxi province leads in both production (1307.15 Mt/year) and total employment (590,429 workers), while Inner Mongolia demonstrates high production levels (1174.10 Mt/year) with relatively fewer mines (271), suggesting larger-scale operations. These provincial differences provide the foundation for analyzing how different retirement strategies may impact regions with varying mining characteristics.

Fig. 1 illustrates the spatial distribution of coal mine production and employment in China for 2022, revealing a clear geographic concentration in northern and northwestern regions, particularly in Shanxi, Shaanxi, and Inner Mongolia provinces. The production and

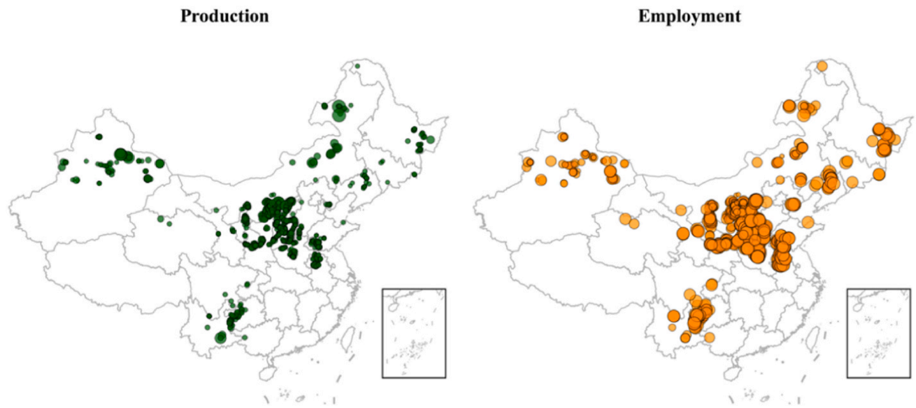

Fig. 1. Coal mine production and employment in 2022.

employment patterns demonstrate strong spatial correlation, with high-capacity mines (large green bubbles) coinciding with major employment centers (large orange bubbles) in the same areas. This clustering reflects the natural resource endowments of northern China, where abundant coal reserves have facilitated concentrated industrial development.

4.3. Supplementary economic data

Coal Mine Production Costs: City-level coal mine average coal production cost are sourced from the Wind Economic Database, following the methodology established by Liu et al. (2024). We use the average transaction price of coal in the city where the coal mine is located to estimate the production costs. These data represent coal sales prices net of taxes and transportation charges, which serve as a proxy for actual production costs of coal mines in this study. To account for geological complexity differences, we adjusted regional coal production costs by mine type: surface mines use original production costs, underground mines face higher extraction difficulty (multiplier = 1.2), and mines with both surface and underground operations use a weighted average (multiplier = 1.1), assuming equal production capacity distribution between the two methods. This market-based cost data provides essential input parameters for the cost-optimal retirement strategy analysis, offering region-specific cost indicators that reflect local mining economics across different geographical areas (Fig. S4).

Provincial Economic Indicators: Per capita GDP data are sourced from the China Statistical Yearbook 2022, providing economic context for assessing the relative impact of coal mine retirement across provinces with different levels of economic development.

5. Results

5.1. Analysis of coal mine retirement across China and provincial scales

Fig. 2 shows the cumulative number of retired coal mines converges by 2060; the temporal dynamics of retirement processes differ significantly. COS maintains the fastest retirement speed, characterized by an aggressive initial decline, while EOS exhibits the slowest pace. These divergent strategies reflect the distinct optimization priorities of each strategy. EOS prioritizes employment preservation by preferentially retiring mines with lower employment intensity, resulting in a more gradual retirement progress. In contrast, COS emphasizes economic efficiency, leading to the most rapid retirement schedule. BAS strikes a balance between efficiency and employment objectives, maintaining a moderate retirement pace that reconciles these competing priorities. Under the CCS scenario, coal mine retirement rates follow the same ranking as in the carbon-neutral baseline, but more mines are retained overall. The three retirement methods yield significantly different outcomes by 2060, with COS retiring the most mines, followed by BAS and then EOS.

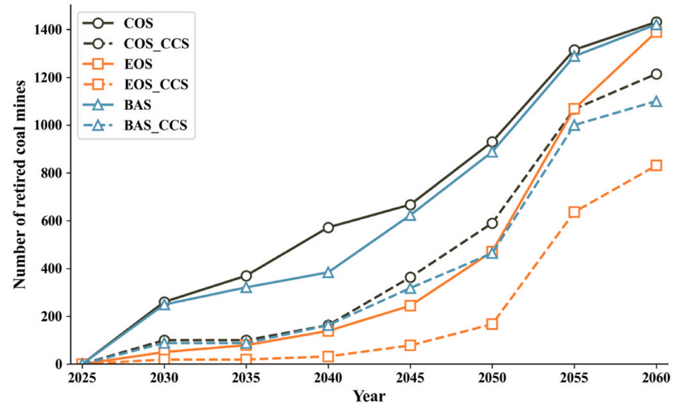

Fig. 2. Coal mine retirement scenarios under different scenarios.

We choose four representatives timepoints for temporal analysis to capture the complete transition trajectory: 2030, 2035, 2040, and 2060. These years mark key milestones in China's national development strategy and industrial planning. Specifically, 2030 and 2035 represent the early stages of the transition, corresponding to near-term climate targets as well as socio-economic development objectives, with 2035 marking the year by which China aims to achieve basic socialist modernization, as set forth by the central government in 2019. The year 2040 denotes an anticipated acceleration phase in coal mine retirement, while 2060 signifies the full realization of the energy transition under China's carbon neutrality goal. This multi-period framework allows us to systematically examine both the near-term dynamics and the long-term pathway of the coal sector's transformation.

Fig. 3 presents the spatial distribution of coal mine retirement at the provincial level in these selected years. By 2035, retirement patterns begin to diverge more clearly among strategies: the COS strategy accelerates retirements in economically inefficient regions such as Shanxi, Shandong and Guizhou, while EOS concentrates retirements in Inner Mongolia's low-employment-intensity mines to preserve jobs in more labor-intensive provinces.

In 2040, different strategies exhibit distinct regional priorities. The COS strategy shows the highest coal mine retirement concentrations in Inner Mongolia, Shanxi, and Shaanxi, indicating prioritization of economically inefficient mines with higher operational costs. However, EOS results in the highest number of coal mine retirements in Inner Mongolia, Xinjiang, and Shanxi by 2040. These provinces are characterized by large-scale operations with relatively low employment intensity due to high levels of mechanization. This outcome reflects the employment-oriented approach, which prioritizes the retirement of

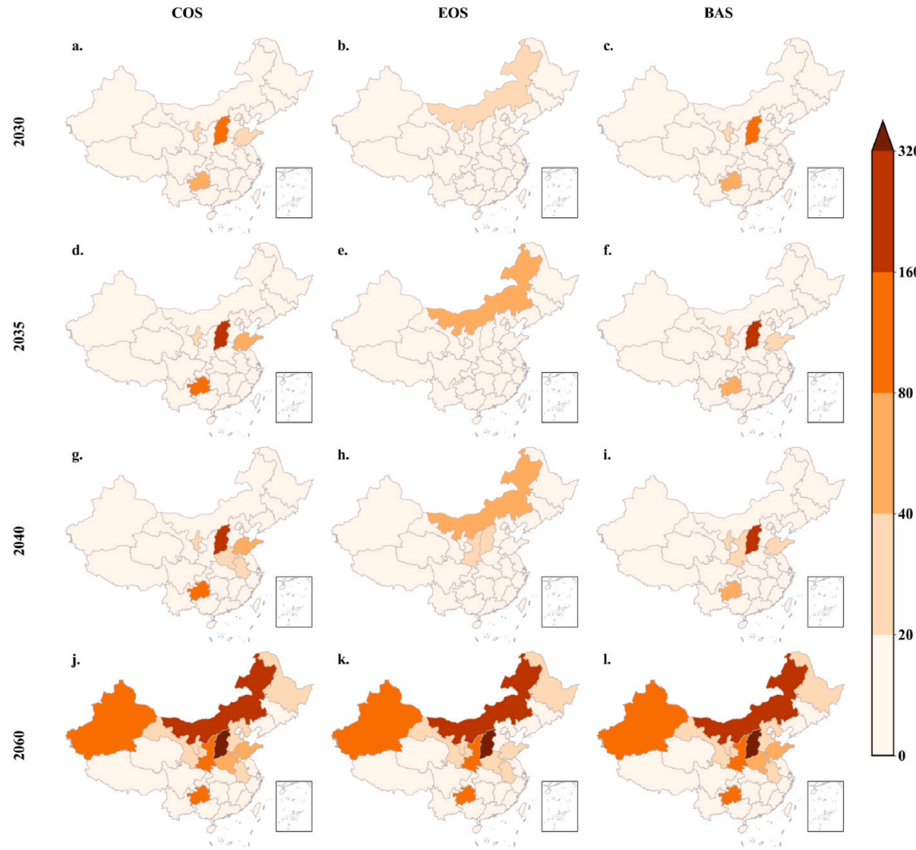

Fig. 3. Spatial distribution of coal mine retirement under different strategies.

low employment-intensity mines to preserve jobs in high employment-intensity operations (Shi and He, 2012). BAS shows a similar pattern, also concentrating retirements in Inner Mongolia, Shanxi, and Xinjiang. This indicates that the balanced strategy tends to favor employment preservation when optimizing between competing objectives, particularly by targeting regions where mines have moderate costs but relatively low employment intensity for retirement.

From a regional perspective, the distribution of coal mine retirements by 2060 becomes remarkably similar across all three strategies, showing consistent spatial patterns. The retirement distribution follows clear regional characteristics: western provinces like Inner Mongolia and Xinjiang account for the largest volumes of retirements, eastern non-coal-producing provinces have minimal retirement activity, and Shanxi Province leads retirements in the central region. This pattern reveals that major coal-producing provinces will undergo a fundamental transformation from their current role as production centers to becoming the primary locations for mine closures. While this spatial distribution aligns with existing industrial patterns and remains consistent across strategies, the choice of strategy significantly affects the timing of retirements and their employment consequences in each province (Lin et al., 2024).

5.2. *Employment impacts of retirement strategies at national and provincial levels*

Fig. 4 demonstrates distinct employment trajectories under the three retirement strategies at the country level. Divergent patterns emerge after 2025, reflecting distinct priorities across these scenarios. When comparing employment outcomes between the two carbon-neutral scenarios, the CCS scenario consistently demonstrates superior performance relative to the carbon-neutral baseline under equivalent retirement strategies. Across the three strategies, COS exhibits the steepest

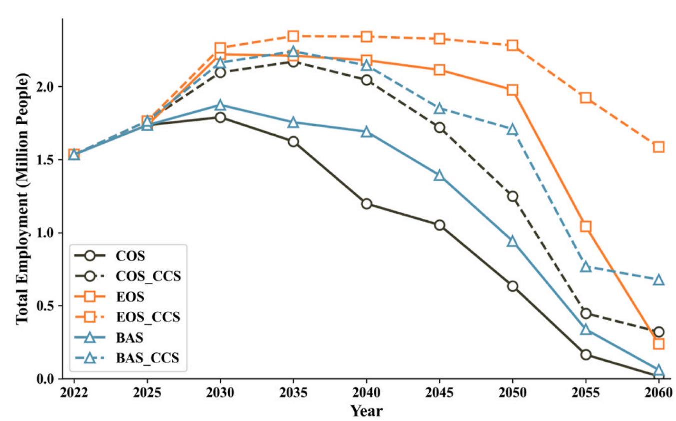

Fig. 4. Total employment trends under different coal mine retirement scenarios in China.

employment decline, with jobs falling precipitously from 2035 onward. This rapid descent reflects the strategy's prioritization of economic efficiency through immediate retirement of high-cost mines, which inevitably comes at the expense of employment stability and may incur severe social disruption during workforce transitions. In contrast, EOS demonstrates the most gradual employment decline, maintaining relatively high employment levels through 2050 and providing extended buffer periods that facilitate worker retraining and job reallocation (X. Zhang et al., 2022). However, EOS's employment trajectory shows a notable acceleration in job losses during the 2050–2060 period, suggesting that while this approach delays workforce impacts, it may still generate considerable social challenges when the concentrated retirement phase eventually occurs in the final transition decade.

BAS maintains an intermediate trajectory between these extremes. By 2060, when the carbon-neutral target is achieved, workers in the coal mining sector are projected to drop by 98.50 % (COS), 84.51 % (EOS), and 95.19 % (BAS), respectively. Although coal mining employment in 2060 differs little across the three strategies, the distinct retirement pathways produce substantial variation in cumulative job-years retained over 2022–2060, a metric that is defined as the sum of annual full-time equivalent jobs sustained over the entire period (International Energy Agency, 2020). Compared to COS, BAS preserves an additional cumulative 1,774,876 job-years during this period, demonstrating its capacity to mitigate employment shocks while achieving comparable retirement objectives and balancing competing priorities effectively.

Additionally, we employ mine-level data to examine the differentiated employment impacts of three retirement strategies across provinces. Fig. 5 illustrates the employment distribution of individual coal mines, where circle size represents employment levels at each facility, and n indicates the total number of operational mines in each strategy and time period.

In 2035, all three strategies retain the majority of existing coal mining operations, EOS consistently maintains the highest number of operational mines throughout this period, while COS shows the most substantial early-stage reductions as it targets high-cost operations for immediate closure. In 2040, mines with substantial employment capacity are predominantly located in traditional coal-producing provinces, including Inner Mongolia, Shaanxi, Henan, Shanxi, and Anhui. Among these regions, Inner Mongolia emerges as a center hosting both the largest total coal mine employment and the highest number of operational facilities nationwide. Taking Inner Mongolia as an example, representative high-employment mines in the region include Shengli East No.2 Coal Mine, Changtan Surface Coal Mine, and Lingdong Coal Mine, which employ approximately 21,735, 14,490, and 13,041 workers respectively. Both Shengli East No.2 and Changtan Surface mines are scheduled to commence production in 2030. Under COS, Inner Mongolia's total employment accounts for approximately 25.3 % of the national retained employment, highlighting its pivotal role in sustaining China's coal mining workforce (Gao et al., 2025).

COS in 2040 shows that southwestern provinces such as Yunnan, Guizhou, and Sichuan have no operational mines, while these provinces retain active mining operations under the other two strategies. This occurs primarily because COS prioritizes economic efficiency, leading to the closure of mines in these regions due to their higher extraction costs and challenging geological conditions (J. Wang et al., 2018). EOS maintains the broadest geographic distribution of operational mines, preserving substantial coal operations not only in major coal-producing regions but also in provinces like Jiangxi and Hubei where other strategies might close mines. BAS demonstrates selective retention patterns, maintaining a moderate number of operational mines that fall between the other two strategies. BAS keeps mine operations in economically marginal areas of traditional coal provinces while closing operations in cost-disadvantaged regions like the southwestern provinces.

By 2060, the spatial distribution of remaining operational mines varies considerably across strategies. COS concentrates operations

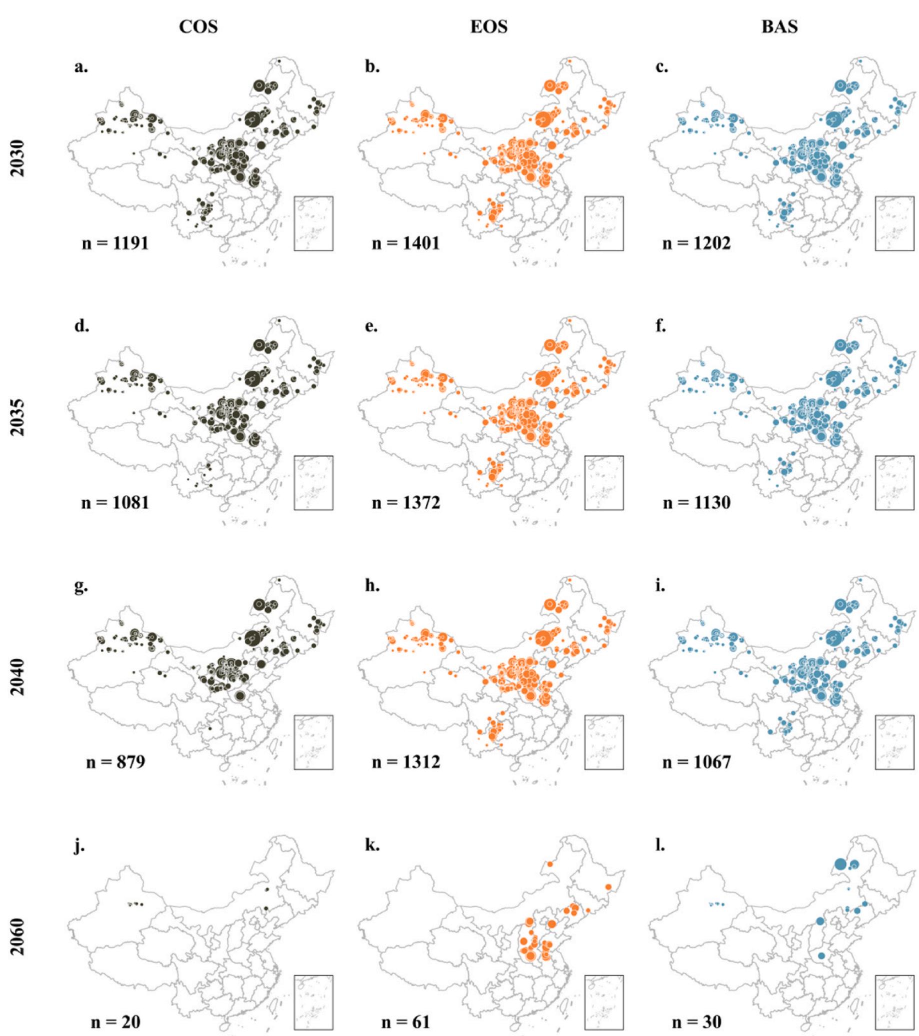

Fig. 5. Coal mine retirement and employment across province in three strategies.

primarily in Inner Mongolia and Xinjiang, EOS maintains broader geographic dispersion across Henan, Shanxi, Liaoning, and Anhui provinces, while BAS preserves substantial mining capacity in Henan, Xinjiang, and Inner Mongolia. The mines that survive until 2060 typically represent highly efficient, modernized operations, with some individual facilities employing over 10,000 workers, indicating their significant economic and social importance within their localities.

These divergent patterns of mine closure and retention across provinces demonstrate that strategy selection fundamentally shapes inter-provincial industrial restructuring and creates differentiated regional transition pathways. The geographic variations in closure patterns mean that different provinces will experience varying degrees of economic and social adjustment depending on the chosen retirement strategy. Therefore, developing a comprehensive understanding of provincial characteristics and their specific implications for coal mine closure becomes essential for designing equitable employment transition policies that address regional differences effectively.

5.3. Classification analysis of provincial employment transitions

Based on 2022 data, we employ a two-dimensional framework to categorize provinces into four distinct types. The first dimension uses per capita GDP as an economic indicator, reflecting provincial economic development levels and capacity for absorbing displaced workers during just transition (Gurgul and Lach, 2011; Q. Wang and Li, 2016). The second dimension employs coal production to measure coal resource endowment and industry dependence within each province (Y. Li et al., 2019). This two-dimensional framework balances analytical tractability with the ability to capture the fundamental trade-offs between economic development capacity and coal industry dependence that are central to just transition challenges (Hamilton et al., 2022).

In Fig. 6, 'High Production - High GDP per Capita' provinces such as Shanxi and Inner Mongolia demonstrate gradual initiation and steady decline patterns, with the EOS strategy providing the most extended employment transitions. These provinces possess relatively strong economic foundations that can support industrial diversification, but they face the challenge of managing large scale workforce displacement. Their transition strategy requires coordinated retraining programs and gradual phase-out approaches to leverage their economic capacity while preventing disruption from rapid employment losses.

'High Production - Low GDP per Capita' provinces, primarily Guizhou and Heilongjiang, exhibit steep decline and concentrated impact characteristics, experiencing severe employment shocks under COS. These provinces face a dual challenge: they must develop alternative industries while simultaneously managing rapid coal employment losses. Their weaker economic foundations make them particularly vulnerable, necessitating external support and targeted investment to prevent regional economic collapse during the transition period.

'Low Production - High GDP per Capita' provincial category exhibits significant internal heterogeneity. These regions benefit from industrial diversity and limited coal dependence, minimizing local transition pressure by naturally absorbing local coal workers into service and

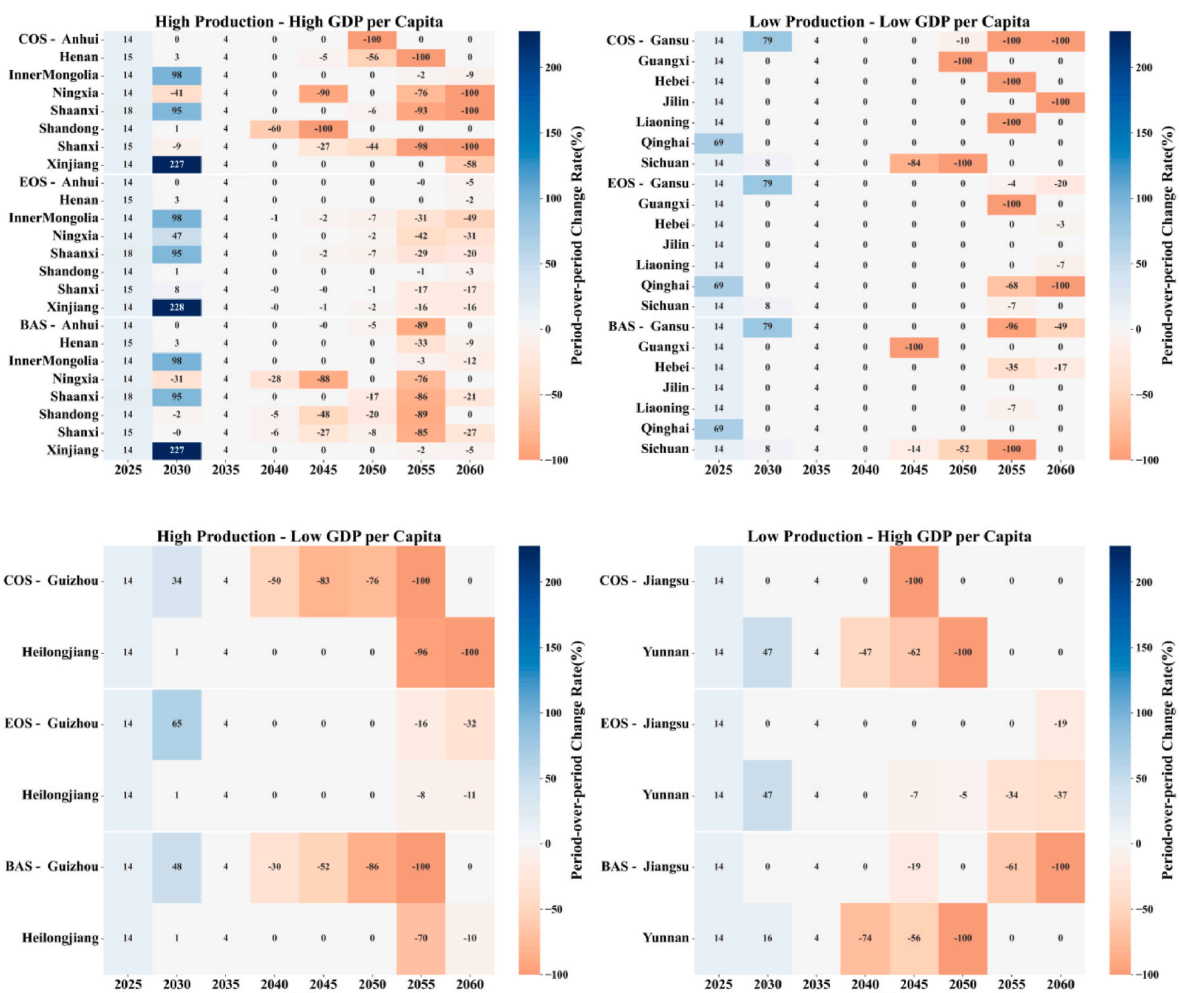

Fig. 6. Period-to-period employment change rates across provincial categories under different strategies. 100 % indicates province fulfill coal mine retirement and energy transition completion goals under the carbon-neutral target.

manufacturing sectors. However, provinces like Jiangsu, as major coal consumers, may drive inter-regional employment spillovers onto coal-exporting provinces, meaning a reduction in their external coal purchases indirectly influences employment stability in neighboring regions. Besides, Yunnan possess high employment sensitivity due to low coal productivity; consequently, although these regions have low overall coal resource dependency, the low labor efficiency makes that when retirement is necessary, the magnitude of the local employment shock remains large, requiring dedicated policy attention for employment stability during the transition (Hamilton et al., 2022).

'Low Production - Low GDP per Capita' provinces display low-level operation and minimal fluctuation patterns across strategies. BAS provides optimal balance for these provinces by ensuring more gradual transitions compared to COS while maintaining cost efficiency relative to EOS. Despite overall low transition pressure, these provinces still face the unique challenge of individual worker transitions within constrained local economies. Their limited economic capacity requires targeted skills training and potential migration support to facilitate successful worker reallocation (Hu, 2020).

The analysis reveals distinct policy implications based on provincial characteristics. High coal production provinces require strategy-sensitive strategies and substantial policy support due to the scale of potential workforce displacement. In contrast, low production provinces can rely more on market-driven transitions, with their economic capacity determining the appropriate scale of government intervention needed (Zhu and Guo, 2022).

5.4. Provincial trade-off analysis between cost and employment

Fig. 7 presents cumulative cost-employment differentials for each province across the entire analysis period, with Table 2 providing the

Table 2
Provincial slopes by strategies difference and quadrants.

Quadrant	EOS-COS	BAS-COS
Q1	Guangxi(32.7),Ningxia(32.6), Guizhou(20.1),Sichuan(15.3), Yunnan(14),Shanxi(13),Gansu (11.9),Shandong(10.9),Anhui (9.68),Jiangsu(8.44), Heilongjiang(7.7),Hebei(6.9), Jilin(6.6),Henan(6.5), Liaoning (5.2)	Guizhou(14.9),Sichuan(14.2), Ningxia(11.9),Anhui(8.7), Heilongjiang(7.6),Shandong (6.6),Hebei(6.5),Jiangsu(6.2), Henan(6.2),Jilin(5.4),Liaoning (4.5),Gansu(4.4)
Q2	None	None
Q3	Xinjiang(150.0),Inner Mongolia (91.7), Qinghai(20.5)	Yunnan(343.0),Shaanxi(244.4), Guangxi(32.7)
Q4	Shaanxi(-6.1)	Inner Mongolia(-9.7),Xinjiang (-6.9),Shanxi(-0.29)

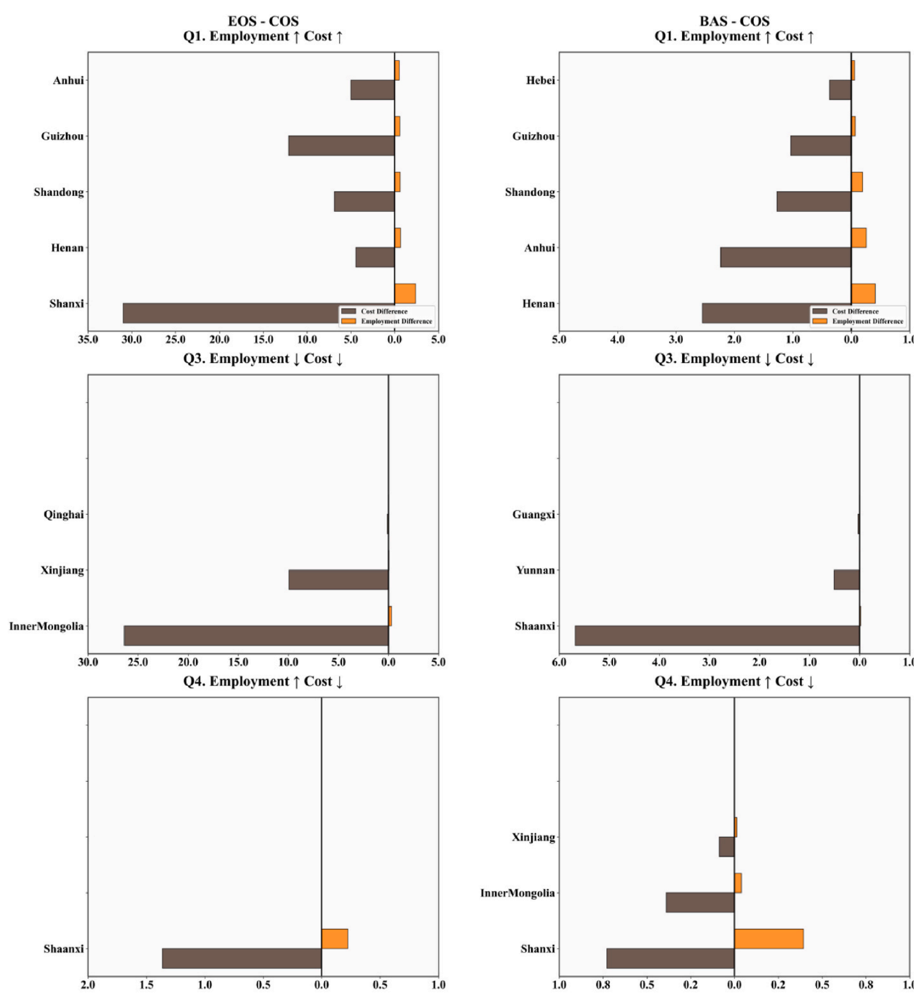

Fig. 7. Provincial comparison of the strategies difference over the period from 2022 to 2060. Quadrants represent different outcomes: Q1 (both increase), Q3 (both decrease), and Q4 (employment increases, cost decreases); Brown bars (left) show cost differences in trillion yuan; orange bars (right) show employment differences in million people; Q1 shows top 5 provinces by employment impact. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

detailed provincial slopes for each quadrant. The slope represents the cost-employment ratio (cost/employment), with interpretation varying by quadrant: in Q1 (positive cost, positive employment), a lower slope indicates greater cost-efficiency, as it represents the incremental cost required per unit increase in employment; conversely, in Q3 (negative cost, negative employment), a higher slope value is preferable as it indicates less unemployment are sacrificed per unit of cost loss. From a national perspective, the BAS strategy (slope = 0.8) demonstrates superior employment retention with minimal cost implications compared to the EOS strategy (slope = 6.2).

Among provinces positioned in the first quadrant (Q1) of the EOS-COS comparison, which represents the majority of cases, adopting EOS over COS yields enhanced employment retention but requires higher implementation costs. Most provinces also fall into Q1 in the BAS-COS analysis, but a comparative examination reveals important differences in cost-effectiveness. Provinces that remain in Q1 under both comparisons exhibit lower slope coefficients under BAS-COS than under EOS-COS, indicating that BAS achieves relatively greater employment preservation with proportionally smaller cost increases compared to EOS for these provinces. However, for Shaanxi province in EOS-Q4, the EOS strategy offers more favorable cost-employment trade-offs than BAS, making EOS the preferable choice when balancing costs against employment retention. Guangxi province shows an EOS-COS differential of 32.7 in Q1 compared to a BAS-COS differential of 32.7 in Q3, suggesting that EOS adoption would create unfavorable cost-employment dynamics. Therefore, the BAS strategy would be more appropriate policy choices for this province.

For provinces positioned in the third quadrant (Q3) of the EOS-COS framework, which includes Inner Mongolia, Qinghai, and Xinjiang, the results reveal that selecting EOS over COS leads to substantial cost reductions with only marginal employment losses. This makes EOS particularly advantageous for coal mine decommissioning strategies in these regions. Similarly, Yunnan is located in Q3 of the BAS-COS comparison, demonstrating that BAS is more suitable than COS for this province. Policymakers in these provinces should reinvest the achieved cost savings into comprehensive retraining programs and the development of alternative economic sectors to absorb the displaced workers.

The most favorable outcomes occur for provinces in the fourth quadrant (Q4) of the BAS-COS analysis. Inner Mongolia, Shanxi, and Xinjiang all fall into this category, where adopting BAS over COS achieves both employment gains and cost reductions. This represents the optimal policy outcome, as these provinces can preserve more jobs with less economic cost. The quadrant analysis reveals different shifts in provincial positioning. While Inner Mongolia and Xinjiang show advantages under EOS through its Q3 position in the EOS-COS comparison, they achieve even better results in Q4 of the BAS-COS analysis. Similarly, Shanxi transition from Q1 positioning in the EOS-COS framework to the more favorable Q4 position in the BAS-COS analysis. Consequently, despite the individual merits of EOS for some provinces, BAS yields increased benefits for Inner Mongolia, Shanxi, and Xinjiang. These provinces should leverage their dual advantages by investing the cost savings into green industrial transformation and creating sustainable employment opportunities in renewable energy and environmental sectors.

5.5. Strategies analysis under different scenarios

The above analysis demonstrates that BAS strategy represents a relatively optimal coal mine retirement strategy suitable for most provinces in China when comprehensively considering economic, employment, and environmental factors. Based on these findings, we introduce the dual carbon CCS scenario as an additional comparative case to further quantify and evaluate the comprehensive effects of retirement-based strategies. We analyze employment and cost differentials between the carbon-neutral baseline and the CCS alternative at both national and provincial levels throughout the entire period.

Fig. 8 illustrates the employment and cost implications of CCS deployment at the national level. Comparing each strategy's performance between baseline and CCS scenarios, we observe that CCS universally enhances cumulative employment by extending operational lifecycles: COS increases by 36.9 %, BAS by 31.2 %, and EOS by 20.4 % (Fig. 8a). From the cost perspective, CCS implementation results in increases: COS 33.5 %, BAS 33.3 %, and EOS 28.7 % (Fig. 8b). Under the CCS scenario, BAS preserves an additional 1.5 million jobs at an additional cost of 1.2 trillion yuan compared to COS, whereas EOS preserves an additional 5.0 million jobs at an additional cost of 32.4 trillion yuan compared to COS. This comparison reveals that while BAS achieves slightly lower employment gains than EOS, it incurs substantially lower costs, making it the more cost-effective strategy. However, at the provincial level, EOS emerges as relatively superior in some provinces, indicating that regional comparisons of these two strategies under the CCS scenario remain valuable.

To compare strategies at the provincial level, we examined the relative changes in employment and cost under the CCS scenario compared to the Baseline (Fig. 8c). For Xinjiang, the growth in employment exceeds the growth in costs under the EOS strategy, indicating that this province's strategic preference would shift toward EOS, and it demonstrates better performance under the EOS strategy (Table S1). Conversely, for Shaanxi, the growth in cost exceeds the growth in employment under the EOS strategy, revealing that strategic preference would shift toward the BAS strategy. For Jilin, EOS and BAS show similar outcomes under CCS, although BAS was preferred in the Baseline (Table S1).

Both Shaanxi and Xinjiang exhibit 'High Production, High GDP' characteristics (Fig. 6), their massive coal bases provide concentrated sources that lower unit capture costs, while proximity to major geological basins (e.g., Tarim) ensures efficient source-sink matching. Consequently, these advantages allow the benefits of employment retention to outweigh implementation costs under CCS scenarios. For 'Low Production, Low GDP' regions like Jilin, the lack of industrial scale results in higher unit costs for CCS deployment due to diseconomies of scale. This increased financial burden diminishes the cost advantage of BAS relative to EOS, leading to similar outcomes between the two strategies under CCS scenarios.

These results demonstrate significant inter-provincial heterogeneity, emphasizing that strategy selection must be tailored to region-specific circumstances rather than applying uniform approaches across all provinces especially in different scenarios. As CCS continues to advance and mature in the future, different provinces may have access to even more diverse and flexible coal mine retirement options.

6. Conclusion and policy implications

China's carbon-neutral goal requires a carefully staged withdrawal from coal. Drawing on the RMC model and mine-level data, this study compared three retirement strategies—a cost-driven option, a worker-centered option, and a balanced alternative—and assessed how each strategy aligns with climate goals, technological opportunities, and the principle of a just transition.

The analysis shows that although all three routes lead to a similar end of a complete closure of coal mines by 2060, their implications on employment and economic efficiency vary significantly. A cost-first strategy delivers rapid savings but causes an early spike in job losses. By contrast, a job-first approach slows closures, cushions employment impacts, and drives up total costs. The balanced strategy occupies the middle ground, preserving 1,774,876 additional job-years relative to the cost-first case without sending the budget spiraling. These divergent outcomes underline the importance of matching national decarbonization ambitions with social safeguards.

Outcomes also vary markedly from province to province. Wealthy coal heartlands such as Shanxi and Inner Mongolia can phase out production in measured steps while building new industries, whereas less-

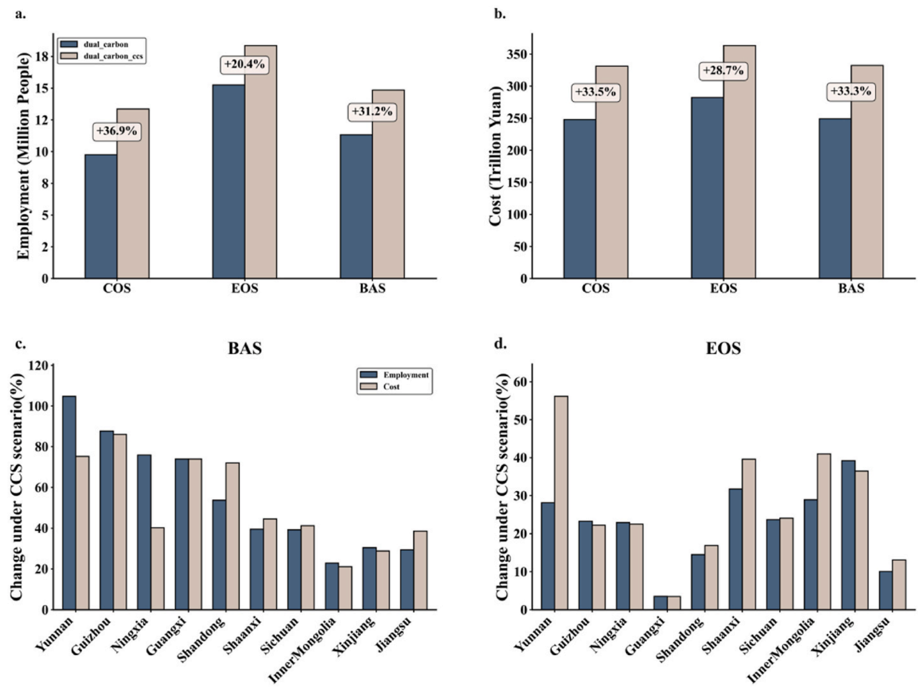

Fig. 8. National and provincial cost-employment analysis under CCS deployment scenarios. Upper panels (a, b) compare national totals between baseline dual-carbon and dual-carbon with CCS scenarios; Lower panels (c, d) show provincial differences (relative change from baseline) comparing EOS vs. BAS for the top 10 provinces.

developed coal regions like Guizhou face heavier social risks if closures outpace training and investment. Environmental pay-offs are similarly mixed: the balanced roadmap yields the deepest lifetime methane cuts in Shaanxi and Shanxi, while the employment-oriented strategy keeps the newest, most efficient mines open in Inner Mongolia and Xinjiang, reducing emissions per tonne there. These patterns confirm that one blueprint will not work everywhere. Technology provides an additional lever. Carbon capture and storage can extend coal mine lifespans, spread lay-offs over time, and ease the transition, but only if its higher costs are shared fairly and any revenue is recycled back into local economies.

This study makes three key contributions to address critical gaps in coal mine retirement and just transition literature. First, we integrate comprehensive mine-level employment data to demonstrate how provincial employment characteristics should guide retirement strategy selection. Second, we develop three distinct retirement strategies that explicitly considers trade-offs between economic efficiency and social equity, addressing current studies' reliance on single-dimensional criteria. Third, we provide systematic analysis across China's 19 coal-producing provinces to examine how regional heterogeneity influences optimal retirement strategy selection, filling the gap in comprehensive cross-provincial comparative studies that systematically analyze retirement strategies for each individual province, which addresses the lack of systematic, province-specific strategic guidance for employment transition policies in China's just transition literature.

Despite its contributions, this study has several limitations. First, while the "production-per capita GDP" framework offers an initial assessment of provincial heterogeneity, this simplified classification has limitations as it does not comprehensively account for some crucial factors like diverse industrial structures, local fiscal capacity, and labor skill compositions. Second, additional factors beyond cost and employment such as environmental regulations, local government capacity, and social acceptance may significantly influence retirement decisions but remain unaccounted for in our framework. Third, our study assumes static technological parameters and cost structures, potentially underestimating dynamic effects of technological learning and policy evolution. Fourth, we do not analyze employment transitions from coal mining to renewable energy sectors and quantify employment substitution effects, which represents a critical dimension of just transition.

For policymakers, the first priority is to chart province-level retirement roadmaps that reflect local budgets, labor mixes, and emissions profiles instead of imposing a single national calendar. These differentiated roadmaps should account for provincial variations in industrial structure diversity, fiscal capacity, and labor skill composition, as these factors play an important role on region's economic resilience, transition financing capability, and workforce adaptability during coal phase-out. Special attention should be paid to the phased vulnerability of different worker groups: while non-contract workers exit early, contract workers will face intensifying employment pressures in the later stages of transition, particularly after 2050. To implement this strategy effectively, specific policy instruments, such as central fiscal transfers and green investment policies, should be used to support structurally disadvantaged regions. Alongside this, forward-looking retraining and social-protection measures tailored for contract workers need to be activated well before the peak retirement period, including expanding the scope of social insurance subsidies and steering green-finance channels toward clean industries capable of absorbing displaced miners.

The strategic deployment of key transition technologies, including CCS, methane-to-power, and digital mine rehabilitation, should be pursued only where geology and economics align. Policymakers can leverage technologies like CCS not only for emission reduction but also to stabilize vulnerable workforce segments, such as contract workers, during the transition. The implementation of these technologies should be supported by regulatory frameworks that address cost-sharing and skills training, with local workers trained to operate the new systems. Finally, a live dashboard that tracks jobs, incomes, and emissions can serve as a crucial instrument for adaptive governance, allowing authorities to revisit retirement schedules every couple of years, keeping pace with the rapid changes expected in the 2050s.

Phasing out coal is therefore more than an engineering exercise or an accounting challenge. It is a test of society's ability to balance climate responsibility with economic opportunity and social justice. Future research would benefit from mapping technology learning curves, distilling lessons from provincial pilots, and gathering household-level data on the impacted workers. A dynamic and evidence-based roadmap will keep China's energy transition on course toward a climate-safe and equitable future.

CRediT authorship contribution statement

Shiyu Li: Writing – review & editing, Writing – original draft, Visualization. **Zanfeng Wang:** Writing – review & editing, Validation, Data curation. **Wenji Zhou:** Writing – review & editing, Software, Project administration, Methodology, Funding acquisition, Conceptualization. **Anlan Lin:** Writing – review & editing. **Hongtao Ren:** Writing – review & editing, Software, Methodology.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.115038.

Data availability

Data will be made available on request.

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