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Strategic phase-down of China's coking plants unlocks major climate and environmental co-benefits

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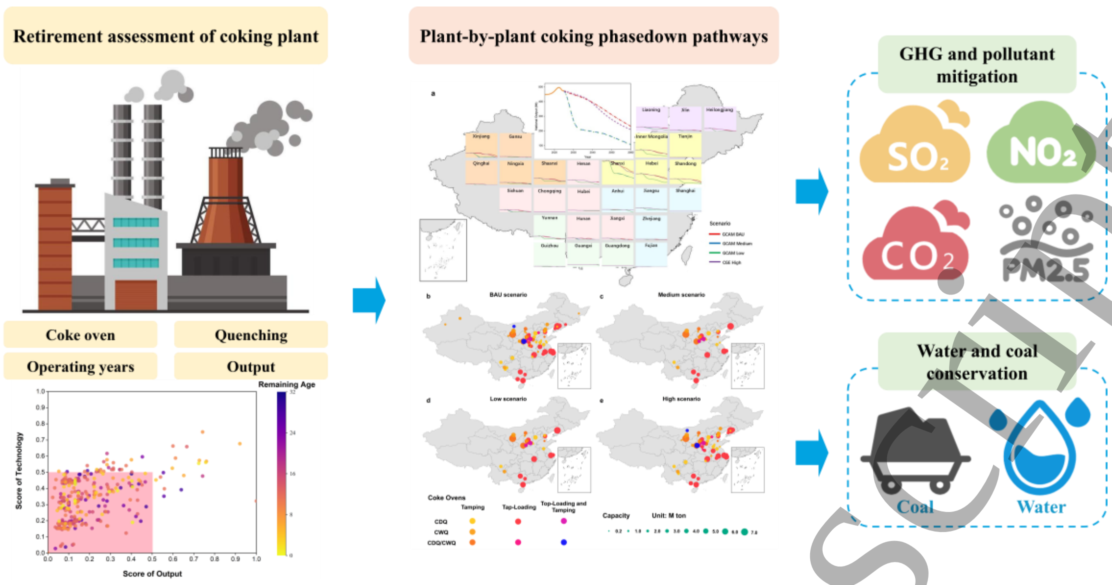


ABSTRACT: China dominates global coking production with a 70% proportion, making the decarbonization of this highly energy- and emission-intensive industry critical for resource and environmental benefits. Despite discussions of decarbonization potentials at regional level, plant-specific co-benefits and technologically driven pathways remain unclear. Here, we integrate detailed data from 329 individual Chinese coking plants—characterizing their location, capacity, technology, and age—with national carbon neutrality scenarios to develop optimized, multi-criteria retirement pathways. Plants mainly located in Shanxi are phased out first before 2030 in BAU scenario while retirement are proportional across provinces in low coke production scenario. Considerable co-benefits are observed, 53.4~57.1% of water saving and emission mitigation towards 2060. Trade-offs exist due to ascending coal use if higher technical penetration of dry quenching. Our analysis quantifies the distinct contributions of demand reduction (driven by steel industry transformation) and structural efficiency improvements within the coking sector itself. These results provide the first granular, data-driven roadmap for managing China's critical coking transition, offering crucial insights for maximizing environmental gains during industrial decarbonization globally.

KEYWORDS: coking industry, phase down, carbon mitigation, environmental co-benefits, plant-by-plant

1. INTRODUCTION

Achieving the 1.5-2°C target set by the Paris Agreement requires an urgent phase-down of coal, a significant challenge for global energy systems[1]. China confronts heightened urgency in its coal-intensive industries, particularly coking. The coking sector is under mounting pressure for accelerated decommissioning, driven by both climate mitigation imperatives and a sustained decline in coke demand from the iron and steel industry. China's total coking capacity is expected to undergo significant reduction to align with its carbon neutrality targets[2]. Consequently, the majority of China's coking capacity is expected to be phased out.

Half of existing coking plants in China commenced operation during 12th Five-Year Plan. The young age of the infrastructure may exert socioeconomic risks if their retirement is accelerated, as analogous challenges have been seen in the coal power, iron and steel, and cement industries[3-5]. Potential capacity expansion and ultra-low emission transformation further exacerbate the lock-in effect, which encompasses broader economic impacts and decision-making uncertainties. Current researches focus more on mitigation pathways for iron and steel (IS) industry, where coking is integrated as a processing unit[6-9]. Several researches have quantified the driving forces and mitigation pathways of coke production under varying climate goals[10-11]. However, plant-specific metrics for retirement and transformation remain unassessed, resulting in limited understanding of the implications for individual coking plants amid rapid coal phase-down and declining coke demand.

Despite the importance of climate-change mitigation, the coking industry remains critical for energy and resource saving as well as environmental protection. Therefore, China must prioritize its green transformation and low-carbon development pathways. As the world's largest coke producer, China's coke production accounted for 68.6% of global production (492 Mt) in 2023[12], and China's coking industry consumed annually 700 Mt coals. Furthermore, coke production is highly resource- and emission-intensive[13]. Previous studies have demonstrated the co-benefits of energy saving and CO_2 emission mitigation from the phasing-out and upgrading of outdated coking capacities[14]. The widespread adoption of ultra-low emission technologies has led to a gradual decline in the coking industry's emissions from 2012 to 2022[10]. Consequently, future phase-down of coking capacities could generate substantial co-benefits in coal consumption reduction and water saving, and emission mitigation.

In this work, high-resolution, plant-by-plant phase-down strategies for China's coking industry are developed under carbon neutrality targets. Plant-specific datasets across 329 coking plants are integrated, applying retirement criteria based on age, output size and technical performance indices. Future coke demands are projected through a hybrid modeling framework, combining the top-down Global Change Analysis Model (GCAM) with a computable general equilibrium (CGE) model, supplemented by scenario analysis of the low-carbon transition of steel and coke production under carbon neutrality targets. Accordingly, the resource and environmental co-benefits from coking plants phase-down are quantified using a bottom-up accounting framework. The results provide a detailed picture of coking plants phasedown driven by technical change and demand decline, illustrating the green and decarbonization pathways for coking industry under carbon neutrality targets.

2. METHODS AND DATA

2.1. Database construction of China's coke industry. In this study, a resource and environmentally sustainable development database of China's coking industry is developed, including 329 plants operating in 28 provinces. Multiple variables, both collected and estimated at the plant level, are integrated into the database, encompassing location with latitude and longitude, operation years, production capacity, as well as coke oven technologies and quenching methods. Additionally, coal input, water use, CO_2 emissions and pollutant emissions of PM, SO_2, and NO_x are systematically documented (see Extended Data 1).

Data on coal input, water use, CO_2 emissions and pollutant emissions from different processing routes per ton of coke production are collected from existing studies, then projected to 2060 using a logistic fitting method. Last, annual resource and environmental impacts of each plant are calculated based on the resource and emission intensities

$$R_{i,k,t} = RI_{i,k,t} * Qcok_{i,t} \quad k = \{energy, water\} \tag{1}$$

$$E_{i,j,t} = EI_{i,j,t} * Qcok_{i,t} \quad j = \{PM, SO_2, NO_x, CO_2\} \tag{2}$$

Where $R_{i,t}$ and $E_{i,j,t}$ denote energy (or water use) and jth environmental emissions of the plant i in year t; $RI_{i,j,t}$ and $EI_{i,j,t}$ is energy (or water) intensity and jth environmental emission intensity of the plant i in year t; $Qcok_{i,t}$ is the yield of the coking plant i in year t.

2.2. Coke production projection based on GCAM and CGE model. Both Global Change Analysis Model (GCAM) and computable general equilibrium (CGE) model are applied to project the coke demand in China under carbon neutrality target, and then to design different scenarios for coke production. First, the analysis embodies that the two model simulate equilibrium quantity of coke production and consumption and fixed export ratio. Second, the production of coke is assumed to in line with the demand of iron and steel industry because metallurgical coke accounts for 90% of China's current coke consumption. China's total output of crude steel and its production structure are simulated under the carbon neutrality target, using GCAM model. In this model, nine technologies including BLASTFUR, BLASTFUR CCS, BLASTFUR CCS with hydrogen, BLASTFUR with hydrogen[15,16], Biomass-based[17,18], EAF with DRI, EAF with DRI CCS, Hydrogen-based DRI[19-20], and EAF with scrap[21,22], are employed to produce crude steel. These technologies are aggregated into three types: traditional blast furnace (BF), hydrogen- and biomass-based Blast furnace (HB-BF), EAF-DRI, and scrap-based EAF (S-EAF).

Considering that only traditional blast furnace technology consumes coke during its production process, three coke demand and production scenarios are then designed: a) steel production with BF and S-EAF, i.e., Business-as-usual (BAU) scenario; b) steel production with BF, S-EAF and HB-BF technologies, i.e., Medium coke production scenario; c) steel production with BF, S-EAF, HB-BF and EAF-DRI technologies, i.e., Low coke production scenario. However, the carbon mitigation potential of blast furnace with hydrogen remains relatively limited, which is far inferior to hydrogen-based DRI. Recently, many scholars advocate for large-scale replacement of blast furnace with hydrogen by hydrogen-based DRI in the future to meet decarbonization targets, given the mature green hydrogen production technology[23,24]. Thus, based on GCAM outputs of technology shares, this study reasonably assumes a future transition from blast furnace with hydrogen to hydrogen-based DRI in both low and medium coke production scenarios.

Meanwhile, the ideal scenario is set to characterize the substitution of the wet with dry coking quenching technology based on the low coke production scenario, and the complete penetration of the dry will be achieved before 2030. Furthermore, future coke production is projected using ACCESS model, an improved CGE model, developed by Beijing Normal University, and defined as high coke production scenario. The improved ACCESS model project larger coke production of 209.2 Mt towards 2060 with well-expectation of coal chemical industry (Supplementary Table 1).

$$Qcok_t = Qcok_0 * Qstl_{BF,t}/Qstl_{BF,0} \tag{3}$$

$$Qcok_t = Qcok_0 * Qcci_t/Qcci_0 \tag{4}$$

Where $Qcok_0$ and $Qcok_t$ represent total coke production in base year and in year t, respectively; $Qstl_{BF,t}$ and $Qstl_{BF,0}$ are steel production in base year and in year t, respectively using traditional BF technology, projected by GCAM model; $Qcci_t$ and $Qcci_0$ are output of coal chemical industry in base year and in year t, respectively, projected by CGE model.

2.3. Integrated retirement assessment for coking plants. A two-step and multi-criteria comprehensive evaluation method is developed to assess the integrated competitiveness of currently operating coking plants and then to identify the priority orders of retirements. Three indices, including production capacity, operation years, and technologies of both coke oven and quenching processing routes, are adopted to embody technological level and resource-environmental impacts. Specifically, simple [0,1] normalization is applied to quantify capacity at the plant level to retrieve integrated ranking score for size (i.e., plant output) and operating-year (i.e., plant age). The similar assignment also occurs in plant age [1985, 2022]. Technology attributes are given rank scores [1, 2, 3, 4] for coke oven processing routes and [1, 2, 3] for quenching processing routes, and later they are also normalized [0,1] to eliminate the issue of data scaling, respectively. Referred to the study of Cui et al. (2021)[3], equal weights (1/3) to each criteria are adopted to calculate integrated retirement scores of coking plants. The low scores represent early order to retire the plants. The details are shown in Supplementary Table 2.

2.4. Projection of future resource and emission intensities. With technological advancements and process improvements, resource and emission intensities of coke production are expected to gradually decrease. Logistic equation curve, an S-shaped curve commonly used to forecast the energy-related indicators[25,26], is utilized to stimulate the future decline of emission intensity and water use intensity of China's coking industry.

$$x_t = \frac{k}{1 + a \times e^{-r\times(t-t_0)}} \tag{5}$$

Where x_t represents the emission intensity or water use intensity in year t. t_0 is the initial year. k, a, and r are coefficients, which respectively indicate the upper or lower limit, growth rate, and impact factor of the growth rate. The historical decrease trend in emission intensity is calculated based on the emissions[10] and production[27] of Chinese coke industry from 2012 to 2022, while the historical decrease trend in water use intensity refers to the data of Chinese Coking Industry Association from 2020 to 2022[28].

$$EI_{i,j,t} = \sigma_{j,t}^{e} \times EI_{i,j,t_0} \tag{6}$$

$$RI_{i,\text{water},t} = \sigma_t^{w} \times RI_{i,\text{water},t_0} \tag{7}$$

$$\sigma_t = \frac{\hat{x}_t}{\hat{x}_{t_o}} \tag{8}$$

Where $\sigma_{j,t}^{e}$ and σ_t^{w} are the decrease rates of the j_{th} emission intensity and water use intensity, respectively. $\hat{x}_t$ represents the result of the logistic model in year t. In addition, it is assumed that the average energy use intensity of Chinese coke industry is expected to uniformly decrease in the future, ultimately reaching the benchmark level by 2060[27].

2.5. Co-benefits quantification of coking industry transformation. The benefits come from three parts of output reduction (demand reduction effect), technological advance (efficiency effect) and structure adjustment (structure effect). Future coke output, driven by the demand, is generally decreasing towards 2060[29,30], while resource use and pollutant emission intensity are reduced by technological advance[31-35]. Also, the transition from wet to dry quenching technologies yet result in less water use and air emissions but increase coal input and CO_2 emissions. Coal input and water use are applied to represent resource criteria, while CO_2, SO_2, NO_x and particulate matter (PM) emissions are used to character environmental criteria.

$$RS_{i,k,t} = \sum_{t0}^{t}(RI_{i,k,t} * Qcok_{i,t} - RI_{i,k,t0} * Qcok_{i,t0}) \quad (9)$$

$$TRS_{k,t} = \sum_{i=1}^{I_r} ES_{i,k,t} \quad (10)$$

$$ES_{i,j,t} = \sum_{t0}^{t}(EI_{i,j,t} * Qcok_{i,t} - EI_{i,t0} * Qcok_{i,j,t0}) \quad (11)$$

$$TRS_{t,j} = \sum_{i=1}^{I_r} ES_{i,j,t} \quad (12)$$

Where $RS_{i,k,t}$ and $ES_{i,j,t}$ denote kth resource saving and jth environmental emission mitigation from year $t0$ to t ($t0 = 2022$) of plant i; $TRS_{k,t}$ and $TRS_{t,j}$ is the total saving of kth resource and total mitigation of jth environmental emission in province r, $r = 28$; I_r is the total number of coking plant in a specific province r.

3. RESULTS

3.1. Production patterns of China's coking industry. Existing coking plants in 2022 was characterized by small-to-medium-scale facilities (Fig. 1): approximately 1/3 exhibited capacities below 1 Mt/a, while 2/3 remained under 2 Mt/a, with individual plant capacities spanning 0.2~8.5 Mt/a. Technologically, 2/3 of plants employed tamping and heating-recovery coke ovens, while 1/3 of plants relied entirely on wet quenching routes, which exhibits larger resource consumption and pollutant emissions than those of dry quenching. These characteristics indicate significant potential for efficiency improvements through agglomerate or upgrade their equipment and processing routes[36,37].

Geographically, China's coking capacity exhibited strong spatial concentration (Fig. 1a and b). Coking plants mainly located in North China. Approximately 70% of coking capacity was clustered in the top ten provinces with largest coking capacity, while Shanxi (22.6%), Hebei (10.7%), Inner Mongolia (8.7%), Shandong (6.4%) and Henan (4.4%) contributed to more than half of total capacity. This is because coking production is highly energy-, water- and emission-intensive. Thus, provinces located in middle and lower reaches of the Yellow River basin became the Agglomeration Zone for coal chemical industry, with extremely abundant coal resources.

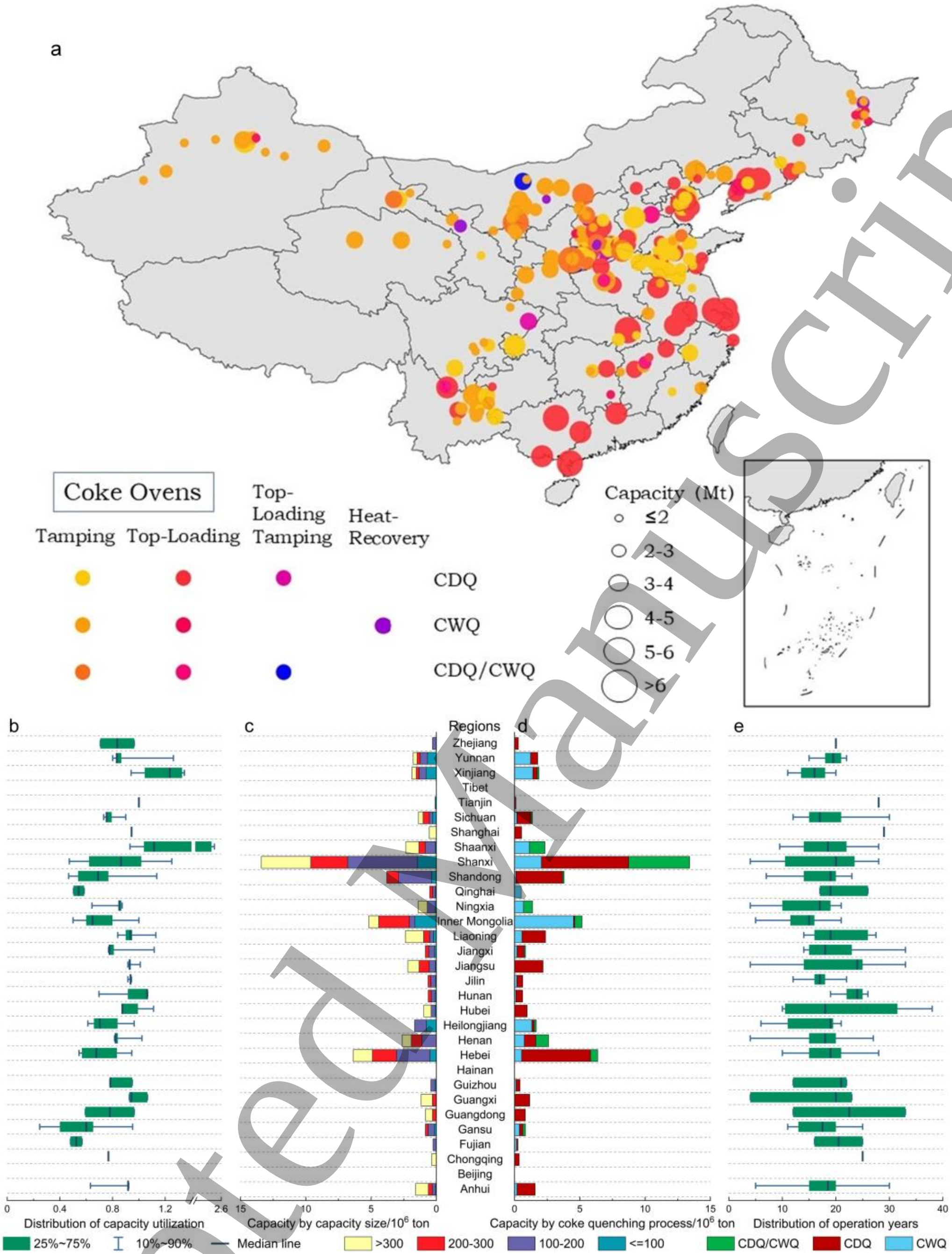


Fig. 1 Existing coking plants in China in 2022. a) The color and size of the dots show the coking processing routes and production capacities. b) and e) show the distributions of capacity utilization rates and operation years of coking plants in each province, respectively. c) and d) show the sums of the coking capacities in each province by the size and processing route of coking plants, respectively. The plants are classified 4 types by coke ovens and 3 types by quenching process, in which CDQ and CWQ refer to dry and wet quenching of coking processing routes.

3.2. Coal input, water use and pollutant emissions from coke production in 2022.

In 2022, China produced 289.5 Mt of dry quenching cokes and 180.6 Mt of wet quenching cokes, consuming 654.4 Mt of coals and 840.9 million m^3 (Mm^3) of water, with 239.5 Mt of CO_2 emissions, 58.9 kilo tons (kt) of CH_4 emissions, as well as air pollutant emissions, including SO_2 (481.2 kt), NO_2 (160.8 kt), PM (251.3 kt), VOCs (1246.6 kt), H_2S (14.6 kt), NH_3 (24.1 kt), CO (178.5 kt), displayed in Fig.2.

The top five provinces with largest output of dry quenching cokes were Shanxi (72.8 Mt), Hebei (39.6 Mt), Shandong (26.1 Mt), Jiangsu (20.4 Mt) and Liaoning (16.9 Mt), while largest output of wet quenching coke was located in Shanxi (38.0 Mt), Inner Mongolia (32.7 Mt), Shaanxi (23.0 Mt), Xinjiang (17.8 Mt) and Yunnan (11.4 Mt). A larger share of dry quenching coke leads to less water use and pollutant emissions. This is because the water use and pollutant emissions from producing 1 ton of coke in wet quenching are 1.8%~27.2% higher than those in dry quenching, while coal input and CO_2 emissions are 2.1% and 5.5% lower, respectively. With abundant coal resources and an earlier-established coking industry, these regions were still equipped with outdated CWQ production capacities, as the adoption of CDQ is hindered by its high capital costs and local technological and economic limitations.

High coke production correlates with elevated resource consumption and environmental emissions, especially in provinces with large coke output. These provinces tended to have relatively significant differences in their coke output and quenching processing routes. For instance, coke production in CDQ only contributed less than 30% of total coke production in Yunnan, Shaanxi, Xinjiang and Inner Mongolia, where capacity upgrading would be of critical necessity. Notably, the water use of coke production varied across provinces, due to the large difference in quenching technical structure. The plants located in Yellow River basin yet consumed amount of water, such as these in Shanxi, exacerbating local water stress. In contrast, Yunnan and Jiangsu had large bearing capacity to address water stress, due to abundant local water resource and high efficiency production.

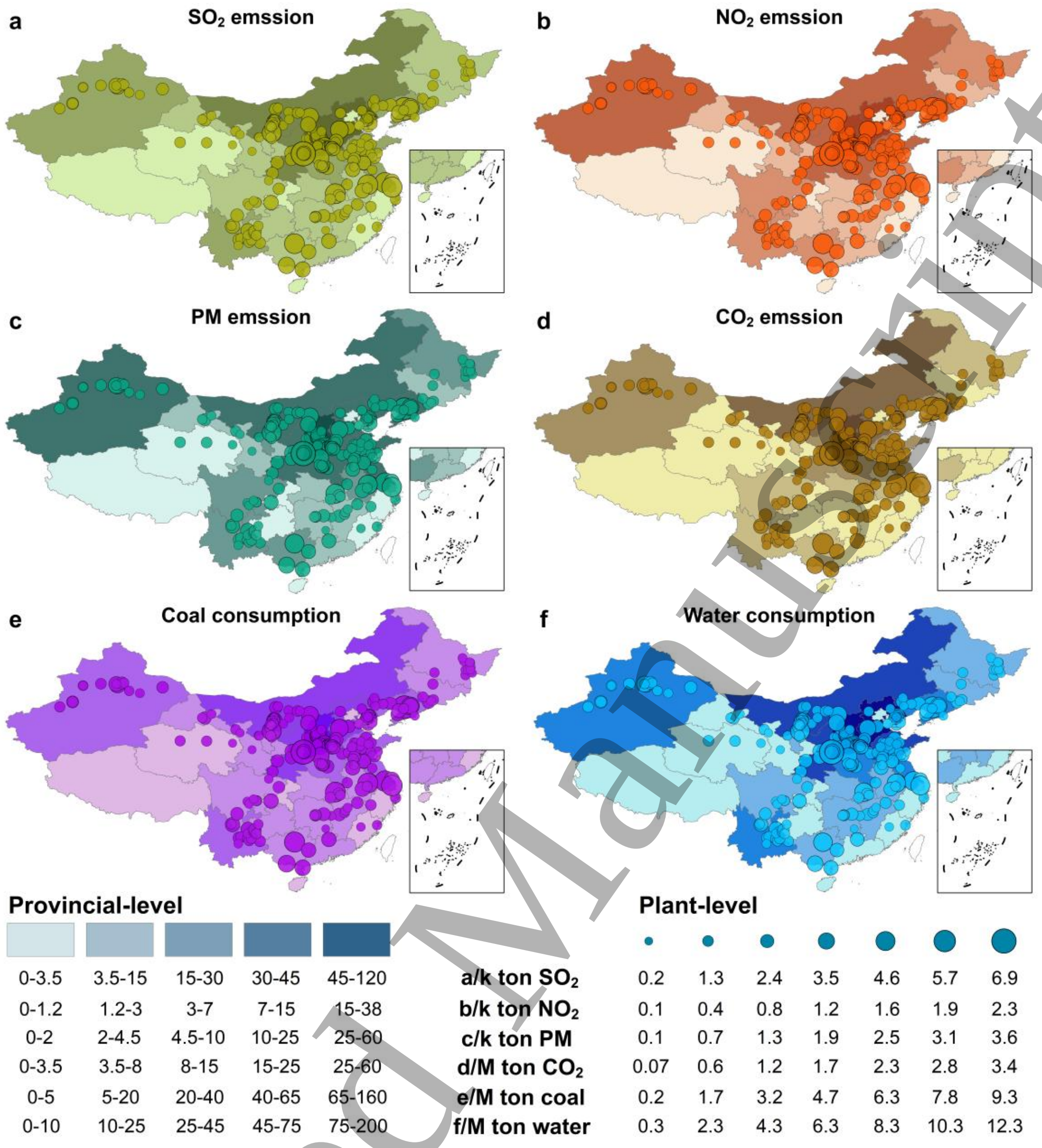


Fig.2 Environmental emissions, coal input, and water use of coking production in China in 2022.

3.3. Coke production and the plant-by-plant retirement strategies. By 2060, coke production is estimated to decrease by 51%~78% below 2020 levels, largely driven by the declining demand of crude steel and the adjustment of production structure. Five scenarios are designed considering the shares of hydro- (or biomass-), scarp-based and electric arc furnace-based (EAF) IS production technologies, which consume less or zero coke. All scenarios assume that China would peak its coke production before 2025 based on existing projection and planning on the development of coking industry. A rapid reduction in coke production is anticipated between 2025 and 2035, driven predominantly by the technological change, which is expected to reduce coke demand by 44.2% during this period.

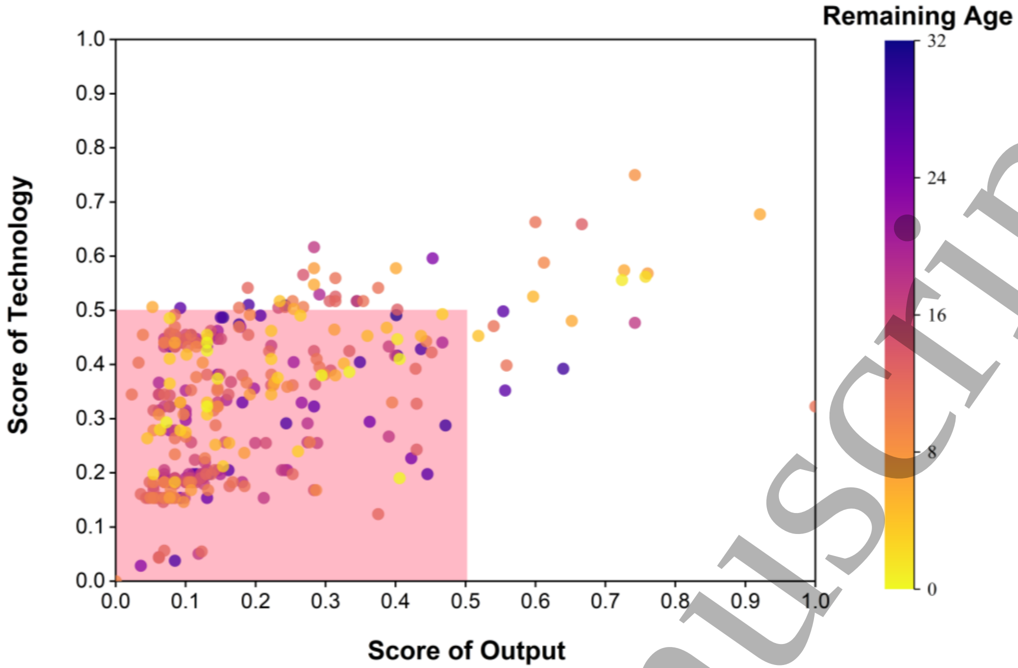


Fig.3 Scores of output size, technical attributes and age for coking plants.

It is obvious that large differences exist in the competitiveness among plants. Different from coal power generation that have strict supervision and planning of both central and local government, coke production as well as its infrastructure construction and retirement are a relatively higher degree of marketability. This assumption caters to current situation that coke production heavily concentrated in the Yellow River basin and North China[38]. Plants mainly located in Shanxi are retired first before 2030 in BAU scenario, while the retirements are more proportional across provinces and rapid in low coke production scenario (Fig.4a). The retired coke plants before 2030 are displayed in supplementary Fig. 1.

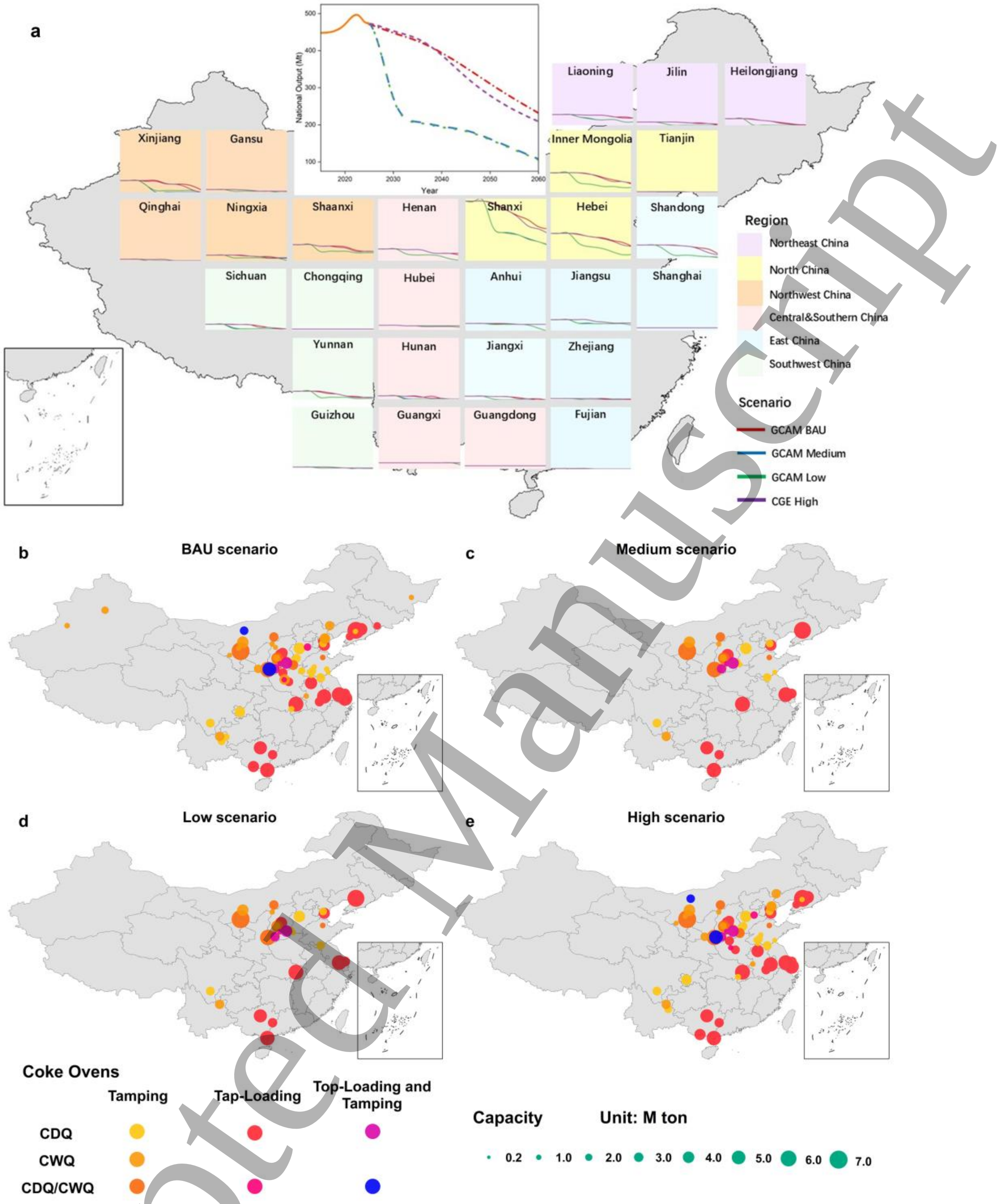


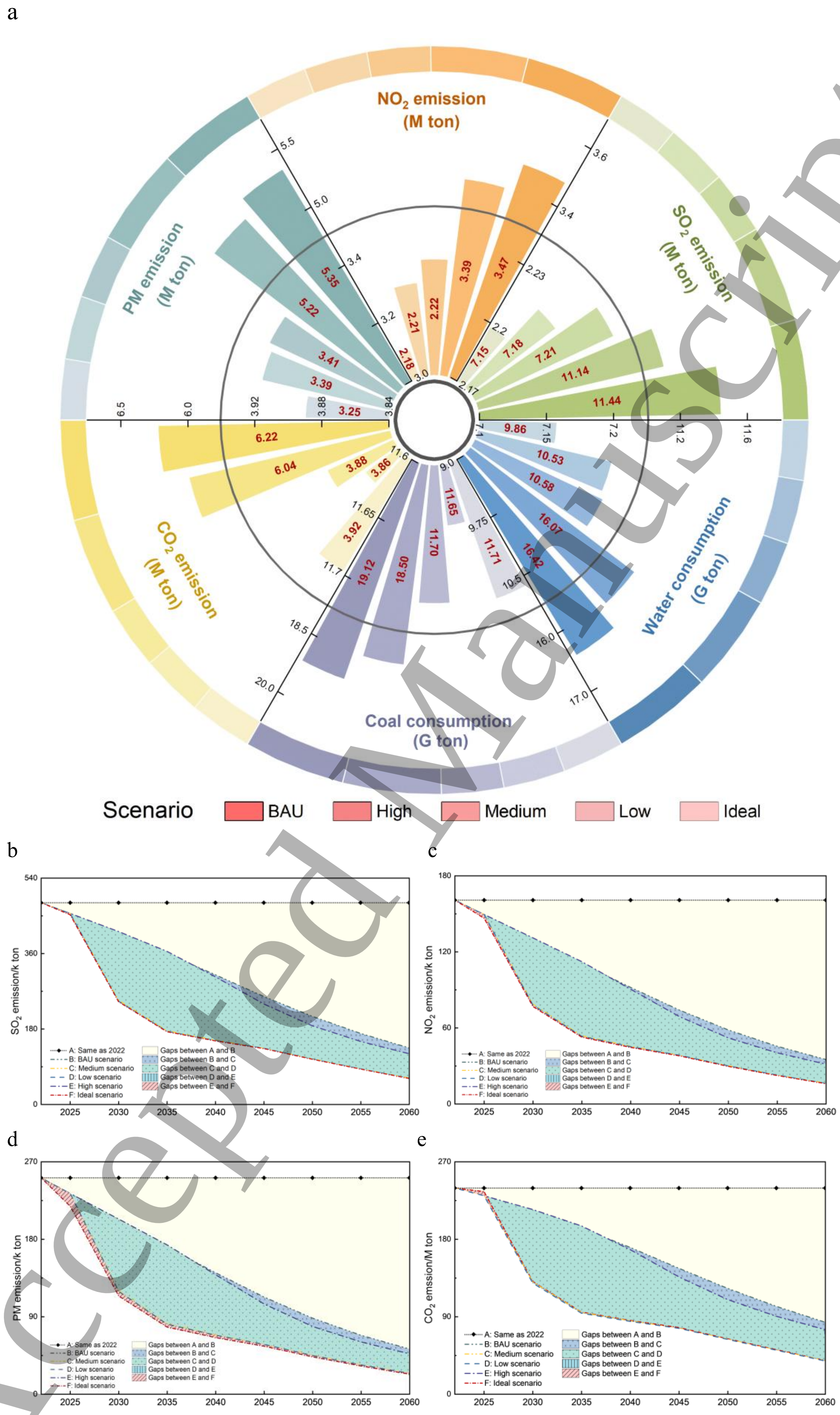
Fig.4 National, provincial and plant-by-plant coking phasedown pathways under four different scenarios. a) represents national and provincial retirement pathways of coking industry under the carbon neutrality target. b), c), d), and e) show the remaining coking plants in 2060 under BAU scenario and low, medium and high coke production scenarios, respectively.

By 2060, the remaining coking landscape exhibits significant divergence across scenarios (Fig. 4b-e). Only 35 plants (in low coke production scenario) to 101 plants (in BAU scenario) would remain operational. In low coke production scenario, Shanxi dominates with 12 of the 35 plants by 2060, accounting for 28% of national capacity. This is followed by Hebei (15.9 Mt), Inner Mongolia (12 Mt) and Guangxi (11.5 Mt).

Except for Shanxi, other provinces would retain only 1~4 coking plants each. In contrast, in BAU scenario, Shanxi hosts 29 of 101 plants but contributes 24.6% of total capacity by 2060, with more plants retained in Shandong, Hebei, Inner Mongolia and Anhui. Coke production shows pronounced agglomeration. Shanxi, Hebei, Inner Mongolia, and Guangxi would collectively produce 60% of national coke output by 2060 in low coke production scenario, while only 54.5% in the BAU scenario.

3.4. Plant- and provincial-specific resource and environmental co-benefits. The resource and environmental impacts of China's coking industry from 2023 to 2060 are provided in Fig.5 and Extended Data 3. Nationally, coal input and water use are first projected to be 138.4~301.4 Mt and 59.1~137.9 Mm^3 by 2060 in five different scenarios. Coking industry would reduce 93.3% of water use by 2060 in ideal scenario, and by 78.8% of coal input in low coke production scenario, compared with those in 2022. Compared with those in low coke production scenario, coal input and CO_2 emissions would increase by 0.7 Mt and 0.5 Mt by 2060 in ideal scenario. This is because coke production with CDQ consumes more coals than that with CWQ under equivalent production conditions, due to the higher coke loss rate. Moreover, the oxidation of coke during CDQ process releases CO_2, leading to higher carbon emissions from coke production with CDQ.

In low coke production scenario, the saved water outweighs the whole water consumption of Shandong in 2022, and the reduced coal input is approximately three-folds of China's coal consumption. Meanwhile, SO_2, NO_x and PM emissions would be reduced by 72.1~87.2%, 78.3~90% and 79.2~90.4% by 2060, respectively. This highlights the remarkable resource and environmental co-benefits from coking plants phase down. Additionally, coal input for coking production will reach 100% reduction in 14 provinces (e.g., Anhui, Heilongjiang, and Xinjiang) by 2060 compared to 2022 levels. This substantial reduction primarily stems from the complete phaseout of coking plants under carbon neutrality targets. The magnitude of water saving and pollutant emission reductions would surpass that of coal reduction, as wet quenching technology would be prioritized for rapid retirement.


a
NO2 emission (M ton)
SO2 emission (M ton)
PM emission (M ton)
CO2 emission (M ton)
Coal consumption (G ton)
Water consumption (G ton)
Scenario
BAU
High
Medium
Low
Ideal
b
c
d
e
SO2 emission/k ton
NO2 emission/k ton
PM emission/k ton
CO2 emssion/M ton
A: Same as 2022
B: BAU scenario
C: Medium scenario
D: Low scenario
E: High scenario
F: Ideal scenario
Gaps between A and B
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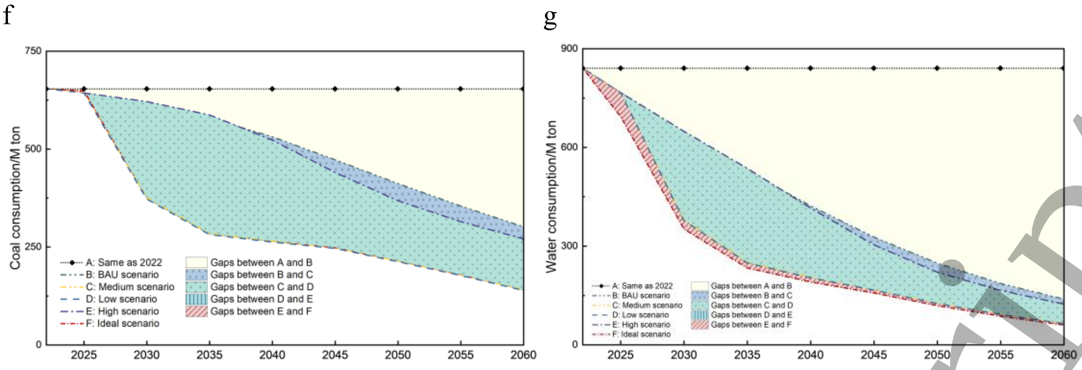

Fig.5 Resource and environmental impacts of Chinese coking industry from 2023 to 2060 under various scenarios. The variations in hues on the bars and rings represent different scenarios. The height of the bars reflects the specific values of those indicators under each scenario, while the length of the outer rings shows the relative magnitudes of these indicators between different scenarios. Additionally, the scales of the radial axes inside and outside the grey circle are different. The coal consumption and carbon emissions in ideal scenario are higher than those in low scenario due to the higher coke loss rate of CDQ.

3.5. Contribution decomposition to resource and environmental benefits. The co-benefits are attributed to the declined coke demand owing to the technological change in IS industry (demand reduction effect and structure effect in IS industry), as well as technical improvement (efficiency effect) and production structure transition (structure effect in coking industry) in coking industry (Table 1). The results reveals that the significant decline in coke demand (demand reduction effect) and EAF and reducing agent substitution (structure effect in IS industry) play a dominated role in the co-benefits from the transition of coking industry. The two effects are driven by the development of IS industry under carbon neutrality target. Technological advancement (efficiency effect) also leads to a large resource and environmental benefits, especially in water saving. Additionally, structure effect in coking industry (from CWQ to CDQ) would only account for -0.3%~0.5% of resource (or environmental) benefits due to the higher coke input and CO_2 emission of coke production with CDQ.

Table 1 Contribution ratios of resource or environmental benefits from various effects by 2060 under ideal scenario

Benefits	Demand reduction effect/%	Structure effect in IS industry/%	Efficiency effect/%	Structure effect in coking industry/%
SO_2 emissions mitigation	58.1	30.6	11.3	0.1
NO_2 emissions mitigation	56.4	29.5	14.0	0.1
PM emissions mitigation	56.7	28.9	13.9	0.4
CO_2 emissions mitigation	59.9	32.1	8.2	-0.3
Coal phasedown	64.1	34.1	2.0	-0.1
Water saving	56.0	28.0	15.5	0.5

From a spatial perspective, the potential cumulative co-benefits of coal phasedown in ideal scenario mainly come from Shanxi (22.5%), Hebei (9.7%), Inner Mongolia (8.0%), Shandong (7.4%), Xinjiang (6.8%), and Henan (5.0%) while water saving from Shanxi (22.8%), Inner Mongolia (9.2%), Hebei (8.8%), Shaanxi (6.6%), Xinjiang (6.2%), Shandong (5.8%), and Henan (5.1%). These decomposition of the contributions to the co-benefits would provide implications for future green and low-carbon transition of China's coking industry.

4. DISCUSSIONS

The transition in the coking industry differs from coal power sector, primarily due to its strong dependence on steel production under climate mitigation targets. A reduction in coke demand alleviates resource and environmental pressures, complemented by efficiency improvements from advanced processing and emission-reduction technologies. China's coking industry has enforced ultra-low emissions since 2024, aiming for 80% compliance by 2028, while systematically phasing out outdated capacities since 2013. Transition strategies encompass mergers, intelligent upgrades, and new utilization method. These measures optimize production efficiency while reducing emissions and resource consumption.

Despite the evident environmental and climate benefits, accelerating the retirement of China's young coking plants poses undeniable socio-economic risks. To mitigate stranded assets, retired coking plants should retain their by-product production functions and pivot toward processing chemical products. Meanwhile, these plants must arrange or compensate unemployed employees to reduce social risks. Stakeholders should prioritize capital reallocation by directing investments toward non-coal industrial development. These measures are based on practices from closed-down coking plants found in literature reviews such as Nyakundi et al. (2022)[39] and Feng et al. (2023)[40], extensive field research, and online interviews of coking and steel making plants located in Shanxi, Inner Mongolia, and Ningxia.

Moreover, the transition and retirement pathways for China's coking plants in the future involve either the shutdown of excess production capacities or technological upgrade of outdated production capacities. The latter typically requires substantial upfront investments, making economic feasibility another critical determinant of successful transformation. In this process, different financing mechanisms will create significant variations in the economic viability of retirement and transition pathways[41]. It is imperative that various regions promptly establish financing mechanisms and subsidy policies, facilitating the orderly transition or phase-out of coking plants.

Finally, if maintaining the share of hydrogen-based DRI as GCAM outputs in low and medium coke production scenarios, the coke demand in 2060 would increase to 181.31 and 179.15 million tons, leading to 68.1% and 68.7% increases in pollutant emissions, water use, and coal input of coking industry. Additionally, Chinese policymakers have established targeted policies to accelerate the adoption of EAF with scrap technology, due to the projected growth of scrap steel resources. To align with this trend, a sensitivity analysis within the low coke production scenario is conducted, assuming an increase in the share of EAF with scrap technology (detailed in Supplementary Table 10). In this case, China's coke demand by 2060 is estimated to be 82.89 million tons, leading to an additional 21.94% decrease in associated pollutant emissions, water usage, and coal input within China's coke sector. These results reflect significant influence of the adoption in both hydrogen-based DRI and EAF with scrap technologies.

5. CONCLUSION

This paper develops optimized, multi-criteria retirement pathways for China's coking industry. The results indicate that the majority of coking plants will be phased out due to low capacity, prolonged operation years, and outdated technologies. This transition will yield significant resource and environmental co-benefits: water use and coal input are projected to decline by 93.3% and 78.8%, respectively, by 2060, while SO_2, NO_x, and PM emissions will decrease by 72.1~87.2%, 78.3~90%, and 79.2~90.4%. These reductions are primarily driven by declining crude steel demand, production structure adjustments. Notably, while the comprehensive adoption of CDQ can reduce water use and pollutant emissions, it may marginally increase coal input and carbon emissions. These findings provide the first granular, data-driven roadmap for China's coking industry transition.

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