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Original Research

Technical alternatives for coke oven gas utilization in China: A comparative analysis of environment-economic-strategic perspectives

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A B S T R A C T

China is the largest coke producer and consumer. There is a pressing need to address the high emissions of air pollutants and carbon dioxide associated with traditional coking production. As the nation pursues a transition towards carbon neutrality, expanding supply chains for coking plants to produce hydrogen, methanol, and other green alternatives has garnered significant attention. However, the relative advantages of these strategies have remained uncertain. In this study, we integrate a life cycle assessment-economic analysis-scenario analysis model to evaluate various coke oven gas (COG) utilization routes (COGtM: COG-to-methanol, COGtLNG: COG-to-liquefied natural gas, COGtSA: COG-to-synthetic ammonia, and COGtH: COG-to-hydrogen). The results indicate that COGtSA emerges as the preferred option for balancing environmental and economic benefits. Meanwhile, COGtM demonstrates economic viability but is associated with higher environmental impacts. Despite being recognized as a significant strategic direction under carbon neutrality initiatives, COGtH faces economic feasibility and risk resilience limitations. COGtLNG encounters both financial and environmental challenges, necessitating strategic development from an energy security perspective. The projected coking capacity is anticipated to experience a slight increase in the mid-term yet a significant decline in the long term, influenced by steel production capacity. In potential future markets, COGtM is estimated to potentially capture a maximum market share of 16–34% in the methanol market. Furthermore, against the backdrop of continuously expanding potential demand for hydrogen, COGtH holds advantages as a transitional solution, but in the long run, it can only meet a small portion of the market. COGtSA can meet 7–14% of market demand and emerges as the most viable pathway from the viewpoint of balancing environmental and economic aspects and covering future markets.

1. Introduction

China is the world's largest coke producer and consumer, accounting for roughly 70% of global total [1]. In 2022, China's coke production reached 473.44 million tons, with a by-product output of approximately 200 billion m^3 of coke oven gas (COG). However, only 98.12 billion m^3 of COG were utilized, with the remainder discharged into the air, resulting in immense environmental pollution, resource waste, and 152.39 million tons of equivalent CO_2 emissions [2].

Approximately 85% of China's coke products are consumed by the steel industry, which is produced by steel joint coking enterprises and independent coke enterprises. However, only 23.7% of the coke production comes from self-owned coking plants of steel mills, while the majority, about 76.5%, is produced by independent coking enterprises [3]. The temporal and spatial mismatch between independent coking enterprises and steel enterprises restricts the direct burning of COG as a heat source for the steel industry. Furthermore, solely using COG as fuel would overlook the intrinsic value of CH_4 and H_2, resulting in a diminished product value. There is immense potential to utilize COG to produce high-value products, achieving substantial socio-economic benefits.

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COG typically contains a certain proportion of coal tar, hydrogen sulfide, ammonia, and naphthalene, which must be mitigated below threshold levels of 10, 20, 50, and 75 mg m^{-3} to comply with environmental regulations [4]. After purification, pure COG usually consists of 54–59% hydrogen and 24–28% methane, as well as a limited concentration of CO (5–8%), CO_2 (1.5–3%), and hydrocarbons (2–4%), rendering it suitable for chemical synthesis [5]. With China's increasingly stringent environmental initiatives, expanded utilization of COG has been strongly encouraged. At present, the domestic COG production of high-value products is mainly based on the production of methanol, natural gas, and ammonia. Currently, China has an annual effective production capacity of 94.37 million tons of methanol, with COG-based methanol accounting for 13% of the total methanol production [6]. COG-to-synthetic ammonia (COGtSA) is also a well-established technology for COG utilization. In the 1960s, Benxi Iron & Steel (Group) Co., Ltd. Successfully produced pure ammonia from COG, which was then used for urea synthesis [7]. Currently, coal-based ammonia contributes to 77% of the total ammonia production, while COG contributes 2% [6]. Furthermore, there has been a significant focus on natural gas production from COG in recent years, with COG-to-liquefied natural gas (COGtLNG) emerging as one of the major utilization pathways in the coking industry, with over 40 plants having COGtLNG projects in operation, under construction or planned [8]. Recently, China has actively promoted renewable energy development under the carbon peak and carbon neutrality goals. COG-to-hydrogen (COGtH) has been widely implemented as a key transition program [9], facilitating the integration of traditional industries into the renewable-energy industry. With multiple utilization pathways available to produce high-value products, there is an immediate need to examine their economic and environmental advantages in order to establish a well-defined roadmap for the coking industry.

Several studies have employed the life-cycle assessment (LCA) to evaluate the environmental and economic impacts associated with COG utilization. Li et al. [1], Kang et al. [10], and Chen et al. [11] investigated the environmental impacts and costs of methanol production from COG, coal, and natural gas using distinct data sources. These studies reached similar conclusions, suggesting the COG pathway outperformed coal to produce methanol but was inferior to natural gas in terms of environmental performance. However, the COG pathway exhibits advantages over coal and natural gas pathways, with 25.1% and 19.8% production cost reductions, respectively. COG to natural gas conversion has garnered significant attention as a strategic reserve technology to ensure energy security in China. Li et al. [12] investigated the production of liquefied natural gas (LNG) from COG by decarbonization and methanation methods. Their results showed that the methanation method had a better environmental performance than the decarbonization method, as it produced more LNG products from an equivalent amount of COG. Considering economic performance, the methanation process with H_2 extraction is recommended. Other studies, like that of Yi et al. [13], investigated CO_2-assisted COG-to-natural-gas technology, which revealed promising potential for capturing CO_2 while also saving energy by up to 6–7%. For H_2 production, studies by Li et al. [14], Abejon et al. [15], Lin et al. [16], and Wang et al. [17] examined the environment-economy performance from various technological routes such as COG pressure swing adsorption, methane reforming, coal gasification and renewable energy sources. Their results suggested that COG is the most viable alternative besides renewables. In addition, Hwang et al. [18] and Gupta et al. [19] concluded that COG-based H_2 has higher overall energy efficiency than renewables-derived H_2 despite more emissions of air pollutants. The study above primarily focuses on traditional life cycle assessment methods, which evaluate the environmental impacts of producing the same product using different raw materials. However, there is a lack of comprehensive comparisons for the various utilization pathways of COG. Hence, there is a lack of systematic guidance for establishing a clear roadmap for the high-value utilization of COG.

More recently, Zhang et al. [20] proposed an LCA-based technology-environment-economy assessment framework to compare the competitiveness of six COG utilization routes. Their economic evaluation, however, solely relied on cost-benefit analysis and did not conduct an integrated evaluation of the environment and economy. Ren et al. [21] integrated life cycle cost (LCC) analysis with LCA to investigate environmental and economic improvement opportunities and quantify the potential for carbon reduction among various utilization routes. These studies have paid insufficient attention to determining comprehensive competitiveness, future scenario changes, and the resilience of policy-market risks, thereby seemingly encountering difficulties in establishing a direct link between COG utilization pathways and policy development. However, these aspects are crucial for guiding decision-making in both business and policy domains.

To fill this research gap, a comprehensive analysis was conducted to examine the life cycle emissions associated with four different utilization pathways of COG to produce methanol (COGtM), COGtLNG, COGtSA, and COGtH. Data was collected from representative enterprises to provide a refined life cycle inventory. Special attention was paid to assessing the interactions between the environment-economy-policy, which was achieved through the flexible setting of the base unit for the LCA and the adoption of scenario analysis methods. In line with the policy of "regulating coking capacity based on steel capacity", this study also predicts the potential of different COG utilization paths to reduce both pollutant and greenhouse gas (GHG) emissions. Building on this, the most favorable transformation strategy was proposed.

2. Methodology

The analytical framework is presented in Fig. 1. We first developed a cradle-to-gate life cycle framework using data from typical operational projects. Unit disposal quantity of COG and industrial added value (IAV) are used as functional units to evaluate the

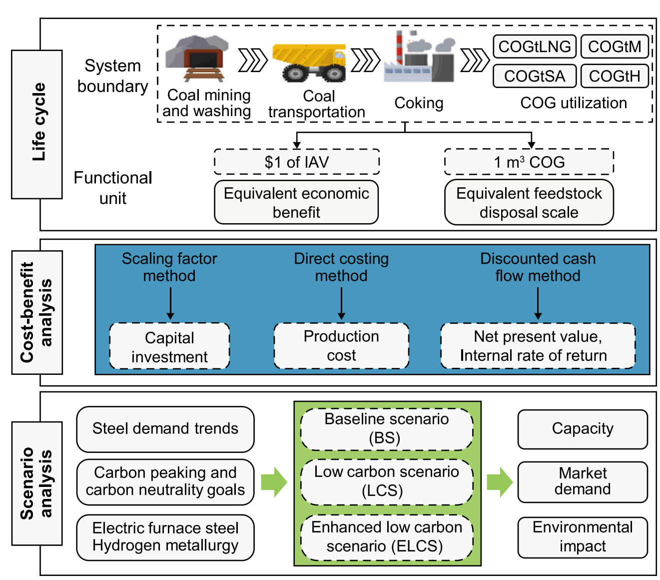

Fig. 1. System boundary and schematic diagram of the analytical framework in this study.

environmental and integrated environmental-economic benefits of various COG utilization pathways. This aims to identify preferred options for enterprises complying with environmental regulations or balancing economic profitability and environmental concerns. Next, we employed a cost-benefit analysis considers equipment and product technical costs. Based on these results, the impact of raw material and product price fluctuations on economic and environmental indicators were assessed, exploring the market risk resilience of different technology routes. Lastly, following the "regulating coking capacity based on steel capacity" policy, future coking capacity was projected. The potential for reducing pollution and GHG emissions, along with economic benefits, was examined under different development scenarios: baseline scenario (BS), low-carbon scenario (LCS), and enhanced low-carbon scenario (ELCS).

2.1. LCA analysis

2.1.1. Assessment model

Life cycle modeling and assessment were conducted using GaBi software and database. The CML2001 and Intergovernmental Panel on Climate Change (IPCC) assessments were used in the environmental impact assessment [22–25], comprising four stages: impact classification, characterization, normalization, and weighting [26]. Acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP) were chosen as key quantitative indicators, taking into consideration the primary pollutants involved and environmental requirements. Characterization aimed to standardize pollutant data and quantify their environmental impact using equation (1), then the normalization results were computed using equation (2):

$$EI_c = \sum_{i=1}^{n} EI_{c,i} = \sum_{i=1}^{n} (I_{c,i} \times CF_{c,i}) \quad (1)$$

where EI, I, CF, c, and i denote the environmental impact results, inventory, characterization factor, category, and substance, respectively. AP, EP, and GWP characterization and normalization factors are obtained from GaBi software.

$$N_{c,j} = \frac{EI_c}{NF_c} \quad (2)$$

where $N_{c,j}$ is the normalization result for impact category c in the jth technology, EI_c is the characterization result, and NF_c is the normalization factor.

To facilitate a more intuitive comparison of the four COG utilization techniques, the entropy weight method was employed to aggregate the three distinct environmental impacts into a single indicator known as the total environmental impact. The information entropy was calculated using equation (3), and the weighting factors for different environmental impact types were calculated using equation (4). The normalization and weighting factors adopted in this work are depicted in Table 1.

Table 1
Normalization and weighting factors for LCA of this study.

Impacts	Normalization factors	Weighting factors	
		1 m^3 COG	\$1 of IAV
AP (kg SO_2 eq.)	2.39×10^{11}	0.287	0.464
EP (kg Phosphate eq.)	1.58×10^{11}	0.205	0.301
GWP (kg CO_2 eq.)	4.284×10^{13}	0.507	0.235

$$E_c = -\frac{1}{\ln 4} \times \sum_{j=1}^{4} \frac{N_{c,j}}{\sum_{j=1}^{4} N_{c,j}} \times \ln \frac{N_{c,j}}{\sum_{j=1}^{4} N_{c,j}} \quad (3)$$

$$WF_c = \frac{1 - E_c}{3 - \sum E_c} \quad (4)$$

In these equations, E_c is the information entropy of the cth normalized environmental impact, and WF_c denotes the weighting factor of each impact category c.

The final step was to calculate the total environmental impact, as demonstrated by equation (5):

$$\text{Total environmental impact} = \sum_{c=1}^{3} WF_c \times N_c \quad (5)$$

2.1.2. System boundary and functional unit

The system boundaries of the COG utilization encompass four stages, namely coal mining and washing, coal transportation, coal coking, and COG utilization, in which the COG transportation stage was negligible since COG utilization facilities are typically built onsite at independent coking plants [27,28]. In order to facilitate the evaluation of the environmental benefits and integrated environmental-economic benefits of various COG utilization pathways, functional units were defined as 1 m^3 of COG disposed of and \$1 of IAV product output for analysis, respectively.

2.1.3. Data inventory and data quality

The data for this study were derived from real projects, public sector development reports, and national statistical yearbooks. The coal mining and washing stage referred to the China Cleaner Production Standard for the Coal Mining and Processing Industry (HJ 4462008) [29]. The data for the coal coking stage were obtained from a typical coke producer in Shanxi Province, producing 114.2–163.1 billion m^3 of COG annually after deducting its heat supply. For the COG utilization stage, surveys were conducted on representative large projects to ensure comparability with current industrialization levels. Energy consumption and emissions data for methanol and ammonia production were collected from a representative coke producer in Shaanxi Province, generating 1.2 million tons of metallurgical coke, 100,000 tons of methanol, and 90,000 tons of ammonia annually. Data on LNG and H_2 production were obtained from a COG liquefaction project in Shanxi Province and a COG purification and conversion to hydrogen plant at a coal chemical enterprise located in Nei Mongol Zizhiqu, respectively. Input and output data, excluding the COG utilization stage, were obtained from LCA databases (updated 2022 edition) as outlined in Table S1.

2.2. Cost-benefit analysis

To provide a comprehensive evaluation of the economics, this study determined the production cost (PC), net present value (NPV), and internal rate of return (IRR) for each route. The upstream economic costs adopted here are implicitly included in the raw material cost of production [30,31]. Thus, the primary focus of the economic cost analysis was the production process for the four products. To calculate the product costs, equation (6) was implemented [32], where C_F and C_U corresponded to raw material and utility costs. C_D denoted depreciation cost, $C_{D\&M}$ indicated distribution and marketing costs, $C_{O\&M}$ signified operation and maintenance costs, C_{PO} represented plant overhead costs, and C_A denoted management costs. Fixed capital investment depreciation followed a linear pattern, while equipment cost investment utilized the proportionality factor exponent in equation (7), adjusted for plant size [31]. Here, I_1 represented reference project equipment, Q_1 reflected the scale of the reference project, I_2 denoted equipment investment for the studied project, and Q_2 corresponded to the scale of the studied project. The regional factor was represented by θ, while n served as the scale exponent, set constant at 0.6 throughout the study [33].

$$\text{PC} = C_\text{F} + C_U + C_\text{D} + C_{\text{D\&M}} + C_{\text{O\&M}} + C_{\text{PO}} + C_\text{A} \tag{6}$$

$$I_2 = \theta I_1 \left(\frac{Q_2}{Q_1}\right)^{\text{n}} \tag{7}$$

The net present value (NPV) was calculated using equation (8) to evaluate project feasibility. This value represents the current worth of both present and future benefits minus the current value of present and future costs. Here, r referred to the discount rate, NCF_t denoted the cash flow in the tth year, and the expected plant lifetime was T. Additionally, equation (9) was utilized to determine the internal rate of return (IRR) [34], which is the discount rate at which the NPV equals zero [11]. The calculation of IRR involved C_0, which represented the total initial investment costs.

$$\text{NPV} = \sum_{t=1}^{T} \frac{NCF_t}{(1+r)^t} \tag{8}$$

$$0 = \text{NPV} = \sum_{t=1}^{T} \frac{NCF_t}{(1+IRR)^t} - C_0 \tag{9}$$

IAV was calculated using the production method and represents the difference between gross industrial output value (GIOV) and intermediate industrial inputs value [20] expressed in equation (10).

$$\text{IAV} = \text{GIOV} - \text{PC} \tag{10}$$

The prices of various raw materials, energy, engineering, and products are based on the average domestic market prices. The costs of labor, plant equipment, and other relevant expenses were calculated based on annual reports of businesses. All costs were measured in US dollars to ensure comparability with the literature and reports. The exchange rate has experienced significant fluctuations this year. To ensure comparability with other studies, this research adopted a relatively stable RMB/USD exchange rate of 6.8982, which has remained relatively stable over the past few years. This rate was based on data obtained from reputable sources cited in the study [1].

2.3. Comprehensive competitiveness analysis

To determine the comprehensive competitiveness of the COG utilization schemes, the extreme value method [35] was applied based on various economic and environmental indicators, including energy consumption, carbon emissions, total environmental impact, fixed capital investment, product cost, NPV, and risk resistance capacity. The comprehensive score for each utilization scheme was calculated using equations (11) and (12):

$$X'_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \tag{11}$$

$$X'_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} \tag{12}$$

where X'_{ij} is the standard value of the jth indicator of the ith COG utilization route.

In this context, the calculation of risk resistance capacity was based on sensitivity analysis. Specifically, this study investigated the impacts of a 10% fluctuation in electricity, steam, COG, and product prices on environmental and economic indicators (AP, EP, GWP, product cost, IRR, and NPV). Based on equation (13), the results were quantified into a sensitivity factor, denoted as SF, to measure the risk resistance capacity of different COG utilization pathways.

$$\text{SF} = \frac{\Delta E/E}{\Delta F/F} \tag{13}$$

In equation (13), $\Delta E/E$ is the rate of change of evaluation indicators (AP, EP, GWP, product cost, IRR, NPV), $\Delta F/F$ is the rate of change of potentially influential factors (electricity price, steam price, COG price, major product prices).

2.4. Scenario setting

Considering the current technological level and development plans of the steel industry, as well as drawing from the Sustainable Development Scenario (SDS) proposed by the International Energy Agency [36], it is projected that China's steel demand will peak at 900 million tons in 2023 and eventually decline to 700 million tons by 2050. The forecast for coke production is determined based on changes in steel production. Given that the consumption of coke in the steel industry has consistently accounted for around 85% of China's total coke consumption over the past two decades and recognizing that other industries face similar transformation pressures and pathways in the low-carbon transition, we adopt this proportion to estimate the national coke demand. For further details and parameters, refer to Table 2. The BS is based on the “14th Five-Year Plan for the Development of the Iron and Steel Industry (2021–2025)" [37] and the “Guiding Opinions on Promoting High-Quality Development of the Iron and Steel Industry (2020)" [38], as well as the “Report on Energy Conservation and Low-Carbon Development of China's Iron and Steel Industry (2020)" [39]. The LCS and ELCS incorporate technological advancements and hydrometallurgical technologies development into the baseline scenario, with a greater reduction in forecasted coke production. The ELCS is based on a study by Zhang et al. [40], while the LCS assumes a five-year lag in developing hydrometallurgical technology.

3. Results and discussion

3.1. Environmental impact analysis

Panels a–d and e–h in Fig. 2 show the life-cycle environmental impacts of various COG utilization paths, with 1 m^3 of COG disposed and $1 of IAV defined as functional units, respectively. The comparative results show the difference between the two strategies of the enterprise: complying with environmental regulations or seeking economic benefits. The assessment includes three typical indicators (AP, EP, GWP) and the normalized total environmental impact.

As shown in Fig. 2a–d, direct discharge of COG poses a significant environmental risk. When considering the disposal of 1 m^3 of COG as the functional unit, the COGtH route exhibits the least

Table 2
Three scenarios and key parameters.

Parameters	2020			2030			2050		
	BS	LCS	ELCS	BS	LCS	ELCS	BS	LCS	ELCS
Steel production (Mt)	1060	1060	1060	900	900	900	700	700	700
Electric furnace proportion (%)	10.3	10.3	10.3	20	20	25	35	35	40
Coke ratio	0.5	0.5	0.5	0.5	0.43	0.43	0.5	0.38	0.35
Hydrogen metallurgy proportion (%)	0	0	0	0	0	3	0	10	15
Coke (Mt)	666.36	666.36	666.36	637.39	637.39	637.39	284.36	182.88	137.8
COG (Bm^3)	108.72	108.72	108.72	103.99	103.99	103.99	46.39	29.84	22.48

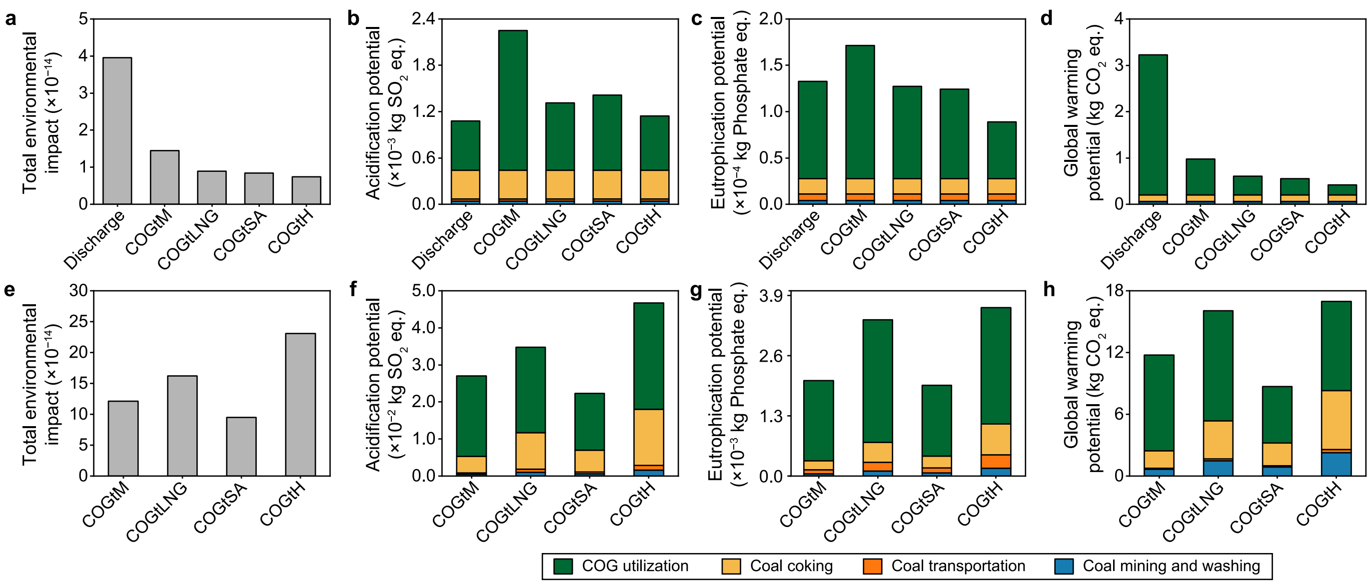

Fig. 2. Environmental impacts and contributions of different processes for various coke oven gas (COG) utilization pathways with 1 m^3 COG as the functional unit (**a**–**d**) and $1 of industrial added value (IAV) as the functional unit (**e**–**f**): total environmental impact (**a, e**); acidification (**b, f**); freshwater eutrophication (**c, g**); and global warming (**d, h**).

environmental impact due to its minimal requirements for electricity and steam. On the other hand, COGtM is the least efficient pathway as it involves high-temperature reactions and significant steam consumption in converting CH_4 to CO and H_2. Notably, according to China's strict atmospheric pollutant control standards, current COG is already obliged to undergo purification treatment, and even if discharged directly, sulfur-containing components are eliminated. Therefore, incorporating COG utilization units into the current coking process would lead to increased consumption of electricity and steam, and fossil fuels, thereby exacerbating the acidification effect. The AP generated by COGtM is nearly twice that of direct emissions, and the other pathways show slightly slower increasing trends. Regarding EP, COGtM still has an adverse impact, while only the COGtH route exhibits a definite positive effect among the four pathways. This indicates that the COGtH is the only one significantly contributing to reducing water pollution. From the perspective of GWP, all four pathways significantly reduce GHG emissions compared to combustion emissions after purification by a factor of 3.3, 5.3, 5.8, and 7.8, respectively. In summary, although all four pathways significantly reduce the total environmental impact, COGtM, COGtLNG, and COGtSA primarily lower GWP, with minimal or negative contributions to reducing AP and EP. Conversely, COGtH exhibits notable improvements across various aspects of mitigating COG pollution.

With $1 of IAV instead of 1 m^3 of COG as the functional unit, the competitive landscape of the four COG utilization pathways undergoes significant changes (Fig. 2), indicating differences between the strategies of complying with environmental regulations and seeking economic and environmental balance. Here, COGtSA exhibits the lowest AP, EP, GWP, and total environmental impact, whereas COGtH and COGtLNG have relatively higher impacts. The widely promoted COGtM pathway demonstrates a favorable total environmental impact, slightly surpassing the COGtSA pathway only regarding GWP. COGtH lacks a competitive advantage primarily due to lower production and prices of hydrogen compared to methanol and ammonia. Consequently, achieving the same net industrial output requires a larger supplementation of COG, resulting in a higher environmental impact of COGtH. In the present market conditions, COGtSA and COGtM pathways demonstrate attractiveness for businesses seeking a balance between environmental regulation and economic benefits. In fact, these two pathways are widely adopted in real practice. Regarding the COGtLNG pathway, it demonstrates mediocre performance both in meeting environmental regulations and achieving economic benefits. Therefore, it appears to be an unfavorable market-oriented choice. However, given the shortage of natural gas resources in China, it is also being promoted in some regions and state-owned enterprises based on concerns about the security of energy supply.

3.2. Energy consumption analysis

With 1 m^3 of COG disposal as the functional unit, the varying energy consumption among all pathways exists in the COG utilization process. COGtM pathway stands out with the highest energy consumption. This is mainly because methanol synthesis involves a steam reforming process, requiring an additional consumption of 3.192 MJ of coal equivalent steam, 1.9 times higher than the steam demand of COGtLNG. The other two pathways require only a minimal amount of steam. As a result, COGtM and COGtH contribute to the most and least emissions of pollutants and greenhouse gases among the four pathways.

As illustrated in Fig. 3b, the energy consumption per IAV demonstrates a large disparity among the four pathways examined here. The COGtH consumes the most energy overall (71.367 MJ $\$^{-1}$) due to the relatively low added value of the hydrogen product. This reflects that to generate equivalent economic benefits, a greater amount of COG (37.199 coal equivalent) must be consumed in the COGtH pathway, nearly double the quantity required by the COGtSA pathway (18.089 MJ). The COGtM pathway exhibits a competitive advantage in terms of energy consumption, primarily attributed to the high prices of methanol products compared to others.

3.3. Cost-benefit analysis

Fig. 4 presents the equipment investment and product costs of various COG utilization schemes. As shown in Fig. 4a, the total equipment investment for disposing of 1 m^3 of COG is as follows: COGtM ($0.177), COGtLNG ($0.098), COGtSA ($0.105), and COGtH ($0.034). The corresponding product costs are presented in Fig. 4b: COGtM ($0.133), COGtLNG ($0.130), COGtSA ($1.1145), and COGtH ($0.1147). This indicates that COGtSA and COGtH offer advantages in terms of product cost. Regarding the composition of product costs, feedstock constitutes the largest proportion, accounting for 47.4%, 53.2%, 54.9%, and 54.2% of the total cost for COGtM, COGtLNG, COGtSA, and COGtH, respectively. The second-largest component of production costs is utility cost, representing 32.2%, 31.7%, 32.1%, and 37.6% for COGtM, COGtLNG, COGtSA, and COGtH, respectively. The COGtM pathway has a relatively lower feedstock cost but a higher utility cost, indicating that the pathway of COGtM is less sensitive to feedstock prices.

The results for taking IAV as the benchmark are illustrated in Fig. 4c. In this case, the investments for COGtM, COGtLNG, COGtSA, and COGtH are $0.789, $0.702, $0.549, and $0.311, respectively.

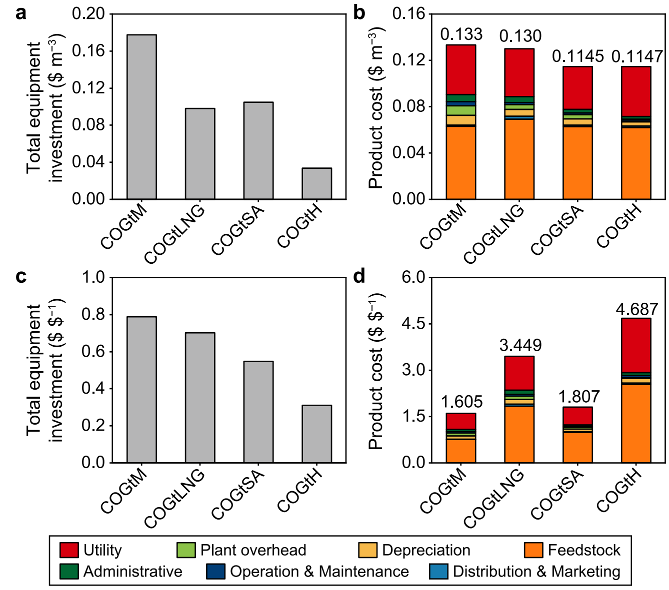

Fig. 4. **a**–**b**, Capital investment (**a**) and product cost (**b**) with a functional unit of 1 m^3 coke oven gas (COG). **c**–**d**, Capital investment (**c**) and product cost (**c**) with a functional unit of $1 of industrial added value (IAV) for COG utilization.

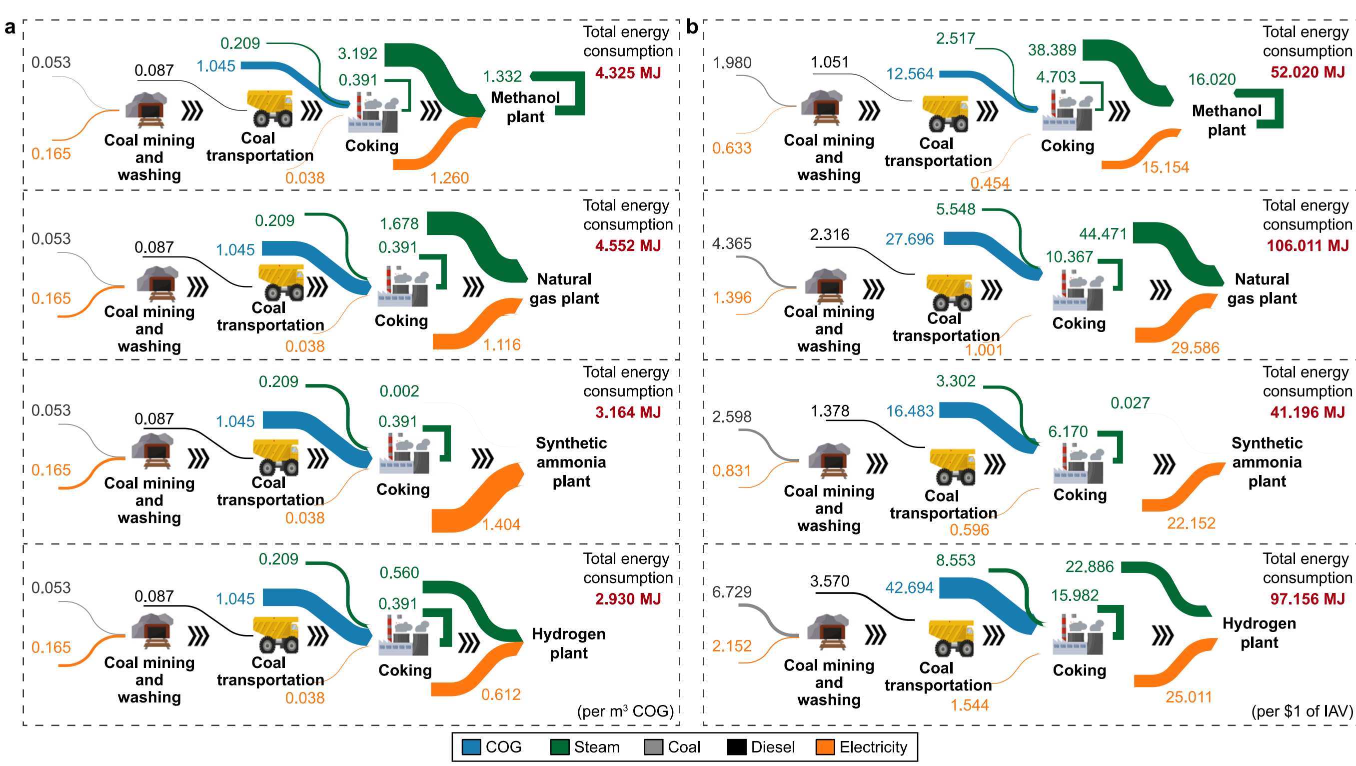

Fig. 3. Energy flow in the life cycle subprocess of various coke oven gas (COG) utilization pathways with the functional unit of 1 m^3 COG (**a**) and $1 of industrial added value (IAV) (**b**).

Notably, the ranking of total equipment investment exhibits a noteworthy departure from the scenario centered on environmental regulatory compliance: COGtLNG surpasses COGtSA and even approaches the level of COGtM. Furthermore, it is worth mentioning that COGtH, although remaining the pathway entailing the lowest investment, experiences a certain diminution in its comparative advantage. Upon reviewing Fig. 4d–a more pronounced shift in the ranking of product costs becomes evident. COGtH, formerly the cost-effective choice when accounting for environmental regulations, is transforming remarkably, manifesting as the most expensive option. In contrast, COGtM transitions from being the most financially burdensome pathway to the most cost-effective one. This finding implies that COGtM emerges as the most favorable selection when prioritizing economic profitability. While COGtH benefits from lower initial investment, it incurs escalated production costs in the long run. It is noteworthy that COGtSA establishes itself as a relatively advantageous alternative, characterized by the least risk exposure, irrespective of whether the emphasis lies in environmental regulatory compliance or economic returns.

3.4. Sensitivity analysis

A comprehensive sensitivity analysis was conducted to assess the ability of different technological pathways to withstand market risks, with results illustrated in Fig. 5. In the current market, the production costs of converting COG into hydrogen and ammonia are roughly equivalent, around \$0.12, while the production costs of methanol and LNG are much higher due to their more complicated production processes. All four technical pathways in Fig. 5b demonstrate NPVs > 0, suggesting profitability. Among various factors, product prices have the greatest impact. Hence, owing to the relatively high price of methanol, COGtM currently has the highest NPV. When the methanol product price drops by 10–15%, its NPV decreases by \$0.016 to \$0.025, gradually approaching the level of COGtSA. If LNG prices increase during this time, they can even rival those of COGtLNG. However, the COGtH pathway is hardly competitive with COGtM. Examining the IRR, which usually represents risk-taking capacity, reveals differences with NPV, primarily due to differences in asset investment. Remarkably, all four pathways exhibit satisfactory levels of IRR under the current market conditions. However, compared to COGtM and COGtLNG, COGtH is much more sensitive to fluctuations in product price and shows significant returns under favorable markets but quickly loses competitiveness under unfavorable market conditions.

Fig. 5d–f further demonstrates the impact of economic indicators on environmental benefits when aiming for the same IAV. Sensitivity analysis shows that environmental impacts are positively correlated with COG, electricity, and steam prices while negatively correlated with the product price. Among these parameters, product prices have the greatest influence on environmental indicators, highlighting the importance of price expectations in determining the optimal strategy. Generally, COGtH and COGtLNG are more susceptible to price changes than COGtM and COGtSA, as evidenced by their higher sensitivity to relative variations. As product prices increase, the environmental impacts of COGtH and COGtLNG quickly approach the levels of COGtM and COGtSA. Specifically, when the hydrogen products price varies by −10% and 10%, the AP, EP, and GWP indicators of COGtH show variations of 131.88% and −36.25%, respectively, whereas these indicators change by 74.73% and −29.96% for the same change in LNG price. The positive environmental impact of price increases is significantly less than the negative impact of price decreases, emphasizing the greater need for certainty in upward price trends. Therefore, regarding economic-environmental synergies, COGtH appears to have greater potential than COGtLNG, as hydrogen is expected to experience sustained price increases in the context of carbon neutrality due to its potential for large-scale applications, while LNG prices remain highly uncertain.

In summary, considering market fluctuations, COGtM and COGtSA appear to be secure options with certain advantages in balancing economic and environmental factors. The advantages of the COGtH route are mainly reflected in the anticipated explosive growth in future hydrogen demand and its lower initial investment. Furthermore, the COGtLNG pathway seems to have no appeal.

3.5. Comprehensive performance analysis

Based on the results above, various environmental and economic indicators were examined, and the risk resistance capacity

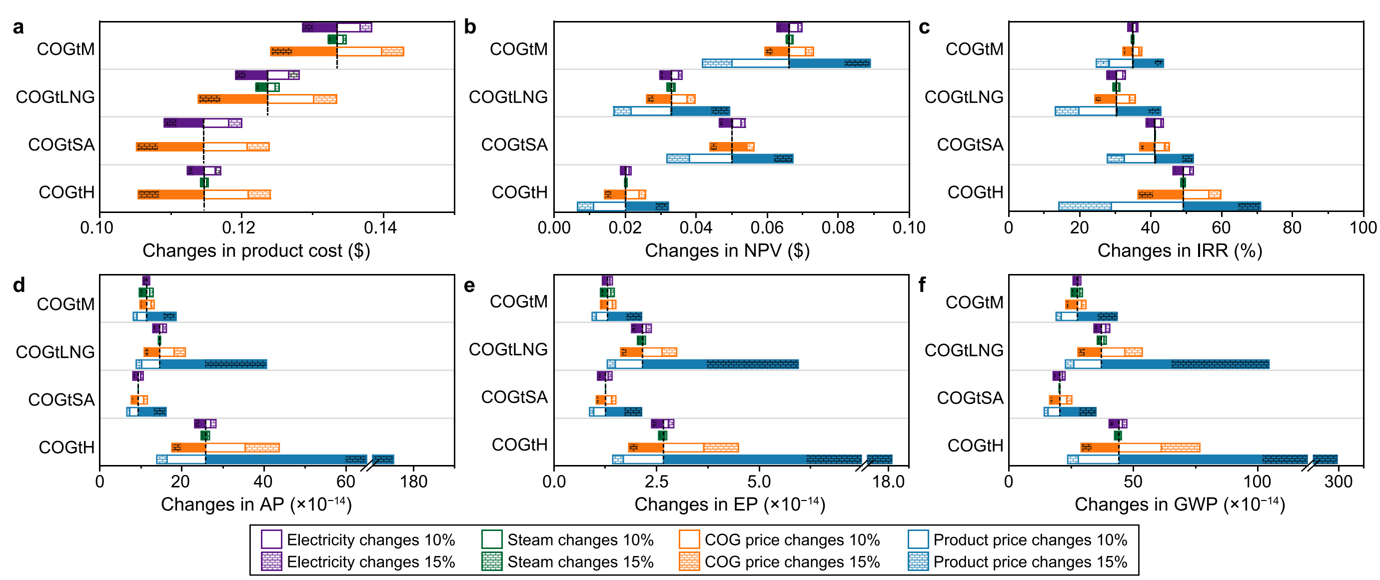

Fig. 5. Sensitivity analysis of feedstock and product prices with a change rate of 10% and 15% on the economic and environmental indicators: product cost (**a**), net present value (NPV) (**b**), internal rate of return (IRR) (**c**); and acidification potential (AP) (**d**), eutrophication potential (EP) (**e**), and global warming potential (GWP) (**f**). Solid bars and hollow bars represent the cases of the independent variable decreasing and increasing, respectively. Shaded fills represent cases where the independent variable changes by 15%.

score was quantified based on the sensitivity analysis. The analysis of the comprehensive competitiveness of different COG utilization pathways is presented in Fig. 6. When establishing factories based on the scale of COG disposal, the comprehensive scores of COGtH and COGtSA are the highest. COGtH receives a high score due to its exceptional pollution and GHG reduction performance, while COGtSA benefits from its balanced environmental and economic performance. The economic performance and risk resistance of the COGtH pathway are both poor, and COGtSA appears to be a more appealing alternative than COGtH. COGtM demonstrates less competitiveness primarily due to its underwhelming environmental benefits. However, this pathway has the best economic performance and risk resistance, making it still an attractive choice in certain aspects.

COGtSA still achieved the highest comprehensive score when aiming for the same profits. Hence, COGtSA appears to be the most reliable choice in the current market landscape. COGtM secured the second position, owing to the higher economic value of methanol than the other three products. For equivalent profits, the environmental impact of COGtM becomes its advantage, leading to an improvement in the comprehensive score. Among all the technological routes, the COGtM pathway necessitates the highest initial investment, thus posing a significant constraint for enterprises. Notably, the COGtH pathway has swiftly gained traction as a crucial strategic direction in China. Nevertheless, its overall competitiveness is suboptimal, and it is poorly resilient to risks despite having a modest advantage solely in terms of initial investment. Therefore, despite the extensive interest in hydrogen in the context of carbon neutrality, opting for COGtH is not a rational choice if profitability is the goal. Similarly, COGtLNG lacks robust competitiveness and does not seem attractive.

3.6. Future scenario analysis

Based on the "regulating coking capacity based on steel capacity" strategy, the future coking capacity and quantification of life cycle environmental impacts are projected, as illustrated in Figs. 7 and 8. In the BS, the coking industry's capacity is estimated to peak in 2025, producing a peak CO_2 emission of 223.13 million tons. However, in the LCS and ELCS, the peak year is predicted to be one and two years earlier, recording peak emissions of 214.96 and 203.39 million tons. The projected conversion of COG into methanol, liquefied natural gas, synthetic ammonia, and hydrogen under an LCS (ELCS) is expected to meet 53% (53%), 22% (16%), 22% (22%), and 6.4% (4.8%), 56% (56%), 9% (7%), 12% (12%), 0.8% (0.9%) of the projected market demand in 2030 and 2060 years, respectively. Methanol production from COG appears to be the most advantageous pathway in terms of market share. Alternatively, COGtSA can fulfill 7–14% of the market demand, proving a viable option among several routes.

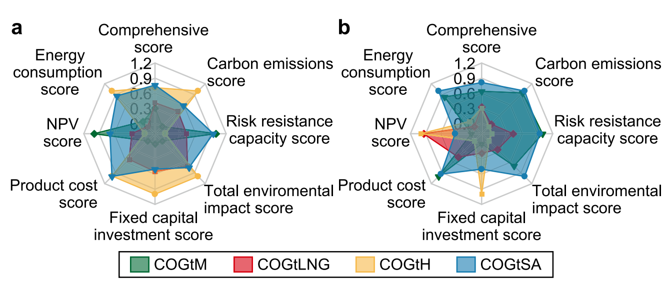

Fig. 6. Comprehensive performances for various coke oven gas (COG) utilization pathways with functional units of 1 m^3 COG (**a**) and $1 of industrial added value (IAV) (**b**).

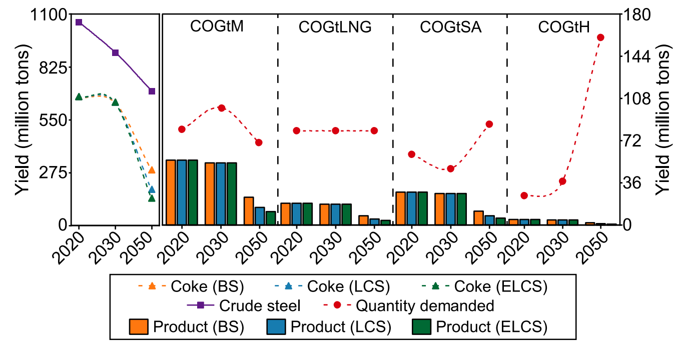

Fig. 7. Demand and production of four products from coke oven gas (COG) under three scenarios for the years 2020, 2030, and 2050.

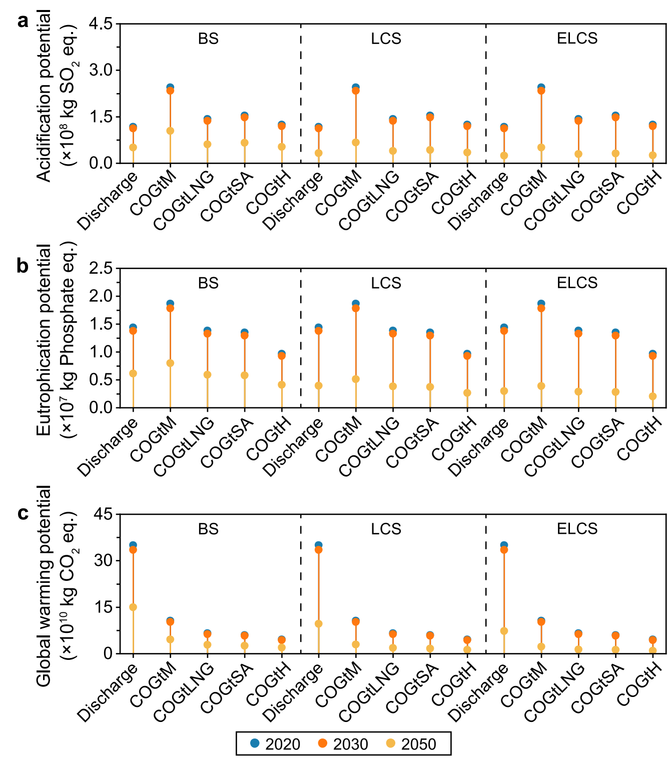

Fig. 8. Scenario analysis of various coke oven gas (COG) utilization routes: acidification potential (AP) (**a**), eutrophication potential (EP) (**b**), and global warming potential (GWP) (**c**).

In the context of AP, various pathways, apart from COGtH, lead to an increased environmental impact, especially the COGtM pathway. The disparity declines considerably as the coking capacity is reduced. COGtH gains the upper hand over other routes concerning AP indicators during the start of the industrial transition, but the difference is negligible towards the end. With the expected widespread employment of ultra-low emission technologies, the future reduction in emissions mainly originates from scale-down production measures. The situation differs notably concerning GWP. Transitioning to COGtM, COGtLNG, COGtSA, and COGtH instead of direct emissions could reduce GHG emissions to 101.69 (21.98), 63.00 (13.62), 57.39 (12.41), and 43.14 (9.33) million tons in 2030 (2050). Although COGtM development initially generates 0.5–0.8 times more GHG emissions than other pathways, the difference becomes insignificant after 2050. All four pathways can support the industry's low-carbon pathway achievement in the long term.

4. Conclusions

This study aims to assess and compare the economic-environmental synergies resulting from four industrialized COG utilization pathways and propose optimal development strategies under various transformation objectives.

Under China's stringent air pollutant control regulations, COG is required to undergo purification, which leaves the utilization of COG with no significant enhancement for AP and EP, with the main advantage being the reduction of GWP. COGtH is the only pathway that can significantly improve almost all aspects of COG pollution, but its potential is limited by economics. Moreover, COGtH is highly sensitive to product price fluctuations, holding advantages in favorable markets but quickly losing competitiveness in unfavorable ones. COGtM emerges as the most economically viable option and has the highest NPV due to the relatively high price of methanol. Notably, when assessing the environmental impacts of obtaining the unit IAV, the GOGtM pathway shows relatively low overall environmental impacts, with only the GWP higher than COGtSA. COGtLNG faces dual challenges in terms of both economic and environmental, and appears to be worth developing only for strategic energy security purposes. Among several pathways, COGtSA emerges as the most prudent technological option from both environmental and economic perspectives.

Furthermore, under the “regulating coking capacity based on steel capacity” strategy, future coking capacity is expected to show a slight increase in the short term and a significant decrease in the long term. Among the potential future markets, the development of COGtM has the potential to capture the largest share of the corresponding product market. Conversely, COGtH appears insignificant in the face of the exploding hydrogen market demand and only serves as a medium-term alternative. Additionally, COGtSA can meet 7–14% of market demand and emerges as the most viable pathway from the viewpoint of balancing environmental and economic aspects and covering future markets. Moreover, while short- and medium-term environmental impacts may vary among different pathways, these differences are expected to diminish in the long term due to the reduction in coking capacity.

CRediT authorship contribution statement

Zichen Di: Conceptualization, Formal Analysis, Investigation, Writing - Original Draft, Writing - Review & Editing. **Feixia Lei:** Methodology, Software, Investigation, Writing - Original Draft, Visualization. **Jiankai Jing:** Investigation. **Hao Peng:** Investigation, Data Curation. **Xi Lu:** Conceptualization, Supervision, Project Administration. **Fangqin Cheng:** Conceptualization, Supervision, Project Administration.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2024.100395.

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