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Security analysis of ethylene glycol production pathways

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ABSTRACT

In the production process of ethylene glycol (EG), which is considered a crucial basic chemical material, China's energy consumption and carbon emissions are greatly affected. This study examines seven different routes for EG production, focusing on their security implications. To evaluate the security of these production routes, a framework is proposed that considers various aspects of the chemical industry chain involved in EG production. The evaluation is conducted across five dimensions, namely the raw materials, technology, economics, environment, and energy consumption. The results show that CTEG and BTEG processes have advantage of high security performance in the raw materials scenario (R-Scenario). Corresponding, CTEG-2 and BTEG-1 routes have advantage of high security performance in the technology scenario (T-Scenario). NTEG and BTEG routes should be adopted according to environment scenario (E-Scenario). In the cost scenario (C-Scenario) and energy consumption scenario (EC-Scenario), OTEG and NTEG routes have the benefit of superior security capabilities because much better economic performance and low energy consumption compared with other routes. The findings of this study serve as a crucial foundation for enhancing the manufacturing process of EG. Additionally, it aids decision makers in selecting the most appropriate production method for EG, taking into account the prevailing circumstances.

1. Introduction

Ethylene glycol (EG) plays a crucial role as an organic chemical raw material and chemical intermediate. (Fowles et al., 2017). In various industries, ethylene glycol is widely used as an antifreeze and a key material for producing polyester (Yue et al., 2012; Yang et al., 2021). In recent years, the demand for ethylene glycol in China has increased significantly in tandem with economic growth. Nevertheless, domestic production of ethylene glycol in China fails to meet the actual consumption requirements (Qingchun et al., 2019b, 2019a). A large proportion of EG is dependent on imports in China. The external dependence of China's EG was 67 % in 2013 which reduced to 29 % in 2023 because a large amount of EG production lines put into operation in 2020, but the external dependence remained high (Li et al., 2019; Jean-Francois, 2019; Tetsu et al., 2024).

More and more people pay attention to EG production technology. However, the comparisons of the security performance of CTEG, OTEG, NTEG, and BTEG routes are rare. In a series of studies, researchers have compared the performance of different energy generation processes. Yang et al. (Yang et al., 2020) found that the coal/oil/natural gas to EG route had drawbacks such as low energy efficiency, high CO_2 emissions, and energy consumption. Xu et al. (Xu et al., 2021) discovered that the CTEG route had the highest global warming potential compared to oil and biomass to EG routes. Qin et al. (Qin et al., 2021) showed that adding renewable energy to coal-based methanol and power poly-generation processes reduced greenhouse gas emissions. Zhou et al. (2021), Dongliang et al. (2021), Jiahao et al. (2023) analyzed the integration of renewable energy with coal to methanol processes for higher product yield and lower CO_2 emissions. Therefore, by incorporating renewable energy sources into the production of hydrogen, we can effectively address the issue of hydrogen scarcity in the coal chemical process while achieving high levels of technological, economic, and environmental performance. Liu et al. proposed a method for the early prediction of abnormal conditions in chemical processes. The method was successfully applied in the crude unit (Liu et al., 2023). Zhang et al. established a re-optimization method based on the system resilience. Optimizing maintenance operational risk involves integrating Job Safety Analysis, Bayesian networks, and Matter Element Theory for a comprehensive assessment (Zhang et al., 2024). Alauddin et al.

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Nomenclature

AGR	Acid Gas Removal
AP	Acidification Potential
ASU	Air Separation Unit
AVD	Atmosphere Vacuum Distillation
BFET	Biomass Fermentation Ethanol
BGS	Biomass Gasification
BTEG	Biomass to Ethylene Glycol
CDR	Carbon Dioxide Removal
CG	Coal Gasification
CNY	China Yuan
C-Scenario	Cost Scenario
CT	Cryogenic Treatment
CTEG	Coal to Ethylene Glycol
DMO	Dimethyl Oxalate
DMOS	Dimethyl Oxalate Synthesis
EC-Scenario	Energy Consumption Scenario
EDTE	Ethanol Dehydration to Ethylene
EG	Ethylene Glycol
EGPSI	Ethylene Glycol Production Security Index
EGR	Ethylene Glycol Refining
EGS	Ethylene Glycol Synthesis
EO	Ethylene Oxide
EOAS	Ethylene Oxide Absorption and Stripping
EOR	Ethylene Oxide Refining
EOS	Ethylene Oxide Synthesis
E-Scenario	Environment Scenario
ETEG	Ethylene Oxide to Ethylene Glycol
EtOH	Ethanol
FTS	Fischer-Tropsch Synthesis
GHG	Green House Gas
GPS	Gas Purification and Separation
GWP	Global Warming Potential
HCS	H_2/CO Separation
LCA	Life Cycle Assessment
MeOH	Methanol
MTO	Methanol to Olefins
NE	Nutrient Enrichment
NG	Natural Gas
NTEG	Natural Gas to Ethylene Glycol
IPCC	Intergovernmental Panel on Climate Change
OTEG	Oil to Ethylene Glycol
PM_{10}	Particulate Matter 10
POCP	Photochemical Ozone Creation Potential
R-Scenario	Raw Material Scenario
SA	Soot and Ashes
SC	Steam Cracking
STM	Syngas to MeOH
T-Scenario	Technology Scenario
VOC	Volatile Organic Compounds
WGS	Water Gas Shift

presented a process dynamics-guided neural network model to improve model generalization, capable of maintaining higher performance in sparse and low-quality data. They evaluated the proposed model against a standard neural network on a regression and a classification task, representing a steady state and transient behavior of processing systems (Alauddin et al., 2023). Nevertheless, there are limited published works that have been systematically designed the security assessment of EG production routes, and there is no detailed analysis of technical security and reliability sources of raw materials for chemical production chain (Jinqiang et al., 2023).

Khan et al. conducted a risk assessment study of a typical petrochemical industry using the software package MAXCRED to provide a quantitative assessment of the accidents likely to be caused and the damage potential. They hoped that these studies would highlight the severity of risk posed by the industry and would thus generate safety consciousness among plant managers. The studies may also help in developing accident-prevention strategies and installation of damage control devices (Khan, Abbasi, 1998). They presented a risk assessment study of a typical chemical process industry and petrochemical industry using optimum risk analysis methodology (Khan et al., 2001; Khan and Abbasi, 2001). Khan et al. discussed how to develop an effective environmental management system through life cycle assessment (Khan. et al., 2002). Rusli et al. presented a methodology for producing and evaluating inherently safer design alternatives using a risk-based approach that was applied to nitration of toluene for preventing and minimizing runaway reaction (Rusli et al., 2013). Yang et al. presented a theoretical approach to solve multi-criteria conflict resolution problem under constrained and uncertain environments (Ming et al., 2013). Mamudu et al. presented a hybrid model to predict oil production and to provide a dynamic risk profile of the production system. They introduced predictive approach combines a multilayer perceptron, artificial neural network model with a hybrid connectionist strategy, which comprises a Bayesian network model and a dynamic Bayesian network model. This model offered a multipurpose tool for dynamic risk assessment and for proper reservoir production optimization (Mamudu et al., 2020). Pasam et al. considered the hazard identification and scenario definition in development of new technologies and processes (Pasman et al., 2023). It is a great practical significance to assess the security of EG production, especially in the situation of global unilateralism and frequent fluctuations of international raw material prices (Bacchetta et al., 2021). Advanced production technologies are predominantly controlled by a select few countries and companies. When break out an international trade dispute or a regional war, there would be a blockade of key technologies. Once raw materials and core technologies are restricted, the production chain would trap into a fatal blow or even paralyzed. Therefore, a secure and reliable chemical production chain is particularly important. If the supply of EG is restricted, which will impact on the polyester downstream industry, and affect the country's industrial layout and people's living standard and materials consumption demand (Nicola et al., 2023). We have thoroughly reviewed the literature on energy security and industrial chain security carefully, and found that five dimensions are suitable for analyzing the security of light olefins production. Concerning energy security, Ang. et al. (Ang et al., 2015a) proposed a framework with three dimensions (economic, energy supply chain and environmental) to evaluate Singapore's energy security. Later on, Yao. et al. (Yao and Chang, 2014) considered four factors (the availability of energy resources, applicability of technology, acceptability by society, and affordability of energy resources) to quantify China's energy supply security. In terms of industrial chain security, Yin (2019) believed that the industrial security should include the following three elements: external dependence, industrial control and international competitiveness, which specifically reflected the resource security, industrial chain security, core technology security, and equipment and product security. Zhang (Zhang, 2021) defined the industrial chain security from two dimensions, i.e., the conditions of open economy as well as the capacity of a country in controlling its industrial chain and guaranteeing the sustainable development of key industries. As can be found, the security can be related to different dimensions. Here, we defined the ethylene glycol production security from five dimensions. The availability of raw materials is one of the most critical security factors in the ethylene glycol production security. Meanwhile, the economics of ethylene glycol productions correspond to the feedstocks price fluctuations and impact the security. The energy consumptions can be regarded as the affordability of energy resources dimension of energy security in the ethylene glycol security productions. Technology localization is inherent attributes of technology security for a region or country. From the perspective of the integrity and liquidity of ethylene glycol production, these five dimensions can cover the most of, if not complete, the process of ethylene glycol production from raw materials to products. In addition, the data of ethylene glycol production can be relatively obtained from these five dimensions. Therefore, in this work, five dimensions (raw materials, economy, technology localization, environment, and energy consumption) are considered for ethylene glycol production security. We mainly discuss the methods for evaluating security from normal dimensions of industrial sectors. Implementation of an extra dimension would be straightforward following the methods proposed in this work. To make it more comprehensive, secondary sub-dimensions are set under the dimensions of raw materials, economy, environment, and energy consumption. For raw material sources, domestic supply and foreign import are the two key sub-dimensions. Similarly, the economy dimension also comprises two different sub-dimensions: cost and profitability. For the environment dimension, there are 5 sub-dimensions, which are global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), nutrient enrichment (NE), and soot and ashes (SA), respectively. The electricity and water consumption constitutes two sub-dimensions of the energy consumption.

The objective of this project is to conduct a security evaluation of EG production routes. The following new aspects are introduced in the work: 1) To develop a security assessment framework for the EG production pathway. 2) The evaluation involves considering and assessing the impact of five different dimensions on the production of EG. The five dimensions are the raw materials, technology, economy, environment, and energy consumption, respectively. The goals of this project are (a) To perform an analysis to identify the source of raw materials for EG production to identify a selected type of EG production technology and to conduct a technical analysis the availability of raw materials, (b) To carry out an analysis the EG production route and perform a technical analysis for each EG production, and (c) To develop an energy economic and environmental assessment for each EG production route, and (d) To develop an security assessments based on each EG production route and five different scenarios, and (e) To identify the sensitivity of each influence factor in EG production route. A case study is utilized to analyze the production of EG per ton from raw materials, showcasing the methodology and deriving valuable insights from the findings. The most significant difference of this work is that we use small sample data to establish a quantitative analysis of the security of ethylene glycol production routes, and the weight of five dimensions is flexible and adjustable, which can be applied to the security performance evaluation of energy, chemical engineering, agriculture and other fields.

2. Technical routes to ethylene glycol

The technical route to EG production starts with raw materials, which are coal, crude oil, natural gas, and biomass (Clauser et al., 2021; Gupta et al., 2021; Zhou et al., 2021). Intermediate products are syngas, methanol, naphtha, ethane, ethylene, EO and DMO. The main technologies used in the transformation of raw materials into EG include coal gasification (CG), steam cracking (SC), Fischer-Tropsch Synthesis (FTS), methanol to olefins (MTO), ethylene oxide refining (EOR), and ethylene oxide to ethylene glycol (ETEG).

CTEG-1 Route. According to research by Yang et al. (Qingchun et al., 2019b, 2019a; Xu et al., 2021; Jian et al., 2021 Qingchun et al., 2022), the production of 1 ton of EG requires 4.25 tons of coal, 51.2 GJ of fuel coal, and 4.20 GJ of electricity.

The CTEG-1 route consists of ten units: ASU unit, CG unit, syngas to methanol (STM) unit, MTO unit, ethylene oxide synthesis (EOS) unit, ethylene oxide absorption and stripping (EOAS) unit, Ethylene Oxide to Ethylene Glycol (ETEG) unit, Ethylene Oxide Refining (EOR) unit, carbon dioxide removal (CDR) unit, EG refining (EGR) unit, as shown in Fig. 1.

CTEG-2 Route. According to research by Yang et al. (Qingchun et al., 2019b, 2022; Xu et al., 2021; Wang et al., 2022; Jiahao et al., 2023), the production of 1 ton of EG requires 3.17 tons of coal, 47.3 GJ of fuel coal, and 3.16 GJ of electricity. The CTEG-2 route consists of seven units: ASU unit, CG unit, water gas shift (WGS) unit, gas purification and separation (GPS) unit, EG synthesis (EGS) unit, EGR unit, and dimethyl oxalate synthesis (DMOS) unit, as shown in Fig. 2.

OTEG Route. The OTEG process consists of three stages: naphtha production, naphtha to ethylene conversion, and ethylene to EG conversion. To produce 1 ton of EG, 13.8 GJ of ethylene is needed, which is equivalent to 2.31 tons of oil according to the value distribution method (Qingchun et al., 2019b, 2022; Xu et al., 2021; Jiahao et al., 2023). These three stages require a total of 3.06 GJ of fuel coal and 2.10 GJ of electricity to produce 1 ton of EG, as illustrated in Fig. 3.

NTEG Route. The NTEG process consists of three distinct stages: ethane manufacturing, ethane conversion to ethylene, and ethylene transformation into EG. Producing 1 ton of EG requires 13.8 GJ of ethylene, equivalent to 2.35 tons of natural gas needed for cryogenic treatment (CT) separation. These processes collectively use 5.89 GJ of fuel coal and 2.85 GJ of electricity, as illustrated in Fig. 4 (Jian et al., 2021; Qingchun et al., 2019b, 2022; Jiahao et al., 2023).

BTEG-1 Route. According to Wei et al. (Jian et al., 2021; Qingchun et al., 2022; Jiahao et al., 2023), the production of 1 ton of ethylene glycol requires 2.48 tons of biomass, 47.6 GJ of coal, and 3.8 GJ of electricity. Fig. 5 illustrates the process flow of BTEG-1.

BTEG-2 Route. The BTEG-2 process consists of four stages: syngas production, syngas to methanol (MeOH), methanol to olefins (MTO), and ethylene to ethylene glycol (EG). According to Yang et al. (Qingchun et al., 2022; Jiahao et al., 2023), the production of 1 ton of EG requires 3.12 tons of biomass, 52.6GJ of coal, and 4.06 GJ of electricity. Fig. 6 illustrates the schematic diagram of the BTEG-2 process.

BTEG-3 Route. The BTEG-3 process consists of three stages: ethanol production, ethanol dehydration to ethylene, and ethylene conversion to EG. To produce 1 ton of EG, 2.16 tons of biomass, 42.3 GJ of coal, and 3.25 GJ of electricity are consumed (Jiahao et al., 2023). Fig. 7 illustrates the schematic diagram of BTEG-3.

3. Methodology

The main EG production technologies in this paper are those that have achieved industrial production and completed industrial experiments. EG production technologies routes can be broadly divided into four categories based on the raw materials: CTEG, OTEG, NTEG, and BTEG.

Based on the life cycle assessment (LCA) method (ISO. 2006a; ISO. 2006b; Lelek et al., 2016), the process involves defining the scope and boundaries, conducting inventory analysis, assessing impacts, and interpreting results, as illustrated in Fig. 8. After defining the scope and boundaries, inventory analysis identifies the inputs and outputs of the production system at each stage. Next, environmental impacts on humans and the ecosystem are evaluated. Interpretation of results assesses the environmental burdens of the production system and supports its sustainable development. (Dantas et al., 2021). The multi-dimensional security evaluation model has been widely promoted and applied in energy and light olefins production routes. For example, a three-dimensional (economic, energy supply chain and environmental) security assessment model has been used to evaluate Singapore's energy security. The five-dimension security model is used to evaluate the security of light olefins production routes in China (Jinqiang et al., 2023).

This research aims to establish an evaluation framework of CTEG, OTEG, NTEG and BTEG routes from the security perspective. First, EG production industry chain security is defined. Security should include a reliable source of raw materials, monopoly-busting technology,

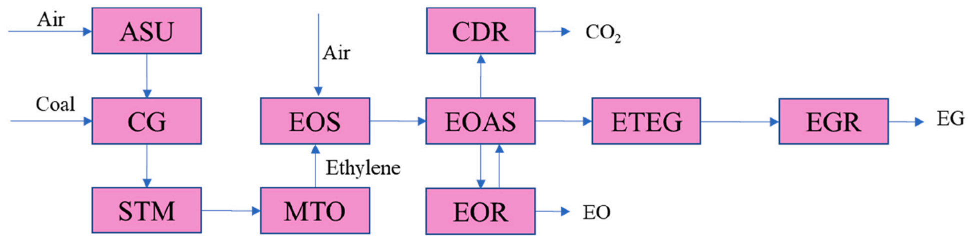


Fig. 1. Diagram of the CTEG-1 route.

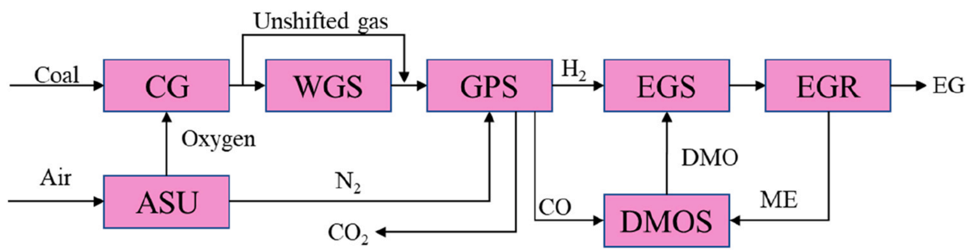


Fig. 2. Diagram of the CTEG-2 route.

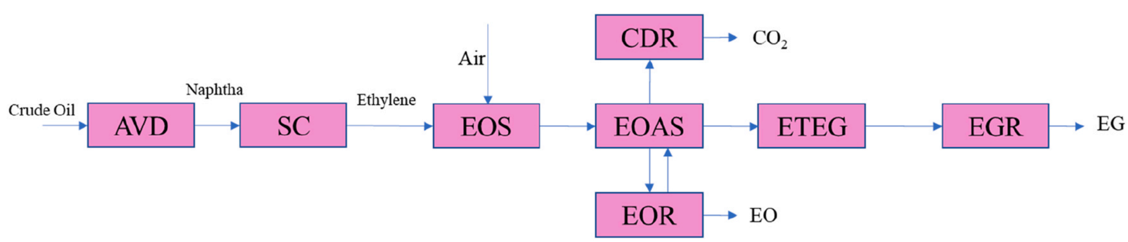


Fig. 3. Diagram of the OTEG route.

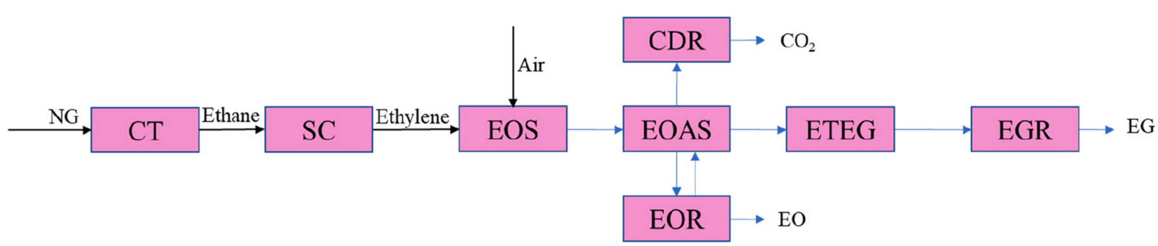


Fig. 4. Diagram of the NTEG route.

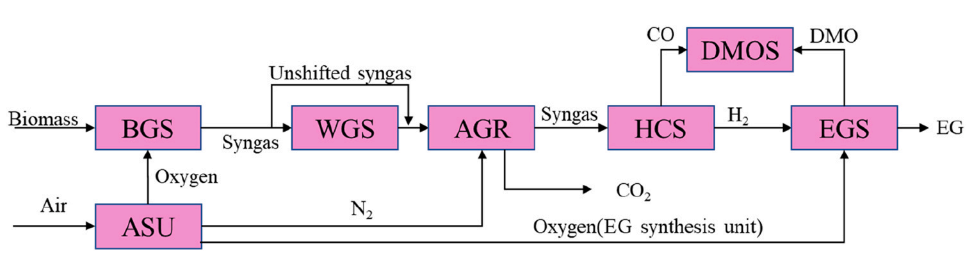


Fig. 5. Schematic diagram of the BTEG-1 route.

environmental friendliness of production process, competitive cost of production and low energy consumption. Therefore, the security performance of EG production chain is determined by five dimensions such as availability of raw materials, technology, economy, environment, and energy consumption. Second, this work covers various activities, including seven different routes of EG production of raw material and processing technologies. For comparison, we use 1 ton of EG product as a functional unit. Here, the main raw materials of the CTEG, OTEG, NTEG and BTEG routes are coal, oil, natural gas, and biomass, respectively. The key technology localization, energy consumption, pollutant emissions, and economic costs of these processes are taken into account. In this study, the material conversion process yields various products,

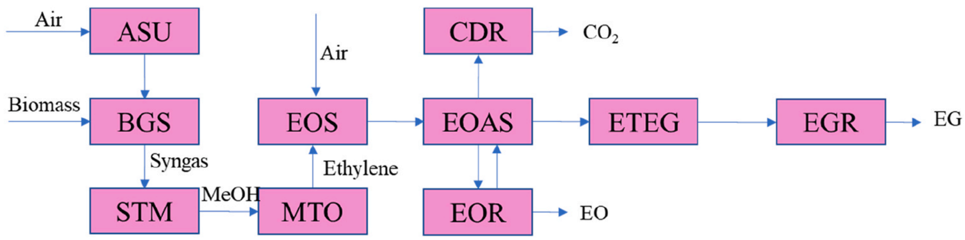


Fig. 6. Schematic diagram of the BTEG-2 route.

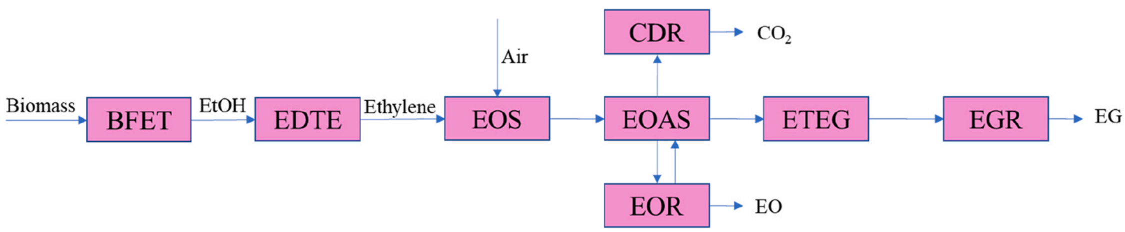


Fig. 7. Schematic diagram of the BTEG-3 route.

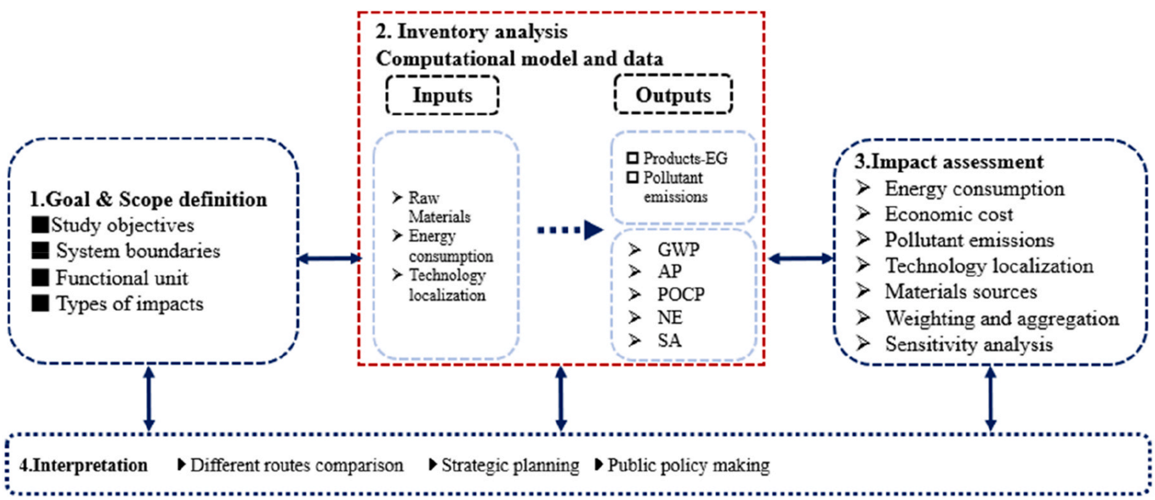


Fig. 8. Framework of the Security evaluation methodology.

which are allocated according to their market values. The main objective of this work is to quantify, analyze and evaluate the security of different ethylene glycol production route. Using the Ethylene Glycol Production Security Index (EGPSI), we can easily find insecurity factors in the production route of ethylene glycol. This is a very meaningful thing, on the one hand to remind companies engaged in ethylene glycol to avoid risks, on the other hand, we can improve the security performance by taking measures to eliminate the factors of instability and upgrade the security level of those uncertain factors. The generalized and flexible modeling framework presented can be further used by energy, policy, economic, and environmental analysts for assessing the savings potential of different technologies, making decisions in research and development investment, and strategic planning for meeting energy and emissions reduction goals. We expect this work can assist the assessment of ethylene glycol production routes in China from a completely new perspective.

3.1. Security indicators

The following steps are typically followed to create an EG production security index. First, a framework is proposed to define the scope and objectives, and to select appropriate indicators. These indicators are then normalized and weighted based on their importance before being combined into form a composite index. Data availability can influence the selection of indicators and normalization methods. The resulting composite index measures a country's EG production chain security.

3.1.1. Raw materials dimension

The EG production chain consists of two categories of raw materials: domestic and imported. The main raw materials for EG include coal, oil, natural gas, biomass, with domestic resources quantified by the reserve-production ratio. The security of imported raw materials is assessed using the Simpson index, originally used to measure biological diversity but now serves as a key parameter for assessing energy security at a national or regional level.

Supposed that the proportion of the raw material import quantity i to the total import is Pi, then the joint probability of two proportion randomly selected is Pi squared. To sum up the probabilities of all the raw material import and get Simpson's index A (Jinqiang et al., 2023; Stanković et al., 2022).

$$A = 1 - \sum_{i=1}^{S} P_i^2 \quad (2)$$

where, S represents the total number of random species. The Simpson diversity index ranges from 0 to 1–1/S. A value of 0 indicates that all individuals belong to the same species, while a value of 1–1/S suggests that each individual belongs to a different species.

The calculation for determining the availability of raw materials is as follows.

$$F_1 = D \times P \times \Psi + I \times A \times \gamma \quad (3)$$

where, F_1 represents the accessibility of raw materials, D represents the percentage of domestic supply in the overall demand for raw materials, P represents the ratio of storage to production, I represents the percentage of imported raw materials in the overall demand for raw materials, and A represents the Simpson index. Ψ and γ represent the weights assigned to raw materials sourced domestically and imported, respectively.

3.1.2. Technical dimension

The technical aspect comprises the five summarized technologies mentioned in chapter 2. The localization application of each technology is detailed in Table 1. Seven EG production routes are composed of different technologies, and the contribution of technology localization of EG production routes can be obtained from Formula (1).

$$T = x_1 \bullet x_2 \cdots x_i \cdots x_n \quad (1)$$

where x_i refers to each technology localization, T refers to value of the total localization of EG production path.

Technical localization is a qualitative measure that uses a categorical scaling method to quantify the level of nationalization of technology. The scale ranges from 0 to 1, with 1 indicating complete nationalization and a market share of 100 %. A score of 0.75 indicates that state-owned technology outperforms foreign technology in market share. A score of 0.5 denotes equal market share between state-owned and foreign technology. A score of 0.25 indicates that state-owned technology is in the early stages of industrialization. A score of 0 represents the worst-case scenario, where industrial production is monopolized by foreign technology.

3.1.3. Economic dimension

Economic performance is a vital consideration for decision makers within the company and plant. Low raw materials price and great products price determine the industry getting much more profitable (Moshood et al., 2022). From a security perspective, the better economic performance of a chemical production, the more secure the industrial chain. The economic indicators include the cost of acquiring raw materials and the consumption involved in the production process, the profit from distribution product after deducting the cost. That is, there are two main economic aspects of EG production route, one is cost and the other is revenue.

3.1.4. Environment dimension

The EG production process depletes natural resources and emits pollutants into the environment. This paper examines the emissions of air pollutants including CO_2, CH_4, N_2O, CO, NOx, SO_2, VOC, and PM_{10}. To evaluate the impact of various substances on environmental pollution, a new environmental impact contribution value can be derived by combining the impact factors of each pollutant using an equivalent model. This approach enables the assessment of the total environmental impact caused by each pollutant. In this study, five indicators are utilized to evaluate the environmental impacts of EG production: global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), nutrient enrichment (NE), and soot and ashes (SA), with the impact of SA measured in terms of PM_{10} emissions. Emission inventory data is used to derive the corresponding environmental impact assessment indicators. Based on previous research (Liu and Ma, 2009; Ou et al., 2010), the environmental impact factors for the materials are represented in Eqs. 4–8.

Carbon dioxide emissions are primarily generated through the combustion of fuels. Other sources of CO_2 emissions include the coal gasification process, the deacidification of natural gas, and the removal of carbon dioxide from syngas. Calculations for each option take the emissions generated from fuel combustion into account, the effects of electricity consumption, and the estimation of CO_2 equivalent units for output streams and gas preprocessing.

This study focuses on three types of greenhouse gases (GHGs): CO_2, methane (CH_4), and nitrous oxide (N_2O). The emissions of these GHGs are calculated using Eq. 4, as outlined by the Intergovernmental Panel on Climate Change (IPCC et al., 2006) and in the literature (Xunmin et al., 2009). The emissions of these three GHGs are then accumulated and converted into CO_2 equivalents based on their global warming potential over a 100-year time period, as determined by the IPCC in 2007 and the British government in 2011(IPCC. 2007; British Standards Institution, 2011).

$$GWP = CO_2 + 25 \times CH_4 + 298 \times N_2O \quad (4)$$

$$AP = 0.7 \times NO_x + SO_2 \quad (5)$$

$$POCP = 0.01 \times CH_4 + 0.03 \times CO + 0.6 \times VOC \quad (6)$$

$$NE = 1.35 \times NO_x \quad (7)$$

$$SA = PM_{10} \quad (8)$$

3.1.5. Energy consumption dimension

From the perspective of the chemical industry chain, EG production security can be assessed by considering energy consumption. This evaluation takes into account both the direct and indirect energy consumption during the production process (Manfredi Simone, 2012). Direct energy consumption refers to the use of electricity, gasoline, and diesel within the production system. Indirect energy consumption, on the other hand, depends on the calorific value and is associated with the energy production (Hamedani et al., 2019; Xiang et al., 2015). In this study, energy consumption primarily involves to the utilization of

Table 1
The contribution of EG production routes.

No.	Route	Feedstocks	Intermediate Product					Technology					Total
			1	2	3	4	5	x_1	x_2	x_3	x_4	x_5	T
1	OTEG	Crude oil	naphtha	ethylene	EO	EG		1.00	1.00	0.75	0.50		0.375
2	NTEG	NG	ethane	ethylene	EO	EG		1.00	1.00	0.75	0.50		0.375
3	CTEG−1	Coal	syngas	MeOH	ethylene	EO	EG	1.00	0.25	1.00	0.75	0.50	0.094
4	CTEG−2	Coal	syngas	DMO	EG			1.00	1.00	1.00			1.00
5	BTEG−1	Biomass	syngas	DMO	EG			1.00	1.00	1.00			1.00
6	BTEG−2	Biomass	syngas	MeOH	ethylene	EO	EG	1.00	0.25	1.00	0.75	0.50	0.094
7	BTEG−3	Biomass	EtOH	ethylene	EO	EG		1.00	1.00	0.75	0.50		0.375

electricity and fuel during EG production.

3.2. Ethylene Glycol Production Security Index (EGPSI)

When designing a security accounting framework for China's EG production chain, special consideration is given to the country's unique national circumstances. Drawing on previous energy security studies (Ang et al. 2015a; Ang et al., 2015b), the framework includes specific sub-indexes for each dimension of EG production security to ensure a comprehensive assessment. Emphasis is placed on technology localization and material sourcing in evaluating the security of EG production routes, enabling policymakers to identify areas requiring special attention. The proposed framework, outlined in Fig. 9, incorporates the EG Production Security Index (EGPSI) with five dimensions: raw materials, technology, economy, environment, and energy consumption. The economic dimension is further divided into cost and revenue phases, while the raw materials dimension considers both imports and domestic production. The technology dimension encompasses all technologies within the EG production chain. Each dimension is assigned a sub-index, with varying weightings allocated to raw materials, technology, economy, environment, and energy consumption. In this framework, the five dimensions are weighted as follows: 20 % for raw materials, 40 % for technology, 10 % for economy, 20 % for environment, and10 % for energy consumption. Additionally, the weight for raw materials is divided between imported and domestic sources, with 20 % for imported and 80 % for domestic. The higher weight assigned to the technology dimension is intended to highlight the significance of possessing and localizing technology. The framework prioritizes the technology dimension to highlight the significance of technology ownership and localization. By considering the specific characteristics of EG production routes, the framework is designed to meet China's need for secure and stable EG production, economic competitiveness, and environmental responsibilities.

The proposed framework offers key advantages. Firstly, the inclusion of sub-indexes prevents over-aggregation. This is important in the creation of EGPSI as combining too many factors together can result in a message that is overly broad for certain applications. Secondly, decomposing the EG chemical industrial production chain into technologies, it allows for the identification of the weakest links in the chain. Thirdly, by taking into account the economics of EG production, the competitiveness of industries can be assessed. The cost of EG has an impact on the chemical industry's costs and a country's export competitiveness. Lastly, China has established CO_2 emissions reduction goals. By incorporating EG-related environmental indicators, policymakers can monitor the environmental performance of the EG production system and develop policies to prevent environmental degradation in the EG production sector.

3.2.1. Normalization

To ensure comparability between data indicators, it is necessary to normalize the data and remove the dimensional influence. By standardizing the original data, all indicators are scaled to the same order of magnitude, enabling comprehensive comparison and evaluation (Huang et al., 2023).

$$x = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{9}$$

3.2.2. EGPSI

There are four different approaches to weight indicators: subjective weight, objective weight, combined weight, and correlation degree analysis. After testing these methods and considering factors such as data availability and practicality, subjective weight assignment was the most appropriate method for EGPSI. This method is commonly used in construction of EGPSI. The EGPSI is determined using a simple aggregation formula and is evaluated based on factors such as raw material availability, technology localization, economy, pollutant emissions, and energy consumption. The subjective weight allows for flexibility in adjusting the index based on user perception.

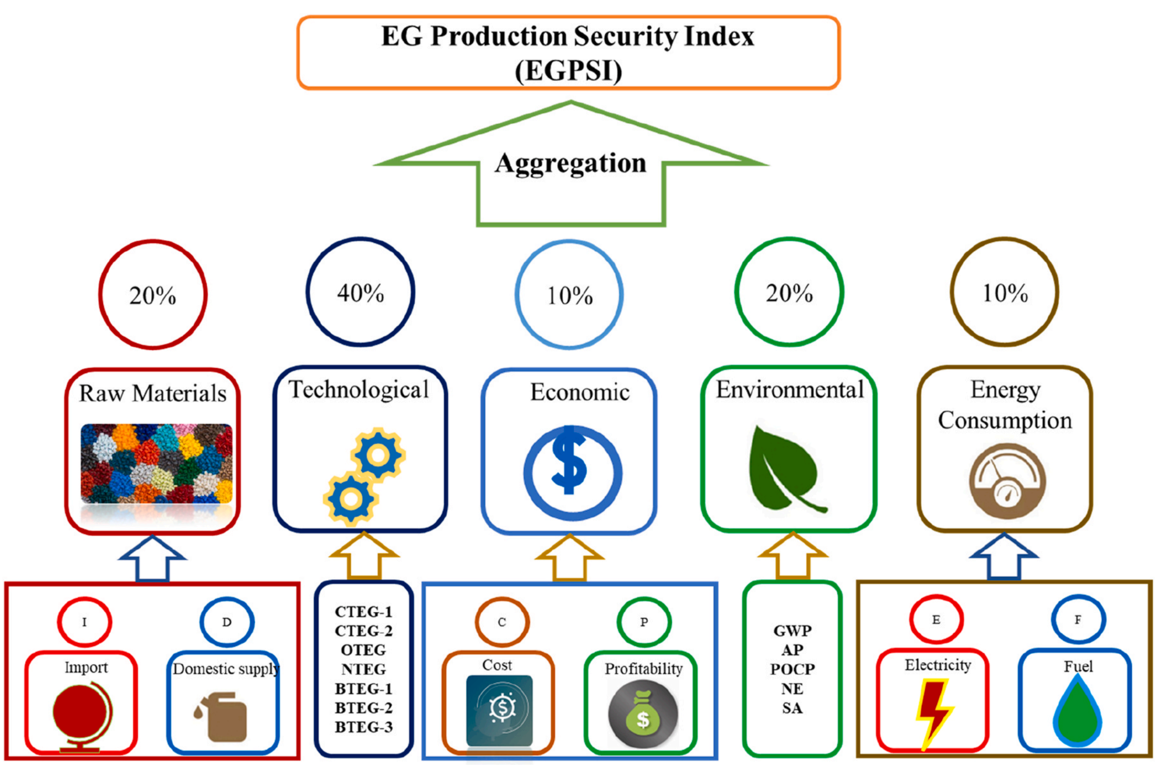


Fig. 9. Framework for constructing EGPSI.

$$EGPSI = \sum_{i=1}^{5} \omega_i f_i \tag{10}$$

where, EGPSI is the security index of EG production, ω_i represents the weight of each influencing factor, f_i represents the specific influencing factor with i ranging from 1 to 5.

4. Results and discussion

4.1. Contribution from different dimensions

Table 3 displays the assumed prices of coal, crude oil, natural gas, and biomass, which are 650, 3200, 2800, and 800 CNY/t, respectively (Anicic et al., 2014; Pa et al., 2013; Shi et al., 2020). Fig. 10 illustrates the production costs of EG. The external costs per unit of various emission substances are presented in Table 2, based on studies by Yang et al. (Jiahao et al., 2023; Qingchun et al., 2022).

4.1.1. Economic dimension

OTEG and NTEG processes have the highest production costs among the seven routes. The majority of the total production cost is attributed to the raw materials expenses, with crude oil accounting for 95.16 % and natural gas accounting for 92.88 %. This indicates that the production cost of OTEG and NTEG are heavily influenced by the prices of oil and natural gas. On the other hand, the CTEG process is relatively less affected by raw materials prices. In the case of the CTEG and BTEG routes, the next highest production cost ratio is for utilities. In the CTEG-1 route, utilities account for 40.7 % of the total cost, while in the BTEG-1 route, utilities account for 18.41 %. However, for the OTEG and NTEG processes, utilities only account for 4.84 % and 7.12 % respectively. Therefore, it is necessary to reduce production costs by reducing utilities for both the CTEG and BTEG routes.

4.1.2. Energy consumption dimension

Fig. 11 illustrates the energy consumption for the production of 1 ton of EG. The CTEG and BTEG routes are exhibit higher energy consumption than the OTEG and NTEG routes. This is primarily due to the gasification reaction stage, which requires more energy in the CTEG and BTEG processes. However, the OTEG and NTEG routes require relatively less energy. Additionally, the petroleum industry has a long-standing history and mature technologies, making it more advantageous in terms of energy saving and resource efficiency. Therefore, developing methods to utilize coal in a clean and efficient manner is an important direction for addressing current challenges.

4.1.3. Environmental dimension

Compared to BTEG, CTEG incurs significantly higher environmental costs. The environmental costs of CTEG-1, CTEG-2, and OTEG are 3.99, 3.63, and 3.06 times higher than those of BTEG-1, respectively. The elevated external costs of CTEG and OTEG are primarily attributed to their high CO_2 emissions. The external environmental costs of CTEG-1, CTEG-2, and OTEG routes due to CO_2 emissions are 7012, 6720, and 4650 kg/t-EG, respectively. In contrast, the carbon emissions of BTEG-1, BTEG-2, and BTEG-3 routes are −310, −293, and −289 kg/t-EG, respectively. These findings suggest that the BTEG route offers greater benefits in terms of CO_2 emissions. Substituting fossil energy with

Table 3
Prices of raw materials and products (CNY/ton).

Items	Price	Items	Price	Items	Price
Crude oil	3200	Naphtha	6000	Methanol	2100
Propane	4200	CO_2	300	Ethane	3600
Coal	650	EG	5000	Ethylene	8300
Natural gas	2800	Biomass	800	Electricity*	0.65

* Unit of Electricity is CNY/(kW•h).

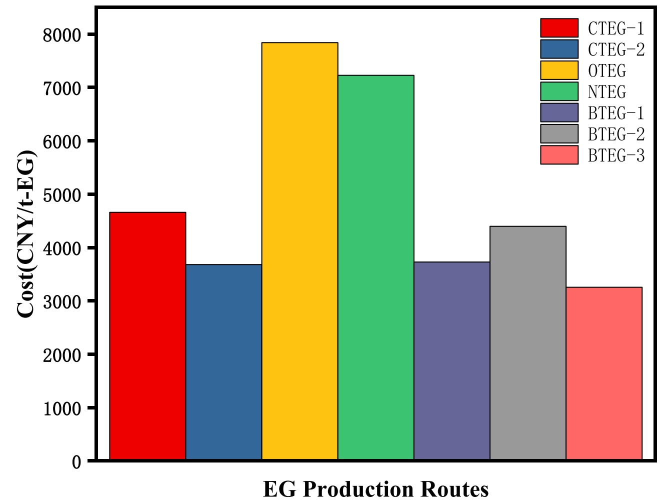


Fig. 10. Cost of EG production routes.

renewable resources can help mitigate issues related to resource depletion and environmental degradation.

The Global Warming Potential (GWP) is determined by the direct emissions of CO_2, CH_4, and other greenhouse gases, which constitute the majority of emissions in the EG production stage. Fig. 12 illustrates the environmental impact assessment of different routes for CTEG, OTEG, NTEG, and BTEG. In Fig. 12a, CTEG-1, CTEG-2, and OTEG routes have the highest GWP values, approximately 7669.23, 7332.29, and 4897.75 kg/t-EG, respectively. The production processes for NTEG and BTEG are similar, with the main difference being the gasification unit. Since coal is carbon-rich, the gasification process emits more CO_2 compared to biomass. Additionally, coal has a lower H_2/CO ratio than biomass, leading to more CO_2 production in the WGS reactor during the reaction of CO and steam. To reduce the GWP impact of EG production, it is necessary to recycle CO_2 in the CTEG route. From a carbon cycle perspective, the BTEG process absorbs a significant amount of CO_2 from the atmosphere during crop growth, making it a negative carbon emission process during biomass acquisition. This highlights the environmental advantages of the BTEG process. However, when considering factors such as AP, SA, POCP, and NE, the advantages of the BTEG process are dimmish. In Fig. 12b, the OTEG route generates a large amount of waste gas during the refinery stage, leading to higher levels of SO_2 and NOx emissions. This results in an AP value of 8.86 kg/t-EG, which is 4.95 and 4.10 kg/t-EG higher than CTEG-2 and BTEG-1 routes, respectively. The POCP of the OTEG route is 2.29 kg/t-EG, which is 3.74, 8.68, and 3.16 times higher than CTEG-2, NTEG, and BTEG-1 routes, respectively. The NTEG route has lower NA and SA contributions compared to CTEG, OTEG, and BTEG processes due to lower emissions of NOx and PM_{10}. The NG after pretreatment has a reduced nitride content.

4.2. EGPSI

Taking the reference case as an example, the weight assigned to the availability of raw materials, technology localization, economic cost, environment, and energy consumption is assumed to be 20 %, 40 %, 10 %, 20 %, and 10 % respectively. The results indicate that the BTEG-1 route exhibits a higher level of security performance compared to the CTEG-1 route. However, despite being a promising production route for EG, the CTEG-1 route face drawbacks such as high energy consumption and pollutant emissions, leading to significant environmental costs and unsustainable development. The discrepancy in security performance between the CTEG-1 and CTEG-2 routes can be attributed to the differences in technology routes (EO to EG and DMO to EG).

The numerical results for EGPSI and its sub-indexes are reported

Table 2
Unit External Cost of Different Air Emissions.

Emissions	CO_2	CH_4	N_2O	CO	NO_X	SO_2	PM_{10}	VOC
E(CNY/Kg)	0.22	1.66	31.05	4.69	36.08	27.67	81.69	24.7

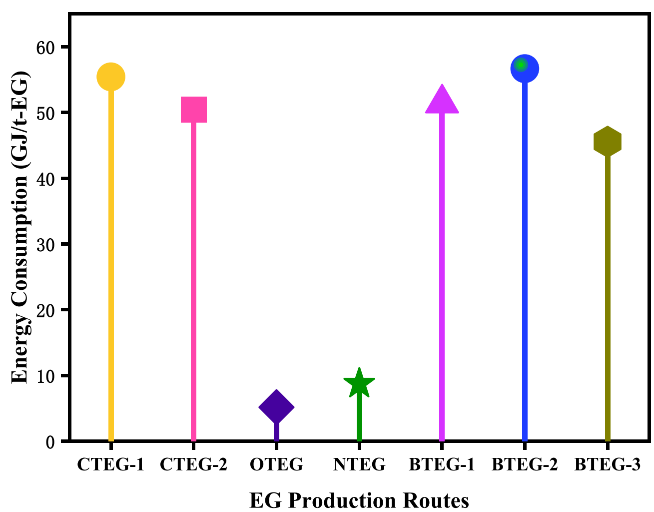


Fig. 11. Energy consumption of EG production routes.

using the rating scheme presented in Table 4 (Ang et al., 2015b). Table 5 and Fig. 13 display the results for the five dimensions based on a three-scale rating scheme, which offers a reasonable level of detail.

As shown in Table 5, CTEG and BTEG processes are superior in terms of the availability of raw materials. Based on the high external dependence of crude oil and nature gas in China, the value of availability of raw materials is lower in OTEG and NTEG than CTEG and BTEG processes. However, CTEG-2 and BTEG-1 routes have the advantage of technology localization than other routes. NTEG and BTEG routes should be adopted from environment sustainable development perspective. OTEG and NTEG routes have the advantage of high economic performance and low energy consumption compared with other routes. Therefore, OTEG and NTEG routes are suitable choices from the prospectives of economic cost and energy consumption.

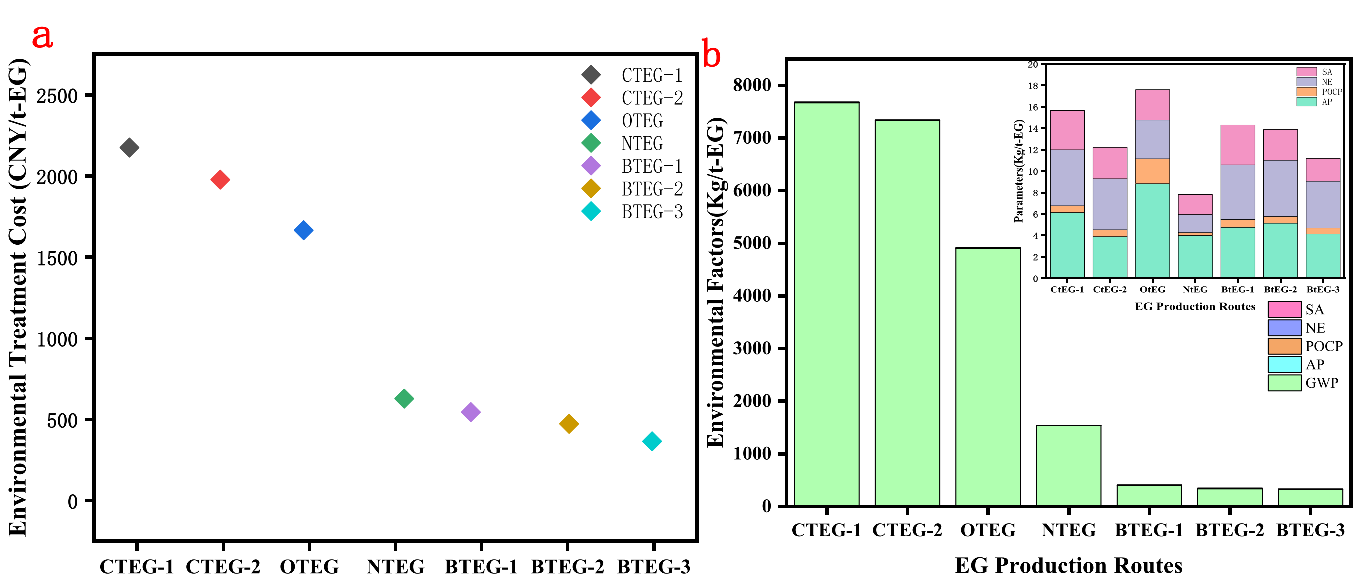
Five scenarios are designed in this work, they are raw material scenario (R-Scenario), technology scenario (T-Scenario), cost scenario (C-Scenario), environment scenario (E-Scenario), energy consumption scenario (EC-Scenario), as shown in Fig. 14. In order to investigate the security performance under different weights, the dimension is set 60 % and other dimensions is 10 %, respectively. In the R-Scenario, CTEG and BTEG processes have advantage of high security performance. However, CTEG-2 and BTEG-1 routes have advantage of high security performance in the T-Scenario. NTEG and BTEG routes should be adopted because the value of security index is higher than other routes in E-Scenario. In the C-Scenario and EC-Scenario, OTEG and NTEG routes stand out for their superior security performance, as well as their significantly better economic performance and lower energy consumption when compared to alternative routes.

4.3. Sensitivity analysis

The weight significantly effects on the value of security index. Fig. 15 a-g presents the relationship between weight and security index for EG production routes. Fig. 15a shows that a ± 20 % change in availability of raw materials, technology localization, economic cost, environment, and energy consumption results in a ± 63.88 %, ± 8.01 %, ± 0.00 %, ± 26.07 %, and ± 2.04 % change in EGPSI, respectively. For the CTEG-2 route, a ± 20 % change in availability of raw materials and technology localization leads to a ± 36.19 % and ± 48.26 % change in EGPSI. Fig. 15 illustrates that the EGPSI fluctuates by ± 5.26, ± 4.50, and

Table 4
Ratings for EGPSI range.

Rating	EGPSI Range	Sub-index Range
Poor	$x \leqq 0.5$	$x \leqq 0.5$
Fair	$0.5 < x \leqq 1.5$	$0.5 < x \leqq 0.8$
Excellent	$1.5 < x$	$0.8 < x \leqq 1.0$



(a) Environmental treatment cost in EG production routes (b) Five environmental factors in EG production routes

Fig. 12. Environment impact analysis of EG production routes.

Table 5
The security performance of five dimensions.

Dimensions	CTEG-1	CTEG-2	OTEG	NTEG	BTEG-1	BTEG-2	BTEG-3
Raw Materials	0.850	0.850	0.130	0.340	1.000	1.000	1.000
	Excellent	Excellent	Poor	Poor	Excellent	Excellent	Excellent
Technology localization	0.094	1.000	0.375	0.375	1.000	0.094	0.375
	Poor	Excellent	Poor	Poor	Excellent	Poor	Poor
Economic Cost	0.306	0.093	1.000	0.866	0.103	0.249	0.000
	Poor	Poor	Excellent	Excellent	Poor	Poor	Poor
Environment cost	0.000	0.109	0.282	0.855	0.901	0.941	1.000
	Poor	Poor	Poor	Excellent	Excellent	Excellent	Excellent
Energy Consumption	0.024	0.120	1.000	0.930	0.102	0.000	0.216
	Poor	Poor	Excellent	Excellent	Poor	Poor	Poor

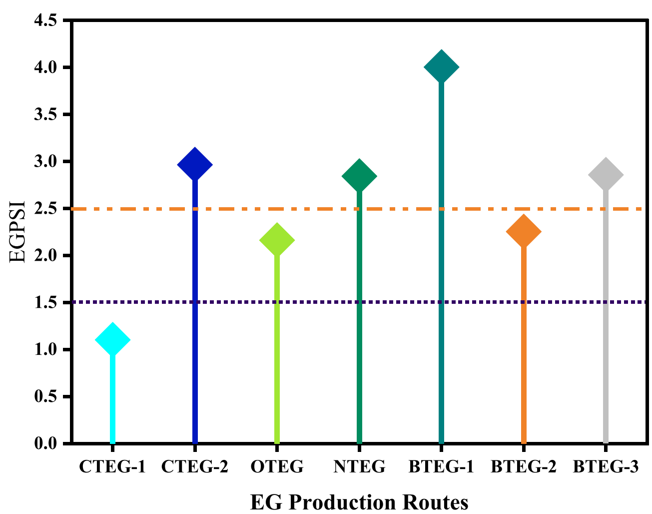


Fig. 13. The security performance of EG production routes.

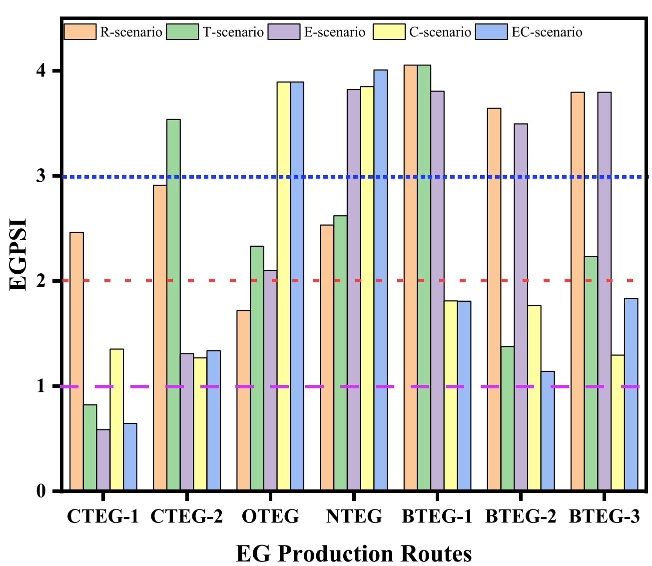


Fig. 14. Security performance of EG production route under different weights.

± 5.79 % when there is a ± 20 % change in the environment, economic cost, and energy consumption. This indicates that the EGPSI is more responsive to variations in the availability of raw materials, while changes in the environment and energy consumption have a lesser impact. Consequently, the CTEG route should prioritize enhancing the contribution of the environment and energy consumption. On the other hand, the OTEG route must focus on increasing the EGPSI by improving the security of raw material availability. However, it is indispensable to increase EGPSI by improving the embarrassment of high energy consumption and cost for the BTEG routes.

5. Conclusions and policy implication

The proposed security evaluation framework is based on seven industrial EG production routes. It comprehensively evaluates the security performance from five dimensions: the availability of raw materials, technology localization, economy, environment, and energy consumption. The findings of the study indicate that:

The OTEG and NTEG routes have a production cost of 7839.15 and 7225.42 CNY/t-EG, while the CTEG-2 and BTEG-1 routes have a significantly lower production cost of only 3681.49 and 3727.22 CNY/t-EG. This indicates that the CTEG and BTEG routes offer a substantial cost advantage. However, when considering pollution emissions and energy consumption, the CTEG and BTEG routes have a disadvantage as they require higher energy consumption compared to the OTEG and NTEG routes. It is an important breakthrough direction to develop a clean and efficient utilization technology for coal to solve the current difficulties.

On the of environmental cost, BTEG route is the same with the NTEG route. The BTEG and NTEG routes are less harmful to the environment compared to the CTEG-1 and OTEG route. The CTEG and BTEG routes have adequate raw materials and economic performance when compared to the OTEG route.

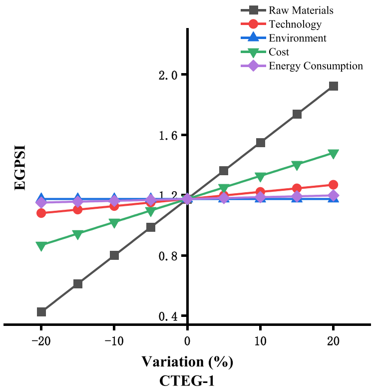
From the security perspective, CTEG and BTEG processes have advantage of high security performance in the R- scenario. However, CTEG-2 and BTEG-1 routes have advantage of high security performance in the T-Scenario. The value of security index is lower than other scenarios, NTEG and BTEG routes should be adopted according to E-Scenario. Compared to other routes, OTEG and NTEG routes offer superior security performance in both the C-Scenario and EC-Scenario. This is attributed to their significantly better economic performance and lower energy consumption.

In China, with the dual carbon target in place, there is a growing emphasis on the significance of low-carbon and climate-friendly practices. It is crucial to improve the efficiency of fossil energy utilization and increase the proportion of renewable energy in the primary energy sources.

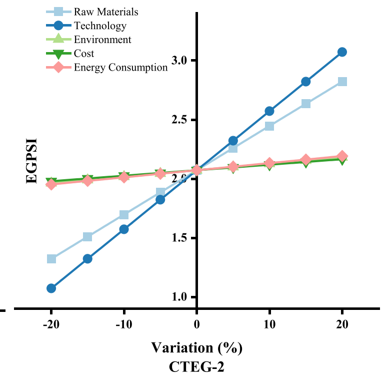
It is extremely important to develop a more efficient technology and upgrade conventional technologies to reduce pollutant emissions and high energy consumption. Currently, enhancing the security level of crude oil and natural gas availability is crucial for improving the security of OTEG and NTEG routes. One effective approach to achieve economic and carbon neutrality is by integrating raw material EG production technologies.

Ethical approval

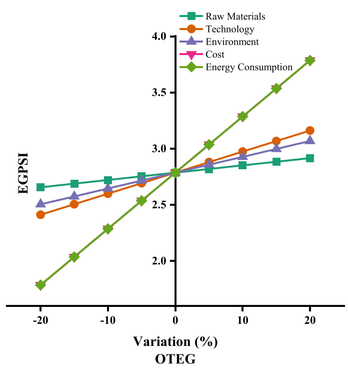
This is not applicable.



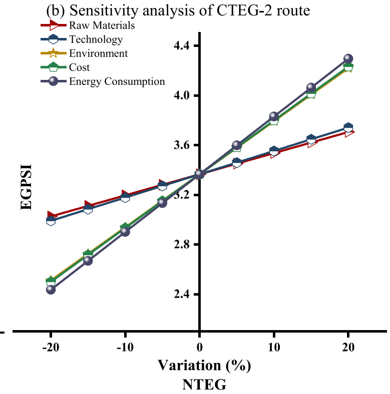
(a) Sensitivity analysis of CTEG-1 route



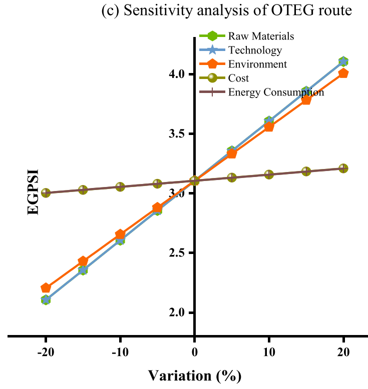
(b) Sensitivity analysis of CTEG-2 route



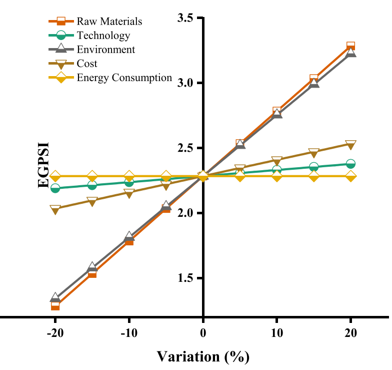
(c) Sensitivity analysis of OTEG route



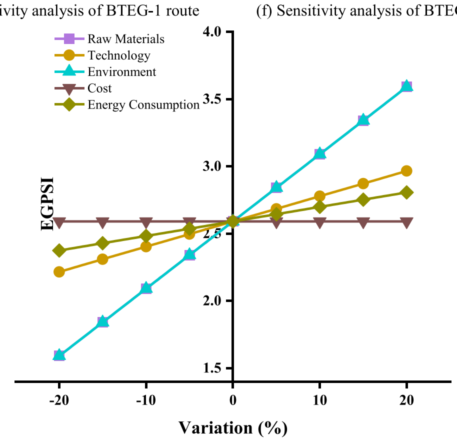
(d) Sensitivity analysis of NTEG route



(e) Sensitivity analysis of BTEG-1 route



(f) Sensitivity analysis of BTEG-2 route



(g) Sensitivity analysis of BTEG-3 route

Fig. 15. Sensitivity analysis of weights.

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.

Consent to Participate

This is not applicable.

Consent for Publication

This is not applicable.

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CRediT authorship contribution statement

Danzhu Liu: Formal analysis, Data curation. **jinqiang liang:** Writing – original draft, Software, Resources, Funding acquisition, Formal analysis, Data curation. **Xunming Su:** Project administration, Methodology, Conceptualization. **Yong Yi:** Resources, Project administration. **Xiaoling Xu:** Supervision, Software. **Mao Ye:** Writing – review & editing, Visualization, Validation, Supervision. **Shuliang Xu:** Writing – review & editing, Visualization, Validation.

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