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Comparison of light olefins production routes in China: Combining techno-economics and security analysis

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ABSTRACT

Light olefins including ethylene and propylene are important chemical materials, and a diversity of production technologies have been applied in industrial processes. An index called Olefins Production Security Index (OPSI) is proposed for quantifying the performance of techno-economics and security for different olefins production routes. The results show that Coal via Methanol to Olefins (CMTO) and Coal via Methanol to Propylene (CMTP) routes have the higher security rank in terms of raw materials supply and reasonably good economic performance compared with the Nature Gas via Fischer–Tropsch Synthesis to Olefins (NFTO) and Deep Catalytic Cracking (DCC) routes. Carbon Dioxide via Methanol to Olefins (CDMTO) and Carbon Dioxide via Methanol to Propylene (CDMTP) routes have lower carbon dioxide emissions but higher direct production costs. Basically, CMTO, CMTP, and Nature Gas via Methanol to Olefins (NMTO) routes have the top OPSI grades, which means they are more competitive than other routes in terms of security. We also identify the shortcomings of each olefins production route with regard to the security through sensitivity analysis. It is expected the proposed framework plays a role in searching the most suitable production route for light olefins from the viewpoint of security.

1. Introduction

Light olefins, especially ethylene and propylene, are important chemicals widely used in synthesizing fibers, plastics, rubbers and many other basic materials, and playing an irreplaceable role in our daily life. The light olefins industry has been considered as a cornerstone of a country's economy and social development (Xiang et al., 2014). Owing to the increasing global population together with rising living standards, the demand for light olefins and their derivatives are continuously increasing. For instance, in China the consumption of ethylene has grown from 14.97 million tons in 2010–33.66 million tons in 2020, which is projected to reach 86.4 million tons in 2030 (Li et al., 2022). Previous studies show that the production of light olefins in a country may have a direct relation with its Gross Domestic Product (GDP). The stable light olefins production is of great significance for maintaining healthily development of society and economics in the country.

Traditionally ethylene has been primary produced by steam crackers, and propylene has been mainly recovered as byproducts from the steam crackers as well as fluid catalytic crackers (Song and Guo, 2006). These traditional light olefins production routes rely heavily on the feedstocks available in the country. More than 80 % of the olefins in Europe and Asia

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Nomenclature

AR	Atmospheric Residue
ATR	Autothermal Reforming
AVD	Atmosphere-Vacuum Distillation
CC	Catalytic Cracking
CDMTO	Carbon Dioxide via Methanol to Olefins
CDMTP	Carbon Dioxide via Methanol to Propylene
CDTM	Carbon Dioxide to Methanol
CFTO	Coal via FTS to Olefins
CG	Coal Gasification
CMTO	Coal via Methanol to Olefins
CMTP	Coal via Methanol to Propylene
CPP	Catalytic Pyrolysis Process
CR	Combined Reforming
CRI	Carbon Cycle International
DCC	Deep Catalytic Cracking
ESC	Ethane Steam Cracking
FTO	Fischer–Tropsch synthesis to Olefins
FTS	Fischer–Tropsch Synthesis
GDP	Gross Domestic Product
GHG	Greenhouse Gas
MeOH	Methanol
MTO	Methanol to Olefins
MTP	Methanol to Propylene
NFTO	Nature Gas via FTS to Olefins
NG	Nature Gas
NMTO	Nature Gas via Methanol to Olefins
NMTP	Nature Gas via Methanol to Propylene
OPSI	Olefins Production Security Index
PDH	Propane Dehydrogenation
POX	Partial Oxidation
PSC	Petroleum Steam Cracking
RO	Residual Oil
SC	Steam Cracking
SMR	Steam Reforming
STM	Syngas to Methanol
VGO	Vacuum Gas Oil

Pacific is produced from naphtha distilled from crude oil (Babich and Moulijn, 2003; Ren et al., 2006). The geopolitical tensions as well as the fluctuations in oil markets, however, frequently lead to the unexpected risk of the supply of crude oil worldwide. Substituting the oil-based feedstocks for massive production of light olefins is constantly increasing in many countries. For instance, United States has shifted to use ethane, a shale gas feedstock, for ethylene production owing to the abundant shale gas reserve in the country. The natural gas availability in Middle East has turned the local countries to employ ethane as primary feedstock for steam crackers. In China, though 71% of the total ethylene production is produced from steam cracking of naphtha. Methanol to olefins (MTO), in which methanol is essentially produced from coal at industrial scale, has been rapidly developed in order to reduce China's import dependence of oil. Since it was first commercialized in 2010, MTO has been widely applied in China and accounts for more than 17 % of China's total light olefins production (Chen et al., 2016). Apparently, securing stable feedstocks is becoming common practice to ensure the stable light olefins production in many countries.

The diversity of feedstocks can partly mitigate the risk for light olefins production in a country, but it can also diversify the production routes as different production technologies might be required if different feedstocks are used. This may add risk of the blockade of key technologies used in the light olefins production, as the advanced production technologies are often in the hands of a few countries and enterprises. Any international dispute or conflict might cause a ban of technologies and the associated equipment, catalyst, and other core components purchased from other countries. In addition, the diversification of olefins production routes brings other risks such as high energy consumption, high carbon dioxide emissions, and low profitability. It is important to evaluate the light olefins production routes from the security perspective.

In the past, the light olefins production routes have been evaluated by various research groups (Chen et al., 2016; Zhang et al., 2017; Yuan et al., 2016; Xiang et al., 2015a,b; Man et al., 2014; Chen et al., 2018; Yang et al., 2014). These evaluations, however, mainly focus on the effects of energy consumption, economics, and environmental effects. Chen et al. analyzed the economic and environmental indicators for oil-, nature gas-, and coal-to-ethylene routes (Chen et al., 2016), and showed that the nature gas-to-ethylene is the most economical and environment friendly. Zhang et al. compared coal- and oil-based ethylene production routes in China from the economic and environmental perspectives (Zhang et al., 2017), suggesting that the coal-to-olefins project has slightly higher profit compared to the oil-based ethylene project when the crude oil price is above $70/bbl. If the carbon trading cost and wastewater surcharge are taken into account, the coal-to-olefins may loss its economic advantage. Thus, policy makers and investors should be prudent about the development of coal-to-olefins project in terms of environmental impact. Yao et al. assessed the ethylene production routes in United States based on the primary energy consumption and greenhouse gas emissions (Yao et al., 2016), and found that the primary energy consumption and greenhouse gas (GHG) emissions of the U.S. ethylene industry would dramatically increase given current practices and technologies. Xiang et al. (2015a). studied the techno-economic aspect of the ethylene production routes, and they found that coal-to-olefins has a significant cost advantage. However, it suffers from low energy efficiency and serious CO_2 emissions. Coal-to-olefins with CO_2 capture, coal and natural gas-to-olefins, and coal and coke-oven gas-to-olefins can ensure great reduction of CO_2 emissions and significant improving energy efficiency. They (Xiang et al., 2015b) later on analyzed the life cycle energy consumption and greenhouse gas emissions of olefin production routes when various raw materials are used as feedstocks, and showed that the energy consumption and GHG emissions of natural gas-to-olefins are roughly equivalent to those of oil-to-olefins, while coal-to-olefins suffers from higher energy consumption and serious GHG emissions. Man et al. also considered the energy efficiency and direct/indirect carbon dioxide emissions of the olefins production routes (Man et al., 2014), and found that the energy efficiency of the co-feed process increases about 10 %, while at the same time, life cycle carbon footprint is reduced by around 85 % with the co-feed process of coke-oven gas assist coal-to-olefins compared the conventional coal-to-olefins process. Chen et al. (2018). investigated three main ethylene production routes, i.e., steam cracking, coal to olefins, and methanol to olefins, from the perspective of energy-efficiency and CO_2 emission. They showed that the environmental effect of coal to olefins should be seriously considered in the process development, while steam cracking with imported ethane as feedstock, as well as methanol to olefins with imported methanol as feedstock, might benefit the energy consumption and CO_2 emission reduction. As can be seen, most of the evaluations on the production routes of light olefins have been conducted with the focus on the technological, economical, and environmental impacts. Few studies considered the security of the light olefins production routes, in spite that many researchers have already identified that minimizing the risks and thus ensuring stable production of light olefins for a country are critical for its economics and social development (Yang et al., 2014).

In fact, the quantitative assessment of a particular industrial production route from the perspective of security is still rare. Zhang (2021) proposed to evaluate the industrial chain security, which is defined as, under the conditions of open economy, the capacity of a country in controlling the key links of its industrial chain with international competitors and guaranteeing the survival and sustainable development of its key industries. Yang (2022) analyzed the security status of China's automobile industry by setting up an index system to quantify the security degree of Chinese automobile industry. Yin (2019) believed that the industrial security should consider the following elements: external dependence, industrial control and international competitiveness, which are specifically reflected in resource security, industrial chain security, core technology security, equipment and product security. Though there are seldom works concerning the quantification of the security of production chain, the security of energy supply chain has been carefully examined by many investigators (Zhao and Chen, 2014; Sun et al., 2014; Cao and Bluth, 2013). For example, the availability of energy resources, applicability of technology, acceptability by society, and affordability of energy resources were used to construct for quantifying how China's energy supply security in different historical period (Yao and Chang, 2014). Ang et al. (2015a). proposed a framework with a composite index and three sub-indexes for evaluating Singapore's energy security. Nevertheless, the security of light olefins production routes has been ignored, remaining a subject for further research.

This work aims at the development a framework for evaluating olefins production routes from the view of security. In doing so, the impacts of five dimensions, i.e., economy, technology localization, raw materials, energy consumption, and carbon dioxide emissions, are considered. In particular, an index called Olefins Production Security Index (OPSI) is proposed for comprehensively quantifying the security and techno-economic performance of different light olefins production routes. We expect this work can assist the assessment of light olefins production routes in China from a completely different perspective.

2. Light olefins production routes

A typical industrial production route is composed of three elements: the raw materials, technology roadmap and products. As shown in Fig. 1, it's an inescapable reality that there exists diversity of data sources and some measures have to be taken to ensure a fair comparison. Though there are far more light olefins production routes, thirteen routes, that have been industrialized and will be industrialized soon, were selected in this work. These technologies are basically mature and advanced, with data being industrial data or near-industrial data. In this work, comparisons are based on the either industrial or large-scale experimental data to ensure a fair comparison as soon as possible. The raw materials for olefins production are mainly coal, crude oil, natural gas and carbon dioxide. Some of these raw materials cannot be directly converted to light olefins. In such case, some intermediate products may be produced. These intermediates can be syngas, methanol, naphtha, residue oil, wax oil and light hydrocarbons such as ethane and propane.

2.1. Petroleum steam cracking (PSC)

In petroleum steam cracking (PSC) route, the crude oil is first transferred to naphtha, usually via vacuum distillation of crude oil, then undergoes steam cracking reaction to produce

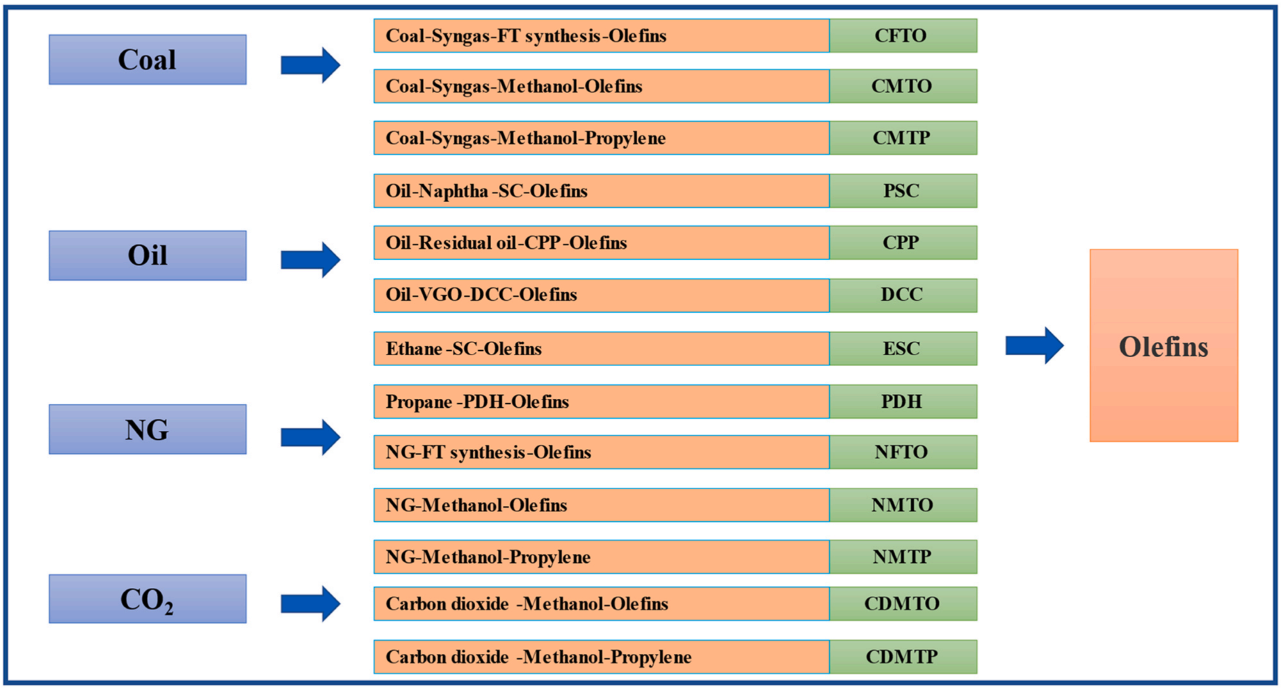

Fig. 1 – Typical light olefins production routes.

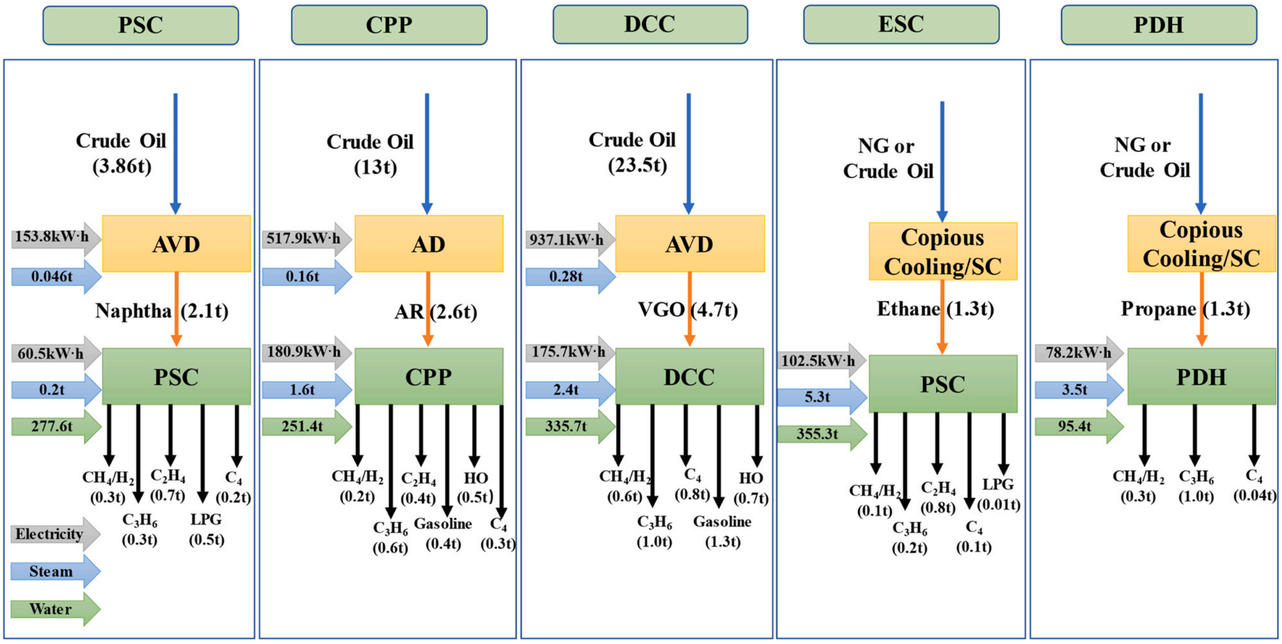

Fig. 2 – Schematic diagram of oil-based light olefins production routes.

small molecule chemicals such as ethylene and propylene at high temperature (750 ~ 900 ℃) in presence of water vapor (Alabdullah et al., 2021). The yields of ethylene, propylene and butadiene increase linearly with the increase of reaction temperature. Typically, it requires about 3.86 tons of crude oil as steam cracking feedstock to produce 0.7 tons of ethylene and 0.3 tons of propylene (Zhao et al., 2017), as shown in Fig. 2.

2.2. *Catalytic pyrolysis process (CPP)*

In the catalytic pyrolysis process (CPP) route, the crude oil is converted to atmospheric residue (AR) in refinery. AR is then used as raw material via catalytic cracking or pyrolysis to produce naphtha, cracking gas, and light oil at temperature of 580–640 ℃. Light olefins and other light components are recovered from the separation unit, and the small alkanes recycling into pipe cracking furnace can be further decomposed into light olefins. It needs about 2.6 tons of AR to produce 0.4 tons of ethylene and 0.6 tons of propylene (Zhu and Xie, 2013; Wang et al., 2013), as shown in Fig. 2.

2.3. *Deep catalytic cracking (DCC)*

Deep Catalytic Cracking (DCC) is a route in which the crude oil is first transferred to vacuum gas oil and residue oil in an atmosphere-vacuum distillation unit. Then the vacuum gas oil (VGO) mixed with 56 % residue oil is processed in a catalytic cracker operating at 530 ~560 ℃ and 0.08 ~ 0.15 MPa, with 4.7 tons of VGO required for the production of 1.0 ton of propylene (Pralhad Haribal et al., 2018; Pramod and Deepak, 1985), as shown in Fig. 2.

2.4. *Ethane steam cracking (ESC)*

Ethane is used as a feedstock for light olefins production by steam cracking, in which 1.3 tons of ethane is dehydrogenated at 750–850 ℃ and 0.15–0.35 MPa, producing 0.8 tons of ethylene and 0.2 tons of propylene (Al-Ghamdi et al., 2013; Albright et al., 1992; Bakare et al., 2015), as shown in Fig. 2.

2.5. *Propane dehydrogenation (PDH)*

Propane Dehydrogenation (PDH) route is to convert propane from natural gas or petroleum into propylene at 500–680 ℃ and 0.015–0.25 MPa (Zhou et al., 2016; Wang, 2015), with about 1.3 tons of propane to produce 1.0 ton of propylene (Yao et al., 2015) as shown in Fig. 2.

2.6. *Coal via syngas to olefins (CFTO)*

In this route, coal is first gasified to produce syngas, i.e., CO and H_2, through a gasifier operating at temperature of 1000–1500 ℃ with air or oxygen as the gasification medium (Wang, 2022). A number of coal gasification technologies have been industrialized (Yang et al., 2020; Chen et al., 2021a). Syngas can be converted to light olefins via Fischer–Tropsch synthesis (FTS). It needs about 10 tons of coal as feedstock to produce 0.4 tons of ethylene and 0.6 tons of propylene, as shown in Fig. 3.

2.7. *Coal via methanol to olefins (CMTO)*

In this route, like CFTO, coal is first converted to syngas. But syngas is further transformed to methanol rather than Fischer-Tropsch products, as methanol can be readily converted to ethylene and propylene via MTO (Wang, 2021). Synthesis of methanol from syngas has been widely applied in industries under reaction conditions of 220–270 ℃, 5.0Mpa, and $H_2/CO = 2.05–2.15$ (Su et al., 2021; Chen et al., 2021b) with the Cu based catalyst. MTO converts 2.9 tons of methanol to 0.5 tons of ethylene and 0.5 tons of propylene at about 450 ℃ and 0.22 MPa with SAPO-34 catalyst. The selectivity of light olefins is 85 %– 90 % when using the DMTO-II and DMTO-III technology by Dalian Institute of Chemical Physics (Wu and He, 2015; Ye et al., 2020; Ying et al., 2015).

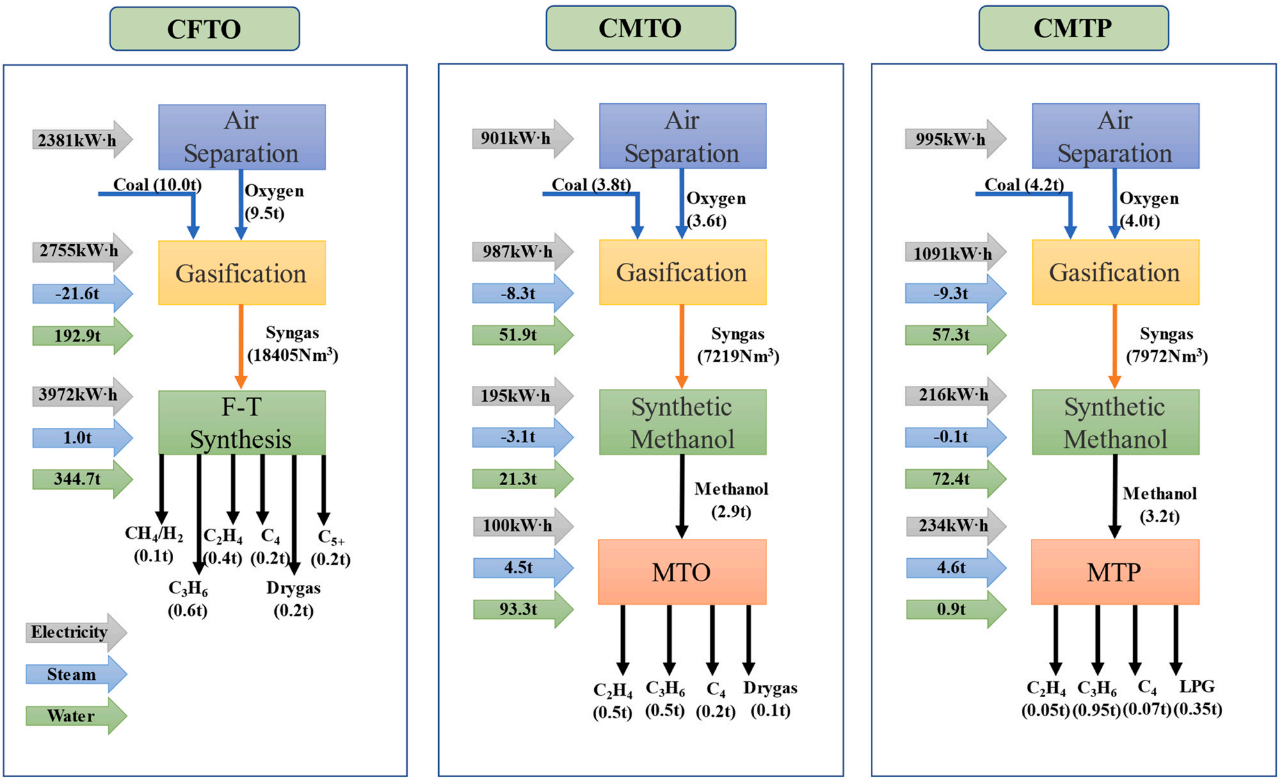

Fig. 3 – Schematic diagram of coal-based light olefins production routes.

2.8. *Coal via methanol to propylene (CMTP)*

In this route, coal is first converted to syngas, which is then converted to methanol. This is exactly the same as CMTO route. But in this route methanol will be transformed to propylene via MTP technology. Typically, MTP is operating at 400–500 ℃ and 0.15 MPa with a ZSM-5 zeolite type catalyst in fixed bed reactors. It requires about 3.2 tons of methanol to yield 0.05 tons of ethylene and 0.95 tons of propylene (Jasper and El-Halwagi, 2015; Amghizar et al., 2017; Zhong et al., 2019), as shown in Fig. 3.

2.9. *Nature gas via FTS to light olefins (NFTO)*

In this route, natural gas is reformed to syngas, and then syngas is converted to light olefins via FTS. The production of syngas from natural gas can be achieved through partial oxidation (POX), steam reforming (SMR), autothermal reforming (ATR) and combined reforming (CR) (Julián-Durán et al., 2014; Ehlinger et al., 2014). CR is to further optimize and integrate SMR and ATR process to achieve more energy saving, in which natural gas is first reformed with a small amount of steam to generate CO and H_2, and then the mixed gas and O_2 enter the ATR reformer for transformation. In the process, SMR reaction is mild, and H_2/CO can be generated to meet the needs of methanol synthesis. Therefore, syngas is prepared by CR process (Julián-Durán et al., 2014; Ehlinger et al., 2014), and 0.4 tons of ethylene and 0.6 tons of propylene are obtained from 8.6 tons of NG, as shown in Fig. 4.

2.10. *Nature gas via methanol to olefins (NMTO)*

In this route, natural gas is reformed to syngas under CR process and syngas is then converted to methanol, which is followed by MTO. It requires about 2.4 tons of NG to yield 0.5 tons of ethylene and 0.5 tons of propylene (Julián-Durán et al., 2014; Ehlinger et al., 2014), as shown in Fig. 4.

2.11. *Nature gas via methanol to propylene (NMTP)*

In this route, natural gas is reformed to syngas under CR process and syngas is then converted to methanol, which is followed by MTP. It needs about 1.9 tons of NG to yield 0.05 tons of ethylene and 0.95 tons of propylene (Julián-Durán et al., 2014; Ehlinger et al., 2014), as shown in Fig. 4.

2.12. *Carbon dioxide via methanol to propylene (CDMTO)*

In this route, CO_2 is first hydrogenated to produce methanol, and then methanol is converted to light olefins via MTO process. Iceland's Carbon Cycle International (CRI) has completed the 4000 t/a pilot plant experiments for CO_2 conversion to methanol with H_2 using geothermal energy as energy input (HALPER, 2011). Dalian Institute of Chemical Physics also completed the first 1000 t/a pilot plant experiments for converting CO_2 to methanol with green hydrogen obtained via solar energy (Wang et al., 2022), and 0.5 tons of ethylene and 0.5 tons of propylene are obtained from 4.3 tons of CO_2, as shown in Fig. 5.

2.13. *Carbon dioxide via methanol to propylene (CDMTP)*

In this route, CO_2 is first hydrogenated to produce methanol, and then methanol is converted to propylene via MTP process as discussed above. It needs 4.8 tons of CO_2 as feedstock to product of 0.05 tons of ethylene and 0.95 tons of propylene (HALPER, 2011; Wang et al., 2022), as shown in Fig. 5.

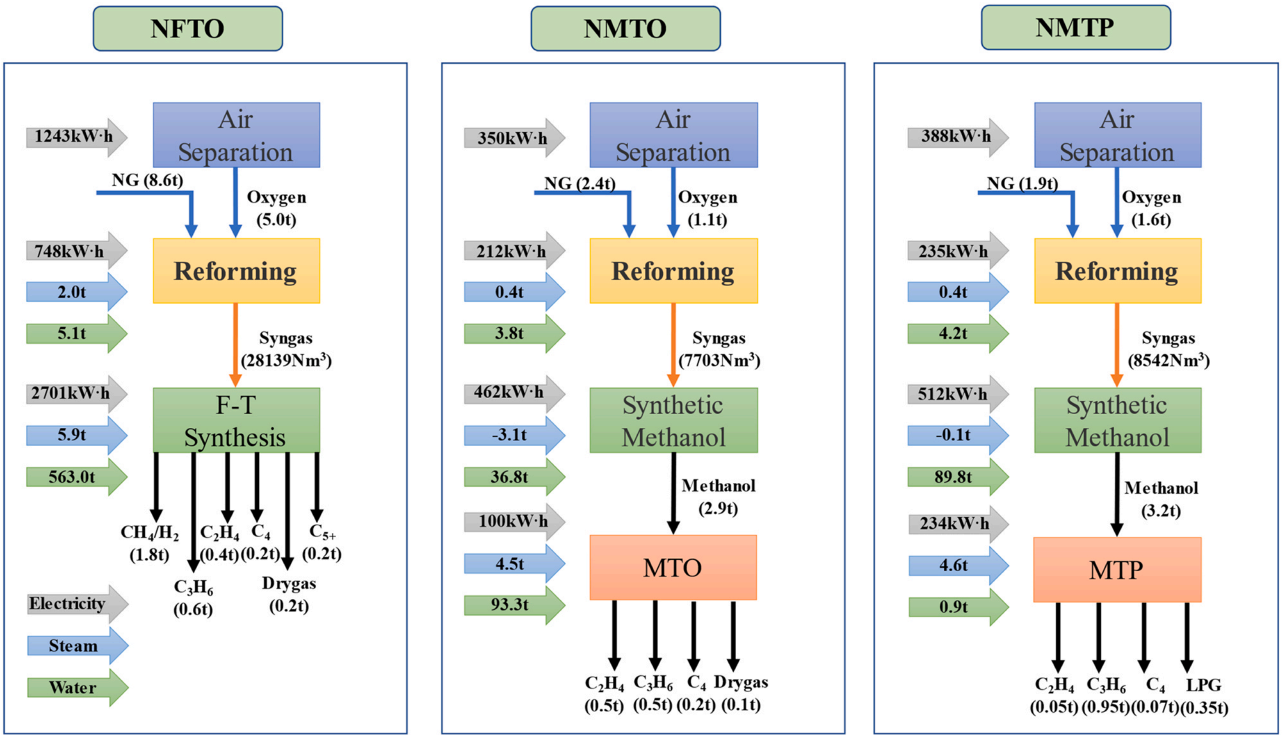

Fig. 4 – Schematic diagram of natural gas-based light olefins production routes.

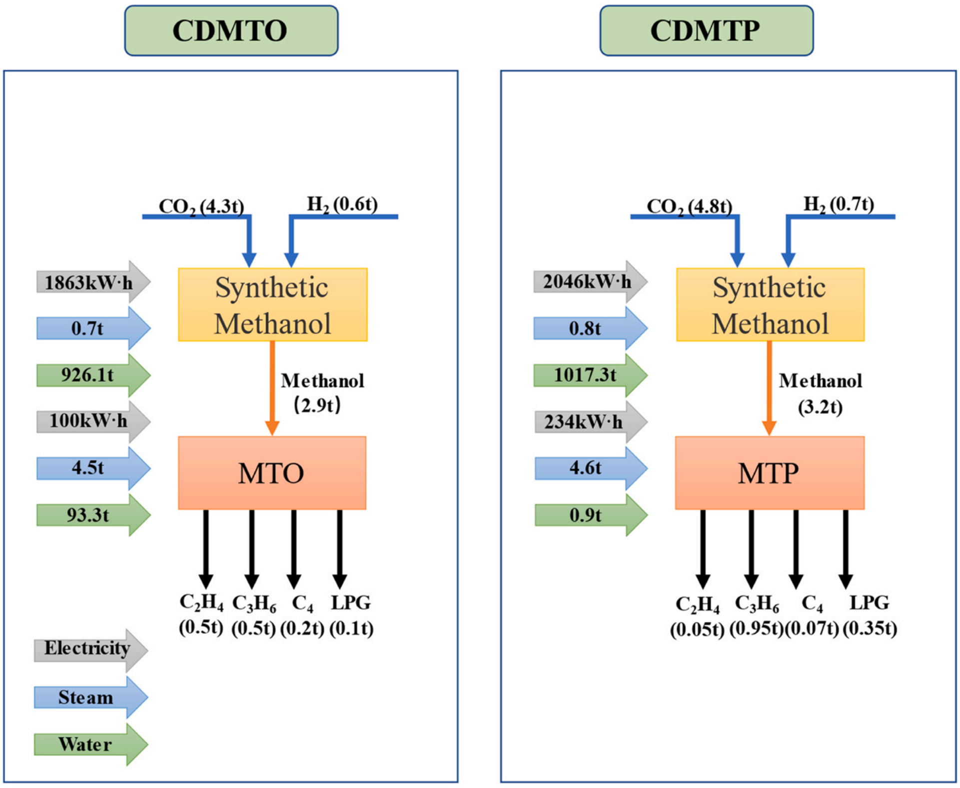

Fig. 5 – Schematic diagram of carbon dioxide to light olefins routes.

3. Methodology

The evaluation of a light olefins production route from the perspective of security should focus on the ample liquidity of all links of olefins production, such as the continuity of uninterrupted supply of raw materials, and the unremitting of market demand, distribution and digestion of light olefins. Thus, a composite index is constructed to consider the security of the olefins production route. A framework is proposed to address the scope, objective, and structures indicator selection. The selected indicators, which are weighted according to their perceived importance, are normalized and aggregated to form the composite index OPSI as shown in Fig. 6.

3.1. *Security indicators for five dimensions*

In traditional evaluation practices of olefins production routes, more attention has been paid to the unfailing of product profitability and satisfactory capital flow. The economics is surely important. As mentioned above, from the viewpoint of security, however, the continuous supply of raw materials and distribution of light olefins products from the market also play a critical role. In addition, carbon dioxide emissions and energy consumption are the key factors to meet the target of carbon neutrality. From the national level, it is particularly important to master proprietary technology with independent property rights.

We have gone through 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. (2015a). proposed a framework with three dimensions (economic, energy supply chain and environmental) to evaluate Singapore's energy security. Later on, 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. Concerning 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 (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 olefins production security from five dimensions. The availability of raw materials is one of the most important security factors in the olefins production security. Meanwhile, the economics of olefin productions correspond to the feedstocks price fluctuations and impact the security. The carbon dioxide emissions and energy consumptions can be regarded as the environmental and affordability of energy resources dimension of energy security in the olefin security productions. Technology localization is inherent attributes of technology security for a region or country. From the perspective of the integrity and liquidity of light olefins production, these five dimensions can cover the most of, if not complete, the process of olefin production from raw materials to products. In addition, the data of light olefins production can be relatively obtained from these five dimensions. Therefore, in this work, five dimensions (economy, technology localization, raw materials, energy consumption, and carbon dioxide emissions) are considered for light olefins 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 generic, secondary sub-dimensions are set under the dimensions of economy, raw materials and energy consumption. For raw material sources, domestic supply and foreign import are the two important sub-dimensions. Similarly, the economy dimension also comprises two different sub-dimensions: cost and profitability. The electricity and water consumption constitutes two sub-dimensions of the energy consumption.

A framework to account security of olefins production routes is designed, in which China is taken as the country of reference though this frame can be extended to production routes in any other industrial sectors in any other countries. Lots of research have been carried out for studying energy security (Ang et al., 2015b). Similarly, appropriate sub-indexes that weigh the contributions of different dimensions to the security of the olefins production route have been used to gauge the olefins production routes security across dimensions. The proposed framework is shown in Fig. 6, which is built upon five dimensions: economy, technology localization, raw materials, energy consumption, and carbon dioxide emissions. The OPSI is composed of five dimensions, and a secondary dimension is set under the dimensions of economy, raw materials and energy consumption. Domestic supply and foreign import are the two sub-dimensions of raw

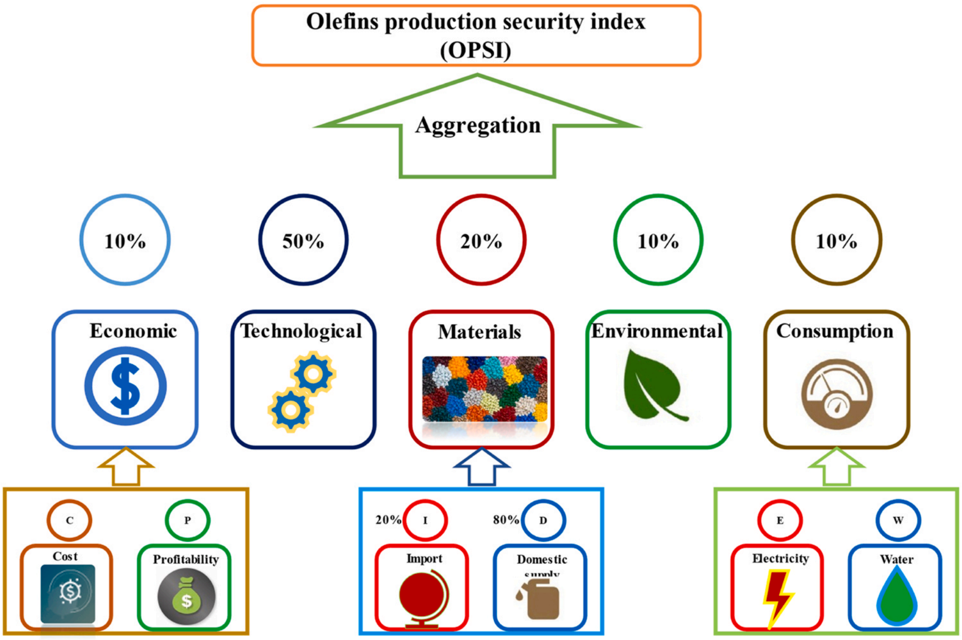

Fig. 6 – Construction of olefins production security index.

Table 1 – Prices of raw materials and products (CNY/ T).

Items	Price	Items	Price	Items	Price
Naphtha	6000	Atmospheric residuum	4000	Process water	15
Propane	4200	Wax oil	4000	Cooling water	3
Coal	500	Refinery gas	3800	Steam	200
Natural gas	2800	C_4 fraction	5000	Electricity[a]	0.65
H_2	10,000	Ethane	3600	CH_4/H_2	3600
CO_2	300	Ethylene	8300	Methanol	2100
Pygas	4500	Propylene	7900	Pyrolysis heavy oil	3000

[a] Unit of Electricity is CNY/(kW•h).

material sources, and their weights are assumed to be 80 % and 20 %, respectively. The economy dimension comprises two different phases: cost and profitability. The electricity and water consumption are the sub-dimensions of the energy consumption dimension. In the reference case, the weighting of the five dimensions is 10 %, 50 %, 20 %, 10 % and 10 % respectively, and those of the four sub-dimensions of the economy and energy consumption dimension are 50 %, 50 %, 50 % and 50 %, respectively. The larger overall weight given to the technology localization and raw materials dimensions is to emphasize the importance of having localized technical and uninterrupted raw materials supply. The framework implicitly considers the technology and raw materials trilemma, which is suitable for China as it has to secure its olefins production chain for uninterrupted olefins production and supply for downstream industry of olefins, maintain the economic competitiveness of its industries and also honor its environment obligations as a country.

Though materials sourcing often received much attention by the policymakers, the technology localization also needs special consideration. Therefore, the importance of materials sourcing and technology localization will be emphasized in the security assessment of olefins production routes. The raw materials sources dimension includes import and domestic production, while the technology dimension is jointly formed by all technologies used in the olefins production route. Meantime, the economic dimension which comprises of cost and revenue is also essential for security evaluation. Anyway, the framework implicitly considers the actual situation of olefins production pathways, in terms of stable and secure production of olefins, economic competitiveness in the markets, and environment obligations.

3.1.1. *Economic dimension*

The economic indicators include the cost formed by the price of raw materials, and the revenue per unit product after deducting the cost. Normally the cost for an industrial process also includes the operation expense, but it normally weakly relates to the security of the production route. Therefore, here we mainly consider two economic indicators, i.e., the cost and revenue, for security evaluation of olefins production routes. The prices of raw materials and products considered in this work are shown in Table 1 (Salkuyeh et al., 2016; Yang et al., 2018; Mahinder Ramdin et al., 2021; Zhao et al., 2021).

3.1.2. *Technology dimension*

The technology dimension is quantified by the technologies used in the 13 production routes as summarized in Section 2. The details of all technologies used in the 13 routes are shown in Table 2. Suppose that a light olefins production route is composed of different technologies T_{ij}, the overall score K_j of the j-th light olefins production route is illustrated in Eq. (1).

$$K_j = k_{1j} \cdot k_{2j} \cdots k_{ij} \tag{1}$$

where i is the different stages of olefins production, i = 1⋯3, j is the light olefins production routes, j = 1, ..., 13, k_{ij} is the score of the i-th stage and the j-th route corresponding technology T_{ij}.

The score of each technology is assessed based on the degree of the localization of this technology. Thus, the score of technology localization is considered as a quantitative indicator that is obtained using the categorical scaling method. The score is limited in the range of 0–1 as shown in

Table 2 – The score of technology localization for different light olefins production routes.

NO.	Routes	Feedstock	T_{1j}	Output-1	T_{2j}	Output-2	T_{3j}	Output-3	k_{1j}	k_{2j}	k_{3j}	K_j
1	PSC	Crude oil	AVD	Naphtha	SC	Olefins			1.00	1.00		1.00
2	CPP	RO	CC	Pyrolysis gas	Separation	Olefins			1.00	1.00		1.00
3	DCC	VGO	CC	Pyrolysis gas	Separation	Olefins			1.00	1.00		1.00
4	CFTO	Coal	CG	Syngas	FTO	Olefins			1.00	0.75		0.75
5	CMTO	Coal	CG	Syngas	STM	MeOH	MTO	Olefins	1.00	0.25	1.00	0.25
6	CMTP	Coal	CG	Syngas	STM	MeOH	MTP	Propene	1.00	0.25	0.50	0.125
7	NFTO	NG	Reforming	Syngas	FTO	Olefins			1.00	0.75		0.75
8	NMTO	NG	Reforming	Syngas	STM	MeOH	MTO	Olefins	1.00	1.00	1.00	1.00
9	NMTP	NG	Reforming	Syngas	STM	MeOH	MTP	Propene	1.00	0.25	0.50	0.125
10	ESC	Ethane	SC	Olefins					1.00			1.00
11	PDH	Propane	PDH	Propene					0.00			0.00
12	CDMTO	CO_2	CDTM	MeOH	MTO	Olefins			0.25	1.00		0.25
13	CDMTP	CO_2	CDTM	MeOH	MTP	Propene			0.25	0.50		0.125

Table 3 – Numerical results of technology localization.

Technology	Score	Technology	Score
AVD	1.00	Separation	1.00
CC	1.00	FTO	0.75
CG	1.00	STM	0.25
Reforming	1.00	MTO	1.00
SC	1.00	MTP	0.50
PDH	0.00	CDTM	0.25

Table 3 (Yao and Chang, 2014; Ye et al., 2020; Amghizar et al., 2017; Sergei et al., 2022). Specifically, the score of 1 represents the best case, i.e., the technology has been completely localized with fully intellectual property rights, 0.75 represents the technology has been largely localized and the share of the similar foreign technology in the market is smaller than the local technology, 0.5 denotes that the share of local technology is (nearly) equal to that of foreign technology, 0.25 indicates that the local technology is just beginning to industrialized and the share in the market is still much smaller, and 0 represents the worst case, i.e., no local technology in the market and the share of foreign technology is 100% in the market.

3.1.3. *Raw materials dimension*

All the raw materials required for olefins production can be divided into two parts: domestic supply and import. The reserve-production ratio and Simpson index are used to quantify the security of the domestic supply and import of raw materials, respectively. Simpson index, which was originally used to describe the diversity of biological community, has been introduced to measure the energy security of a country or region. Here we use it to quantify the availability of raw materials. Summing up the probabilities of all the raw materials imported leads to the Simpson index A as presented in Eq. (2).

$$A = 1 - \sum_{n=1}^{S} P_n^{2} \tag{2}$$

where P_n is import share accounts of the total import volume, S is the number of import source of countries or regions. Take imported crude oil for example, the risk is the greatest if China only imports crude oil from a single country and the Simpson index A is 0. When the share of imported oil is spread among many different countries and regions, it can reduce the risk of imported oil. The higher the Simpson index A, the lower the risk.

The availability of raw materials can be calculated as shown in Eq. (3).

$$F_m = D \times R \times \Psi + I \times A \times \gamma \tag{3}$$

where F_m refers to the availability of the m type raw materials, D is the proportion of domestic supply in the total demand of raw materials, R is the ratio of storage and production, I is the proportion of imported raw materials in the total demand of raw materials, and A is Simpson index. Ψ and γ are the weights of raw materials source from domestic and imported respectively.

3.1.4. *Energy consumption dimension*

Energy consumption is proposed to evaluate the security of the light olefins production routes from the industry chain perspective. Energy consumption is an important index of energy utilization efficiency in the light olefins production routes. The energy efficiency indicators are specified in national industry standards. Manufacturers will face the risk of being shut down whose energy efficiency index value is below the minimum standard specification. In this regard, energy consumption is an important security index of the chemical production chain. In this paper, energy consumption mainly refers to the consumption of electricity, fuel, steam and water in the light olefins production routes.

3.1.5. *Environment dimension*

The environmental index is carbon dioxide emissions in light olefins production. Carbon dioxide emissions are an environmental constraint for environmental law enforcement and decision making. In order to ensure the normal operation of chemical enterprises and liquidity of the light olefins production routes, carbon dioxide emissions should be within legal limits. Exceeding the legal limits may cause the shut-down of the enterprises. Under such conditions, the carbon dioxide emissions is an important security index in the light olefins production routes.

It is true that the environmental dimension normally includes not only CO_2 emissions but also CH_4, N_2O, CO, NO_x, SO_2, and PM_{10} emissions. Zhao et al (Zhao et al., 2017). compared the emissions of greenhouse gases in four propylene production pathways based upon life cycle assessment. The results showed that the dominant contribution is CO_2 and CH_4 only contributes to 5–13% in GHG emissions. Xu et al. (2021). also evaluated the pollutant emissions of coal/oil/biomass to ethylene glycol through life cycle assessment, in which they examined the main environmental impact of these ethylene glycol production methods. They found that the high environmental treatment costs of coal to ethylene glycol and oil to ethylene glycol are mainly due to the high emissions of CO_2 and PM_{10}, accounting for 72.2% and 13.8% of the total environmental treatment costs, respectively. Therefore, CO_2 emission is the dominant factor compared with the other pollutants emissions from the perspective of either quantity or treatment cost in conventional chemical production processes. In this work, however, we mainly considered CO_2 emission as a dimension with regard to security because the quantity of other pollutant emissions (except CO_2 emission) normally only accounts for less than one fifth of the total pollutant emissions. Although the other pollutant emissions are important, they might not pose a dominant effect on the security. Furthermore, the availability of data for other pollutant emissions is also a challenge. Therefore, in this work, only carbon dioxide emission is considered in the environmental dimension.

Life cycle assessment methods are used to evaluate CO_2 emissions from after obtained raw materials to produce qualified olefin products in light olefins production routes. It is taken in considered that CO_2 emissions in each unit operation throughout the olefin production process.

3.2. *Olefins production security index (OPSI)*

3.2.1. *Normalization and baseline identify*

In order to eliminate the dimensional influence between indicators, data normalization is needed to solve the comparability between data indicators as shown in Eq. (4). After the original data is standardized, all indicators are in the same order of magnitude, which is suitable for comprehensive comparison and evaluation. Baseline identification, however,

Table 4 – Ratings for OPSI range.

Rating	Range
Poor	$OPSI \leqq 0.5$
Fair	$0.5 < OPSI \leqq 2.0$
Good	$2.0 < OPSI \leqq 2.5$
Excellent	$2.5 < OPSI$

is also important before normalization of raw data. As to energy consumption and carbon dioxide emissions constraints, the values of the corresponding indicators that are below the national and industry standards will not participate in data normalization, which instead are given a maximum negative value of – 10.

$$x = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{4}$$

3.2.2. *OPSI*

There are four methods to weight indicators, which are subjective weight, objective weight, combined weight, and correlation degree analysis. After testing some of these methods, and considering various constraints such as availability and practicability of data, subjective weight assignment is the most suitable method for OPSI. Here the aggregation method is used to construct OPSI as shown in Eq. (5).

$$OPSI = \sum_{k=1}^{5} \omega_k Q_k \tag{5}$$

where ω_k is the weight of influencing factors, and Q_k is the influencing factor. As can be seen, OPSI is evaluated by the availability of raw materials, localization of technology, economy, energy consumption and carbon dioxide emissions. The subjective weight retains the flexibility so it can be recalibrated based on perception of the users.

The rating range for OPSI was determined following the practices reported in the relevant literatures. Wang and Zhou (2017) divided the countries into five grades according to energy security index: Poor, Weak, Limited, Good, and Excellent. In addition, Ang et al. (2015a). classified eight-scale rating scheme based on the numerical results for Singapore energy security index. Feng et al. (2022). took the pollution grade of metal elements as the research target, and divided the pollution grade into five grades according to the values of enrichment factors. The index of discrimination was selected as the criteria for OPSI grade classification as shown in Table 4, in which the classification of security grades of olefins production routes is divided into four grades.

The proposed framework has several advantages. First, the inclusion of sub-indexes avoids over-aggregation. In the definition of OPSI many different influencing factors are combined together, and with the sub-indexes the quantification becomes possible. Second, by separating the olefins industrial production routes into different technological processes, the risk of the technologies in the production chain can be revealed. Third, by considering the economics of light olefins production, the security of market competitiveness of the industries is considered. Excellent profitability and smooth cash flow are important guarantees to maintain the chemical industry chain security and continuous operation of olefins production. Finally, China has set CO_2 emissions reduction targets and the baseline of CO_2 emissions is explicitly stated in laws and regulations. By identifying the baseline can assist to judge whether the enterprises are facing closure according to the environmental regulations. Production enterprises can receive early warning in advance and take improvement measures to ensure security production. By including olefins-related environmental indicators, the environmental dimension allows policy makers to track the environmental performance of the olefins production system and formulate policies to arrest deterioration in environmental sustainability of the olefins production system.

4. Results and discussion

4.1. *Contribution from different dimensions*

In evaluating light olefins production routes from the security perspective, the availability of raw materials, technology localization, and economy possess positive contributions, while energy consumption and carbon dioxide emissions attribute negatively as shown in Fig. 7. Fig. 7 describes the normalized scores of five dimensions in light olefins production routes. For CDMTP route, the carbon dioxide emissions are essentially negative as CO_2 is used as raw materials in these routes, in which the implicit CO_2 emissions due to energy consumption (heat or electricity) is far less than the CO_2 feedstock input into the CDMTP process. This is critical in achieving carbon neutrality. Therefore, the score of CO_2 emissions in the CDMTP route is zero after normalization, while the scores of CO_2 emissions of other routes are negative, as shown in Fig. 7.

4.1.1. *Raw Materials availability*

China is shortage of oil and natural gas. In 2021, China imported 513 million tons of crude oil and 161.6 billion cubic meters of natural gas, with the oil and natural gas import dependence exceeding 72 % and 44 %, respectively. There are 48 countries and regions that export crude oil to China. The major countries and regions are Saudi Arabia, Russia, Iraq, Oman, Angola, United Arab Emirates, Brazil, Kuwait and Malaysia. The different sources of crude oil imports can reduce the risk of crude oil imports to some extent. However, there are many risks associated with importing crude oil, such as transportation security, geopolitics, and price fluctuations in international crude oil markets. Therefore, the weight of imported crude oil is given 20 %. A similar weight is given to the imported natural gas. In terms of raw materials availability, the contributions of coal, oil and natural gas can be quantitatively calculated according to Eq. (3), i.e., they are 0.75, 0.13 and 0.34, respectively. As carbon dioxide can be readily obtained, and the contribution of carbon dioxide availability is offered as 0.98. In the propane dehydrogenation route, propane is almost entirely imported. Therefore, the contribution of propane in the raw materials available is 0.01. Therefore, according to the availability of raw materials, the security of light olefins production routes used raw materials of carbon dioxide and coal is better than that used crude oil and nature gas in China. But massive collection of carbon dioxide is quite expensive at this moment, which however would be expected to be reduced in the future.

4.1.2. *Energy consumption*

The energy consumption in the production of one ton of light olefins are shown in Fig. 8. The energy consumption of NFTO

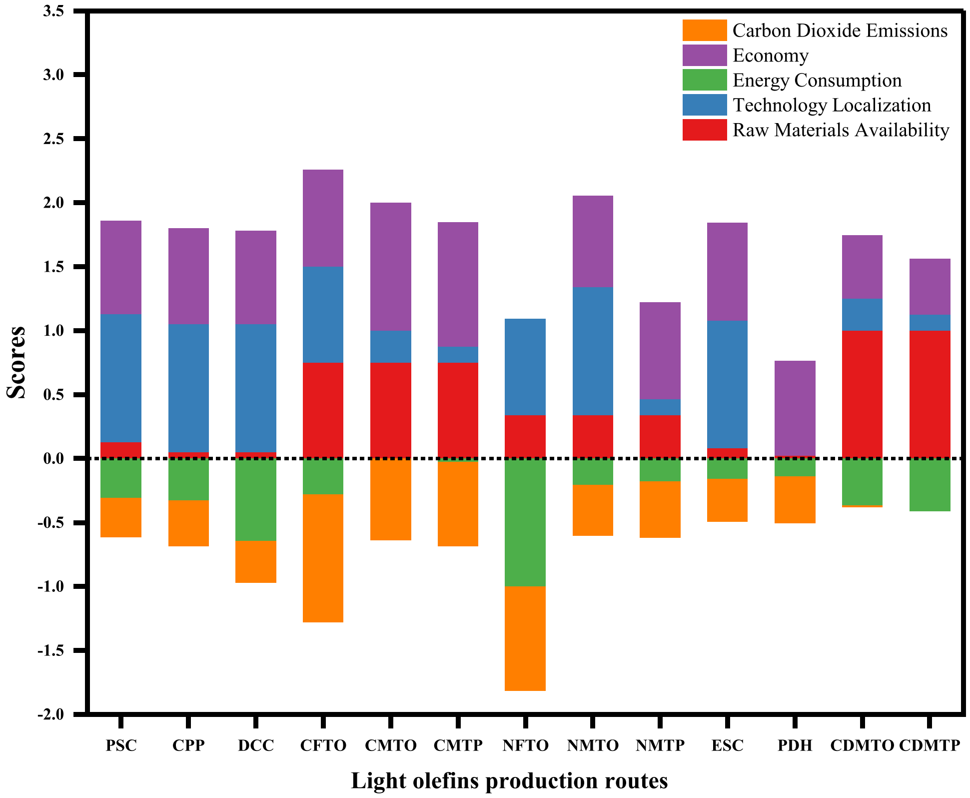

Fig. 7 – The contributions of five dimensions in light olefins production routes.

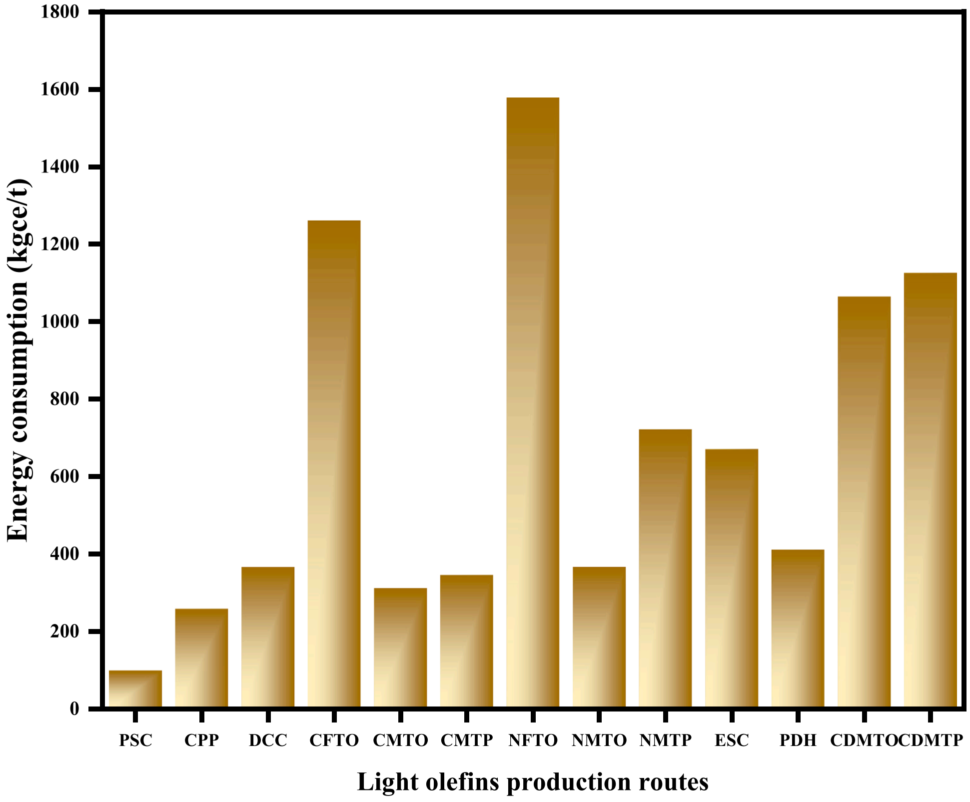

Fig. 8 – Energy consumption of light olefins production routes.

and CFTO routes are 1577.8 and 1261.4 kgce/t, respectively. They are 15.78 and 12.61 times that of the PSC route, respectively, which indicates the PSC route is less energy consumption. Hence, the NFTO and CFTO routes have the disadvantages of high energy consumption compared with PSC, CPP, and DCC. According to national standards of GB30180, the energy consumption limited value of per ton of olefin and propylene production is 4500 and 6000 kgce/t, respectively. The energy consumption values of the 13 routes all meet the requirements stipulated in the national standards.

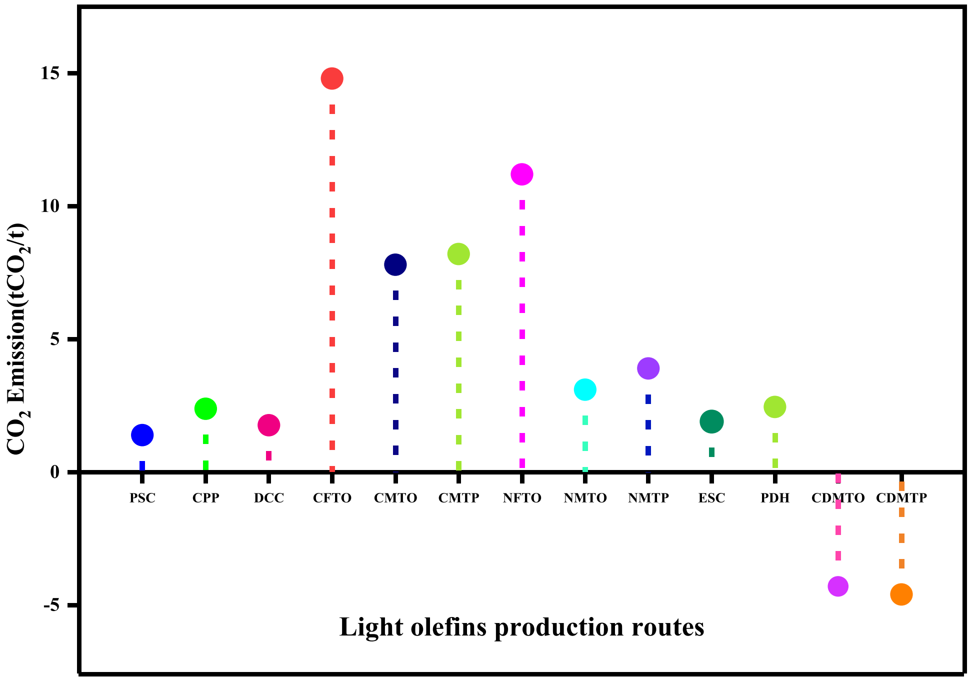

Fig. 9 – The carbon dioxide emissions of light olefins production routes.

4.1.3. *Carbon dioxide emissions*

The carbon dioxide emissions for different routes are shown in Fig. 9. The three oil-based routes, i.e., PSC, CPP and DCC, have lower carbon dioxide emissions compared with the coal- and natural gas-based routes. The carbon dioxide based-routes, i.e., CDMTO and CDMTP, are the most helpful in achieving carbon neutrality on account of the raw materials being carbon dioxide. Essentially the carbon dioxide emissions of these two routes are negative, which is – 4.3 and – 4.6 t/t, respectively. Moreover, the carbon dioxide emissions of PSC and DCC routes are 1.39 and 1.76 t/t, respectively, followed the CDMTO route. Whereas, the carbon dioxide emissions of CFTO, NFTO and CMTP routes is 10.65, 8.06, and 5.90 times that of the PSC route, respectively, which indicates the CFTO, NFTO and CMTP routes are much more harmful to the environment. Higher carbon dioxide emissions mean lower performance in environmental friendliness. The amount of carbon dioxide emitted can measure security of light olefins production routes as the production would be closed if it touches the baseline.

4.1.4. *Economic dimension*

Economics is evaluated by both the production cost and revenue. The production cost mainly comes from the price of raw materials and energy consumption in the industrial process. In this work, for the convenience of comparison, we assume all the production scale and plant investment are the same.

Basically, the prices of raw materials and products will fluctuate in the market due to the change of market supply and demand. Low prices of raw materials and high prices of products would stimulate the enterprises to obtain much more profits. On the contrary, higher cost for raw materials and lower prices of products would bring certain risks for the production route, which may contribute negatively to the security of light olefins production. It can be seen from the Fig. 10 that the cost of CMTO route is the lowest, followed by NMTO, PSC and CDMTO route. That is, the cost of light olefins production from low to high shows the order of coal-, natural gas-, oil- and carbon dioxide-based routes. The price of raw materials is closely related to China's natural energy endowment. China has relatively abundant coal reserve and thus coal as raw materials is easy to obtain with relatively cheap price. The crude oil and natural gas are largely dependent on imports, and the prices are vulnerable to international influences. The cost of carbon dioxide-based routes is decided by the relatively high price of hydrogen, which at present is mainly made from coal and will possibly come from water splitting with renewable energy in the future. With the technology breakthrough, it is expected that the price of green hydrogen can be reduced to a reasonable range, and if so, the carbon dioxide-based routes will have plenty of space for further development.

The implementation of carbon tax will increase the production cost of for most of the enterprises. But for carbon negative enterprises, the carbon tax may increase the revenue. The profitability is different for different light olefins production routes. Except CDMTO and CDMTP routes, the profitability of the light olefins production routes decreases with the increase of carbon tax. In the reference case, when the carbon tax exceeds 100 CNY/t, the revenue of CFTO route may change from positive to negative, as shown in Fig. 11.

4.2. *OPSI*

Based on the four-scale rating scheme which provides a reasonable level of granularity, the results for the reference case are shown in Fig. 12. According to Eq. (5), the security index of light olefins production routes can be calculated. As shown in Fig. 12, the OPSI under three different weights methods is presented. In the first case, the weight values are 10 %, 50 %, 20 %, 10 %, and 10 % for the economy, technology localization, raw materials, energy consumption, and carbon dioxide emissions, respectively. The second case is simply assumed all the weight values are the same. The third case,

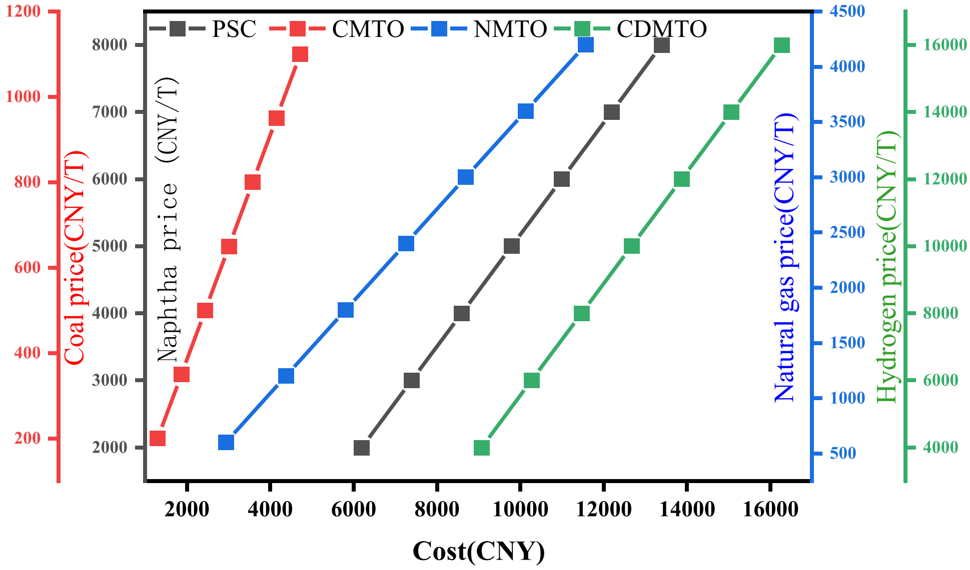

Fig. 10 – The cost of light olefins production process with the raw materials price.

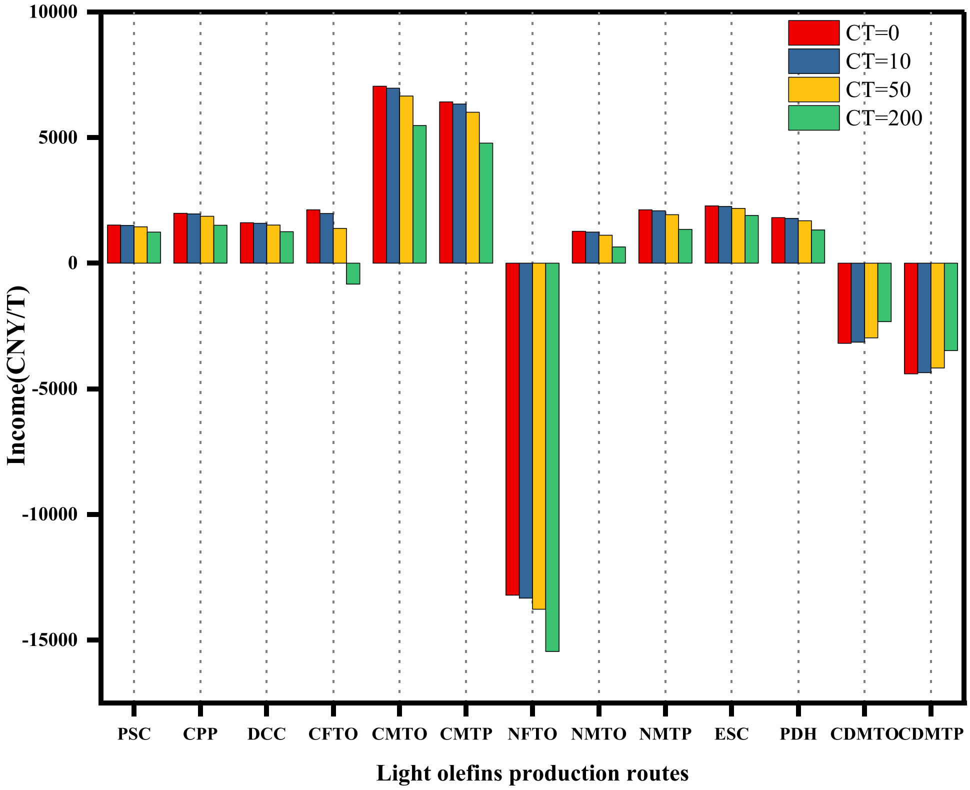

Fig. 11 – Yield of light olefins production process under different carbon taxes.

weight values are assumed to be 10 %, 60 %, 10 %, 10 %, 10 %, respectively.

The first case is reference case. The equal weight is quite different from the other two cases, because in the equal weight, the importance of technology in comprehensive security is reduced, while the proportion of the other four factors is increased. There is no significant difference in the security index between 50 % and 60 % of NFTO technology routes. However, the security index with equal weight changes greatly, indicating that NFTO is greatly influenced by economy, environment and energy consumption. As a reference case, the OPSI of CPP, CMTO, PSC, ESC, CFTO and NMTO routes are 2.58, 2.60, 2.69, 2.72, 2.79, and 2.90, respectively. Nevertheless, the OPSI of PDH is 0.14. The OPSI of CPP, CMTO, PSC, ESC, CFTO and NMTO routes are 18.65, 18.78, 19.41, 19.62, 20.14 and 20.92 times that of the PDH route, respectively. It implies that CPP, CMTO, PSC, ESC, CFTO and NMTO routes have the advantage of high security performance compared with PDH route. Both CMTO and CMTP routes have high security performance and low weight sensitivity. The PDH route is entirely dependent on foreign technology and imported raw materials, which leads to poor security performance. Therefore, it is a big risk warning for policy makers and companies about to start light olefins production with the PDH process.

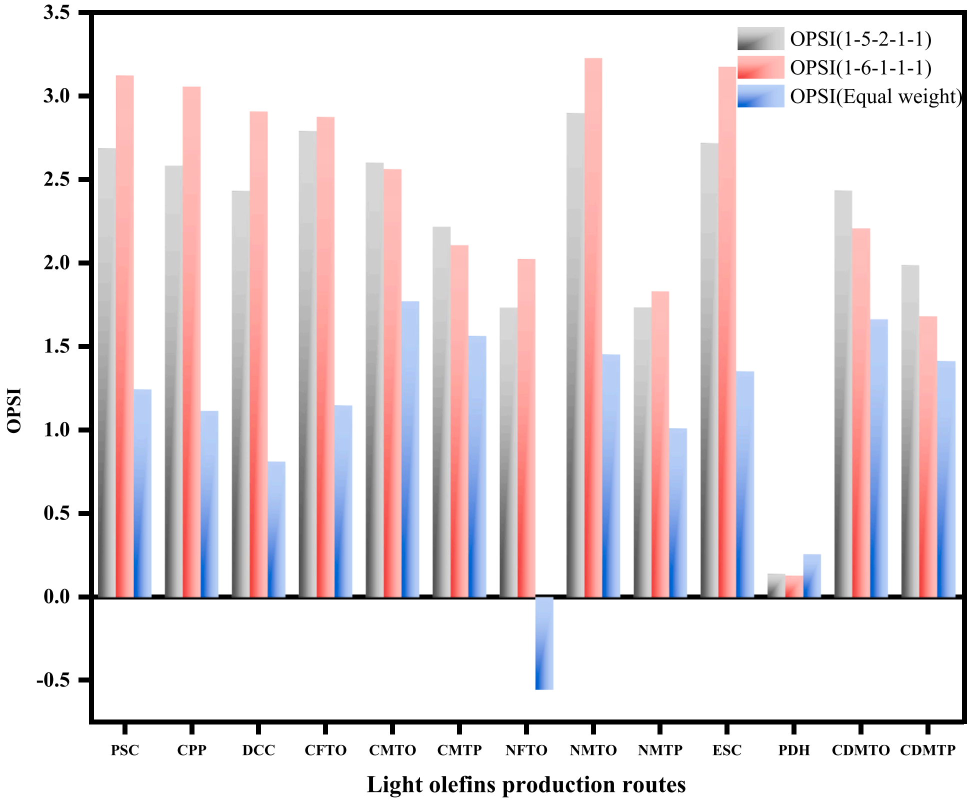

Fig. 12 – OPSI under three different cases.

4.3. *Sensitivity analysis*

It is known that the sensitivity analysis can be used to find out the most sensitive factors. We conducted sensitivity analysis to understand how the fluctuations of weight of five dimensions impact OPSI. By doing so, we can analyze to what extent the weights of five dimensions' influence on the light olefins production security, and then judge the risk bearing ability of the olefins production routes. Meantime, sensitivity analysis is carried out to determine which risks would potentially pose the greatest impact on OPSI. In sensitivity analysis, we examine to what extent the weight of one specified dimension of OPSI affects the scores while keeping the weights of all other four dimensions as the baseline values in reference case. The shortcomings of each olefin production route with regard to the security can be discovered through sensitivity analysis, following which the corresponding measures can be taken to improve its security. Therefore, sensitivity analysis is a profound and significant analytical method.

The changes of OPSI were observed by altering the five dimensions by ± 20 %. This is expected to assist figuring out what would be the main reasons determining the security of different light olefins production routes in China. The Fig. 13 is sensitivity analysis of the weight of five dimensions in four light olefins production routes and the other nine sensitivity analysis figures see the supporting document.

As the weight of economic dimension changes by ± 20%, the OPSI varies by ± 74.03 %, ± 83.71 % and ± 77.58 % for CMTO, CMTP and CFTO routes, respectively. Meantime, if the weight of energy consumption dimension changed by ± 20%, the OPSI only changes by ± 0.74 %, ± 2.29 % and ± 28.8 % for CMTO, CMTP and CFTO routes, respectively. Suppose that the weight of environmental dimension changes by ± 20 %, and the OPSI for CMTO, CMTP and CFTO routes changes by ± 47.32 %, ± 56.98 % and ± 102.43 %, respectively. It implies that the weight of the economic and environmental dimensions is much more sensitive than that of the energy consumption for the coal-based to light olefins production routes. Therefore, reducing carbon dioxide emissions will effectively improve the comprehensive security performance of coal to olefins. With the improvement of the carbon capture, utilization and storage (CCUS), coal chemical industry will go further in ensuring the security of domestic chemicals.

In NMTO, NMTP and NFTO routes, although the raw materials are the same, the five influencing factors have different effects. In NMTO, the weight of technology, environment and energy consumption dimension changes by ± 20 %, and the OPSI changes by ± 68.89 %, ± 27.34 % and ± 14.22 %, respectively. In NMTP, the weight of economic, environmental and technological dimensions changes by ± 20%, and the OPSI changes by ± 125.35 %, ± 72.52 % and ± 20.69 %, respectively. In NFTO, the weight of technology, energy consumption and economy dimension changes by ± 20 %, and the OPSI changes by ± 103.53 %, ± 138.04 % and ± 0.00 %, respectively. Therefore, for the NMTO route, reducing energy consumption and improving the security performance of raw materials sources can effectively improve OPSI performance. For the NMTP route, improving the technical domestic production rate can effectively improve OPSI performance. For the NFTO route, OPSI can be improved by reducing energy consumption and reducing carbon dioxide emissions to improve its economy.

In the CDMTO and CDMTP routes, the weight of raw materials, energy consumption, environment and technology dimensions changed by ± 20 %, the OPSI of CDMTO

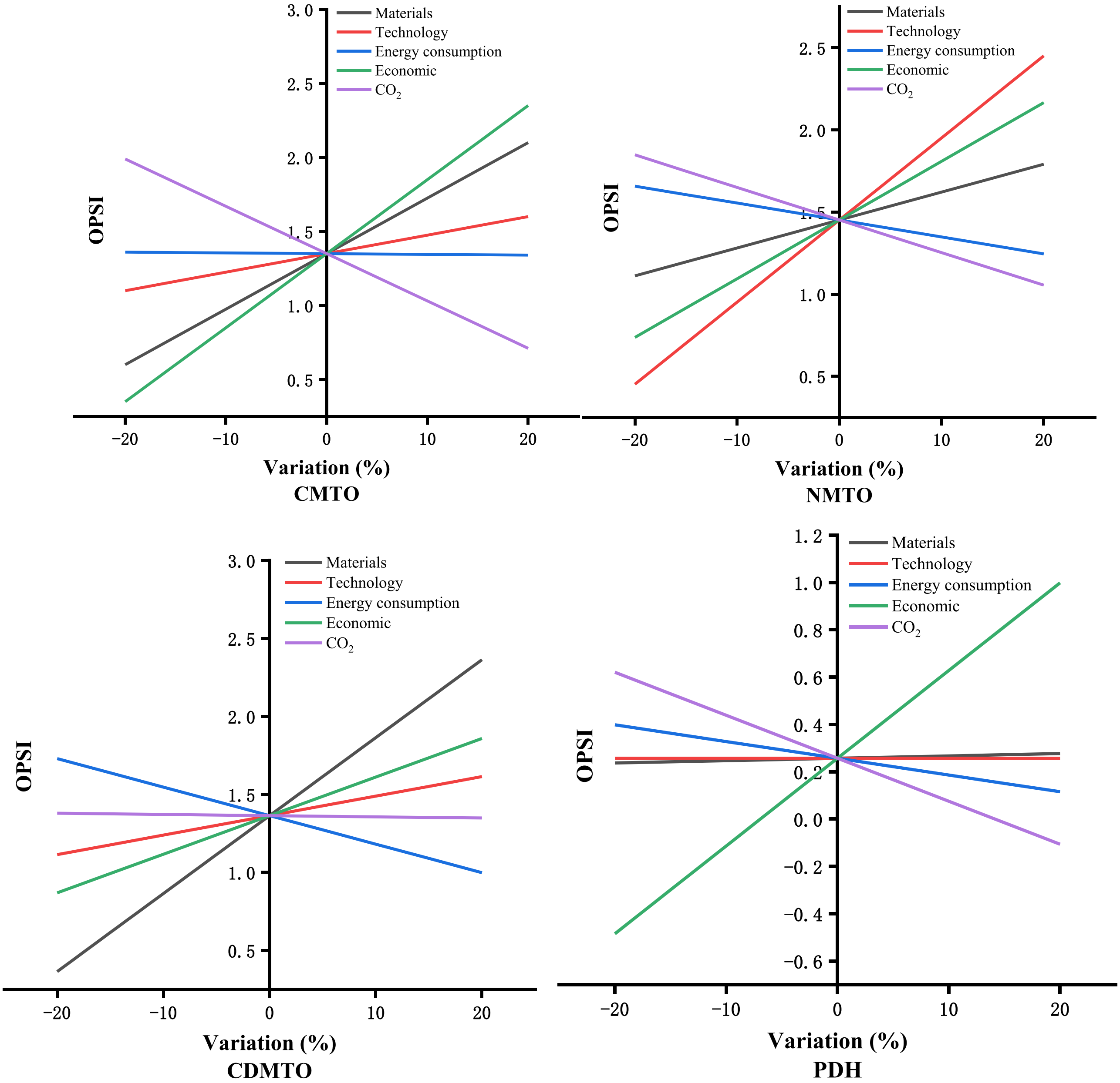

Fig. 13 – Sensitivity analysis of light olefins production routes.

changed by ± 73.32 %, ± 26.81 %, ± 1.13 % and ± 10.90 %, and CDMTP changed by ± 87.20 %, ± 36.04 %, ± 0.00 % and ± 18.33 %, respectively. Therefore, for the CDMTO and CDMTP routes, raw materials and energy consumption are more sensitive than environmental and technical indicators, which implies that the proportion of technology and environment weight is smaller than that of raw materials and energy consumption. Therefore, it is beneficial to improve the OPSI by increasing the technical domestic production rate and reducing the energy consumption.

In the PSC, DCC, ESC, and CPP routes, as shown in Fig. 13, technology and economy are the two more sensitive weights compared to the raw materials dimension. That means the contribution of raw materials to security is the least. Therefore, improving the security of raw materials, reducing the import of crude oil and increasing the proportion of renewable energy can effectively improve its comprehensive security performance.

As to the PDH route, it has the lowest security score because the raw materials and technology used are essentially fully imported. Either of them is at risk will significantly affect the olefin production if PDH is selected as the main route in China. Despite the supply of propane, breaking the technological blockade is critical for PDH.

5. Conclusions and policy implication

A security evaluation framework is proposed based on 13 light olefins production routes. It is evaluated comprehensively from five dimensions: economy, technology localization, raw materials, energy consumption, and carbon dioxide emissions.

In terms of the availability of raw materials, crude oil and natural gas have a high degree of external dependence. Coal is mainly supplied domestically and thus acts as a stabilizer and ballast. Carbon dioxide sources are widely available in China, but hydrogen sources are less, and green hydrogen has a high cost, which has great development potential. In terms of energy consumption, the energy consumption of NFTO and CFTO routes are 1577.8 and 1261.4 kgce/t, respectively. They are 15.78 and 12.61 times that of the PSC route, respectively, which indicates the PSC route is less energy consumption. CFTO and NFTO routes have the disadvantage of high energy consumption compared with the PSC route. CFTO and NFTO routes have much more room to reduce energy consumption in the olefins production. On the environmental dimension, CDMTO and CDMTP routes use carbon dioxide as feedstock, so the CO_2 emissions of these two processes are – 4.3 and – 4.6 t/t, respectively. The carbon dioxide emissions of CFTO, NFTO and CMTP routes is 10.65, 8.06, and 5.90 times that of the PSC route, respectively, which indicates the CFTO, NFTO and CMTP routes are much more harmful to the environment.

From an economic perspective, CMTO and CMTP routes have the lower cost and higher profitable, while NFTO and DCC routes have higher cost and NFTO route is the least profitable. It shows a linear relationship between the profitable and the price of raw materials, the profitability of NFTO and CDMTO routes decreases with the increase of the price of natural gas and hydrogen. With the increase of carbon tax, the profitability of olefins production route will decrease.

In the reference case, the OPSI of CPP, CMTO, PSC, ESC, CFTO and NMTO routes are 2.58, 2.60, 2.69, 2.72, 2.79 and 2.90, respectively, while that of the PDH route is only 0.14. It implies that PSC, CPP, ESC, NMTO, CMTO and CFTO routes have the advantage of high security performance compared with PDH route. Both CMTO and CMTP routes have high security performance and low weight sensitivity. The PDH route is entirely dependent on foreign technology and imported raw materials, which leads to poor security performance. Therefore, it is a big risk warning for policy makers and companies about to start light olefins production with the PDH process. CDMTO and CDMTP routes have the advantage of low carbon dioxide emissions and helpful to achieve carbon neutrality, but the low economic profitability. It is hoped that technological breakthrough can be achieved in the near future to reverse the economic profitability.

At present, the coupling of various light olefins production routes is an effective way to achieve both economic and carbon neutrality. The results provide a security assessment of light olefins production path and provide reference for policy makers and enterprises. 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. The light olefins production with biomass technology is not within the scope of discussion in this paper. In addition, it is also very meaningful to analyze the change trend of light olefins production security from the time dimension.

Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cherd.2023.04.037.

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