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RESEARCH ARTICLE

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Lifecycle carbon footprint and cost assessment for coal-to-liquid coupled with carbon capture, storage, and utilization technology in China

Abstract The coal-to-liquid coupled with carbon capture, utilization, and storage technology has the potential to reduce CO_2 emissions, but its carbon footprint and cost assessment are still insufficient. In this paper, coal mining to oil production is taken as a life cycle to evaluate the carbon footprint and levelized costs of direct-coal-to-liquid and indirect-coal-to-liquid coupled with the carbon capture utilization and storage technology under three scenarios: non capture, process capture, process and public capture throughout the life cycle. The results show that, first, the coupling carbon capture utilization and storage technology can reduce CO_2 footprint by 28%–57% from 5.91 t CO_2/t·oil of direct-coal-to-liquid and 24%–49% from 7.10 t CO_2/t·oil of indirect-coal-to-liquid. Next, the levelized cost of direct-coal-to-liquid is 648–1027 \$/t of oil, whereas that of indirect-coal-to-liquid is 653–1065 \$/t of oil. When coupled with the carbon capture utilization and storage technology, the levelized cost of direct-coal-to-liquid is 285–1364 \$/t of oil, compared to 1101–9793 \$/t of oil for indirect-coal-to-liquid. Finally, sensitivity analysis shows that CO_2 transportation distance has the greatest impact on carbon footprint, while coal price and initial investment cost significantly affect the levelized cost of coal-to-liquid.

Keywords coal-to-liquid, carbon capture, utilization and storage (CCUS), carbon footprint, levelized cost of liquid, lifecycle assessment

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1 Introduction

China has consumed 93900 t of oil (standard coal) in 2020, accounting for 20.6% of total primary energy consumption [1]. At the same time, the energy security concerns are becoming increasingly significant since China's growing relies on crude oil imports, which are affected by global oil prices and supply chains. The clean conversion of coal as a raw material to obtain oil and other chemicals, is thus considered as one of the most important energy strategies for China attributing to its abundant coal resources [2]. Oil production from coal using the coal-to-liquid (CTL) technology mainly includes two pathways: the direct-coal-to-liquid technology (DCL) and the indirect-coal-to-liquid technology (ICL). Since the 1990s, the Chinese government has implemented numerous policies to promote the development of the CTL technology, which is now operating commercially with a world-leading technology level [3]. The Coal Industry Association estimates that 9.31 million t of CTL products are produced in China in 2021, accounting for 4.68% of its total crude oil output. Though China's CTL technology can alleviate the energy status of rich coal and less oil, a large amount of CO_2 emissions would be generated [4]. Coupling with the carbon capture, utilization and storage (CCUS) technology creates a possibility for the low carbon development of CTL [5–7], though CCUS is not yet commercially accessible [8,9] and its high cost is the main obstacle to widely deployment [10,11].

Some scholars evaluated the carbon emissions and costs of CTL or CTL coupled with the CCUS technology in the link of oil production in China. For instance, Bassano et al. used the Aspen Plus software to simulate and evaluate the carbon emissions and cost of ICL coupling CCUS, and found that the CO_2 emissions/t·oil in ICL was 5.99 t and after coupling CCUS that was reduced by 66% [12]. Yang et al. found that the CO_2 emissions/t·oil in ICL is 3.49–5.26 t and the production cost for a ton of oil is \$680–822 [13]. Mantripragada calculated the carbon emissions and cost of ICL coupling CCUS in a case study. They found that a plant using 50000 barrels of oil per day emits 25300–28100 t of CO_2 compared to 100–200 t after coupling CCUS, and under the cap-and-trade regime, coupling CCUS is more economical when the carbon price exceeds 12 \$/t [14]. Some recent studies also focus on lifecycle carbon emissions and costs, but their results vary considerably due to different research boundaries. For instance, Jaramillo et al. evaluated the carbon footprint from coal mining to oil utilization with 5.5–5.7 kg CO_2/L oil for ICL and 2.8–3.0 kg CO_2/L oil for ICL-CCUS [15]. Gao et al. calculated the lifecycle carbon emissions of the CTL system and found that DCL emits 500 g/MJ, while ICL emits about 650 g/MJ [16]. Using the CCUS technology with a capture rate of 60%, the direct carbon emissions of DCL are 240 g/MJ and the indirect carbon emissions are 50 g/MJ [16]. Zhang et al. compared different oil production technologies using a whole lifecycle approach and found that the carbon footprint of DCL and ICL are 0.17 and 0.21 kg/MJ, respectively, while the production costs of DCL and ICL are 0.0122 and 0.0139 \$/MJ, respectively [17].

It can be summarized that there are some limitations in the studies that evaluated the lifecycle carbon footprint or cost of CTL coupled with the CCUS technology. Most studies only consider the oil production process without broadening their scope to include activities such as mining, washing, and the transportation of coal. Some studies focus on the full-chain carbon emissions and cost of the whole life cycle, but do not calculate the change in carbon footprint and cost after CCUS coupling. A few studies involved CCUS technology in their life-cycle analysis, however, they did not fully evaluate the carbon footprint and costs of DCL and ICL. At the same time, research and evaluation are too macro, and specific capture units and transportation distances are not considered when calculating carbon footprint and costs.

Compared with previous studies, this paper has the following contributions. First, it comprehensively evaluates the life-cycle carbon footprint and levelized cost of DCL and ICL by taking coal mining to oil production as the full-chain boundary. Next, it considers the actual reaction of the coal-to-oil process, and establishes multiple emission reduction scenarios according to various CO_2 sources, which is more in accordance with reality. Finally, it takes into account the impacts of different storage options, coal prices and CO_2 transportation distances on carbon footprint and levelized costs of liquid (LCOL) in detail. This paper can provide more accurate and complete reference for China's low-carbon transformation of coal to liquids industry.

2 Methods and data

2.1 Research boundary

Based on the life cycle inventory, the life cycle assessment (LCA) method may evaluate the carbon footprint of a product or service from raw material acquisition, production, use and disposal processes from a micro perspective [18]. CTL coupled with the CCUS technology involves several technological processes, including coal mining, coal washing, coal transportation, direct or indirect liquefaction to oil, and CCUS-related processes (i.e., CO_2 capture, transportation, and storage). Each process requires a varied quantity of energy associated with the micro-computation of carbon emissions. Therefore, the LCA method is used to calculate the carbon footprint of the full life cycle, beginning with coal mining and ending with oil utilization.

Figures 1 and 2 show the DCL and ICL study boundaries, respectively. Following mining, coal is transported to a washing plant for washing, and then to a CTL plant for oil production. In specific, DCL first liquefies coal directly into liquid fuel by adding hydrogen at high temperatures and pressures, and then converts fuel into petroleum products such as gasoline and diesel after desulfurization, denitrification, and deoxidation treatment. CO_2 is mostly produced in low-temperature methanol washing and coal-fired boiler units. ICL first gasifies the coal, then purifies it to obtain carbon monoxide and hydrogen, and lastly, at high temperatures, adds a catalyst to produce petroleum products. CO_2 is mostly produced in low-temperature methanol washing, F-T synthesis, sulfur recovery and other units. CO_2 can be selectively captured from each unit throughout the reaction process, and then transported to a storage facility. Overall, the research boundary covers the direct energy consumption and raw material consumption throughout the entire process from coal production to oil production,

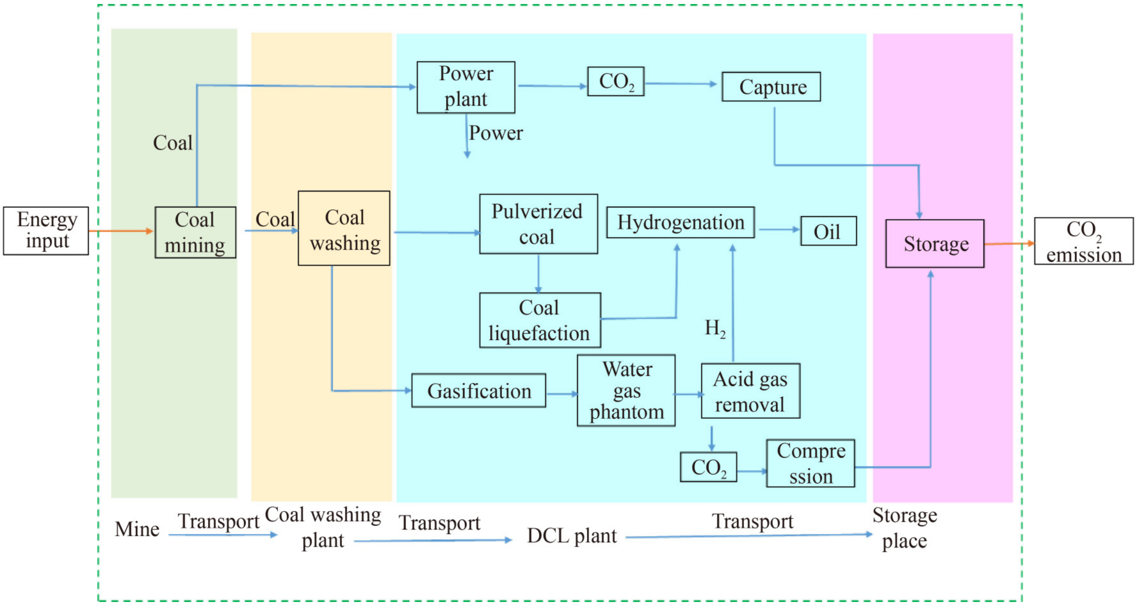

Fig. 1 Study boundary of DCL.

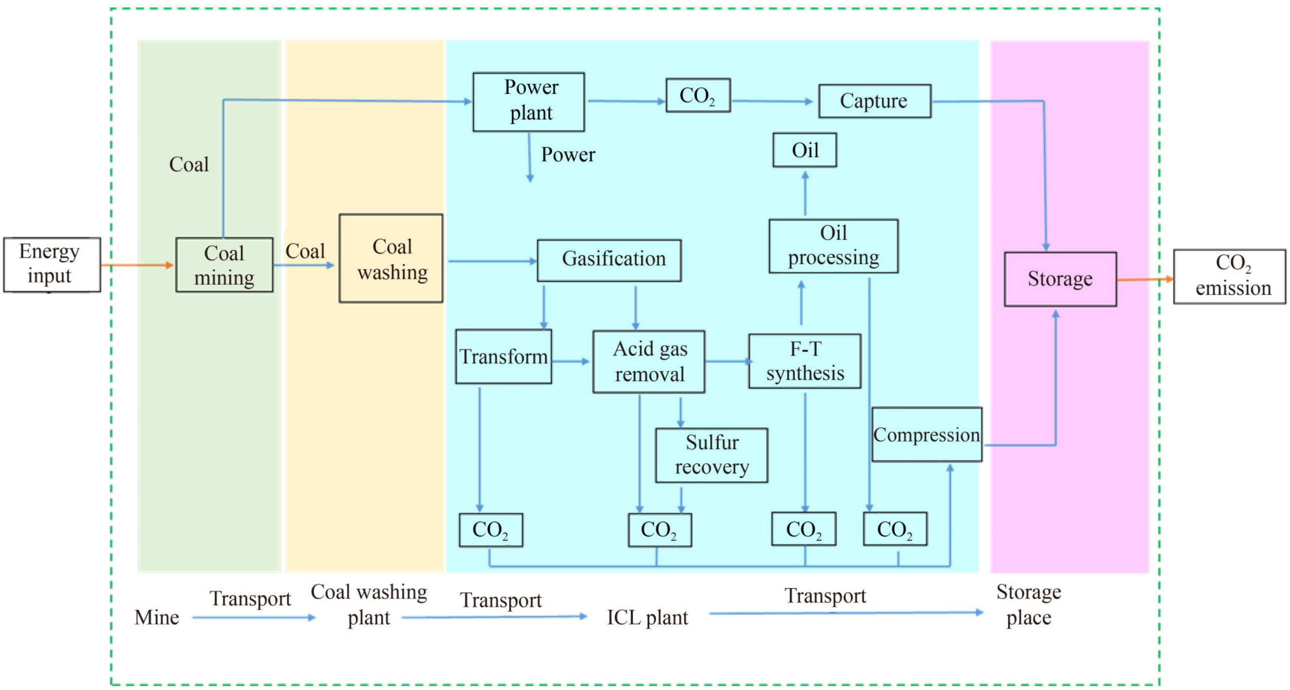

Fig. 2 Study boundary of ICL.

but excludes indirect energy consumption categories such as equipment production, heating, and lighting. For example, energy emissions from coal mining and washing processes are considered, but emissions from lighting are not included in the accounting boundary.

2.2 Lifecycle carbon footprint assessment for CTL coupled with CCUS technology

There are numerous processes for CTL coupled with the CCUS technology, including coal mining and washing, coal transportation, direct or indirect liquefaction to oil, capture, transportation and storage of CO_2. Each process involves various energy consumption and CO_2 emissions, and the formula for calculating carbon footprint can be shown in Eq. (1).

$$C_{CO_2} = C_{coal} + C_{trans} + C_{ctl} + C_{ccus}, \tag{1}$$

where C_{CO_2} (kg/t) represents the lifecycle carbon footprint of CTL coupled with the CCUS technology, and C_{coal},

C_{trans}, C_{ctl}, C_{ccus} (kg/t) represent the CO_2 emissions from coal mining and washing, coal transportation, coal to liquids process, and the CCUS process.

2.2.1 Mining and washing of coal

There are three main uses of coal in CTL, which are liquefaction, gasification, and power generation. These three applications do not have the same requirements for coal types, but the energy consumption of coal mining and washing is mainly related to the type of mine and not much related to the coal types. Therefore, the carbon footprint of the coal mining and washing segment is calculated based on the physical consumption and average low-level calorific value of the different types of energy consumed by the coal mining and washing industry in the *China Energy Statistics Yearbook 2021* using the calculation method provided in the *IPCC National Greenhouse Gas Emissions Inventory* (*2006*) [19]. C_{coal} is calculated by Eq. (2).

$$C_{\text{coal}} = \sum_{i=1}^{n} AC_i \times NCV_i \times CC_i \times O_i \times 44/12 + M_{\text{P}} \times EF_{\text{P}} + M_{\text{h}} \times EF_{\text{h}}, \tag{2}$$

where AC_i (kg/t or m^3/t) denotes the ith type of physical quantity of consumed energy; NCV_i (MJ/kg or MJ/m^3) represents the average low-level calorific value of the ith type of energy; CC_i (kg/MJ) indicates the carbon content of the ith type of energy; O_i indicates the oxidation efficiency of the ith type of energy; M_{P} (kWh/t) indicates the electricity consumed by per unit of coal mining and washing; EF_{P} (kg/kWh) indicates the CO_2 emission coefficient of electricity; M_{h} (GJ/t) indicates the heat consumed by per unit coal of mining and washing; and EF_{h} (kg/GJ) denotes the CO_2 emission coefficient of heat.

The carbon content of per unit calorific value, the oxidation coefficient, and the carbon content are taken from the *IPCC National Greenhouse Gas Emissions Inventory* (*2019*) and Refs. [20,21]. The electricity emission coefficient is 0.5810 kg/kWh, which is from the Ministry of Ecology, China [22]. The heat emission coefficient is calculated by dividing the carbon emissions from the heat production process by the total electricity (heat) production, which is calculated by Eq. (3).

$$EF_{\text{h}} = \frac{P_{\text{h}}}{B_{\text{h}}} = \frac{\sum_{i=1}^{n} (AC_i \times NCV_i \times EF_i \times O_i)}{B_{\text{h}}}. \tag{3}$$

In Eq. (3), EF_{h} denotes the carbon emission coefficient of electricity (heat); P_{h} denotes the carbon emissions from thermal heat supply; B_{h} denotes total electricity and heat production; and AC, NCV, EF, and O have the same meaning as Eq. (1). The thermal emission coefficient of China is 1289.48 t $CO_2/10^{10}$ kJ calculated based on the consumption and production of energy in the *Energy Balance Sheet 2021* [1].

2.2.2 Transportation of coal

Railway transportation and waterway transportation are the two main methods of coal transportation in China, among which there is also a "railway-waterway" combined transport mode [17]. The reality of coal transportation may be by railway or waterway to a particular location, and then the road is responsible for a small number of short-haul transports that are difficult to cover by other transport modes. Therefore, in this paper, the carbon footprint of coal transportation is calculated based on the average distance and volume of each mode of transportation. C_{trans} is given by Eq. (4).

$$C_{\text{trans}} = E_{\text{r}} \times D_{\text{r}} \times R_{\text{r}} + E_{\text{s}} \times D_{\text{s}} \times R_{\text{s}} + E_{\text{h}} \times D_{\text{h}} \times R_{\text{h}}, \tag{4}$$

where E_{r}, E_{s} and E_{h} (kg $CO_2/(10^4$ t·km)) denote the CO_2 emission coefficient of coal transportation by railway, waterway, and highway, respectively. D_{r}, D_{s} and D_{h} (km) denote the average distance of coal transportation by railway, waterway, and highway. R_{r}, R_{s} and R_{h} (%) denote the percentages of coal transported by railway, waterway and highway, respectively.

It should be noted that the emission factors of coal transported by railway and waterway in Table 1 are averaged from the emission factors calculated in the literature for each province in China, and the emission factors of highway transport are calculated from the energy consumption of bulk cargo diesel vehicles in the literature, where the density of diesel fuel is taken as 0.84 kg/L.

Moreover, CTL has other raw materials but their consumption is very small except for water, and the transportation cost is included in the price in the later cost calculation, while water is often taken locally. Therefore, the carbon footprint of other original transportation is no longer considered.

2.2.3 Coal-to-liquid

The emission of CO_2 from coal to oil includes two parts: the emissions generated by the chemical reaction of converting coal to oil, i.e., process emissions, and the emissions generated by coal combustion and power generation to provide power for the entire system, i.e., public emissions. According to the carbon balance, the specific raw material balance table of carbon emissions generated throughout the coal-to-oil process is shown in Table 2 [29].

2.2.4 Capture, transport, and storage of CO_2

The energy consumed in the process of capture, transport, and storage of CO_2 is mainly electricity. Therefore, its carbon footprint can be calculated according to the Eq. (5).

$$C_{\text{ccus}} = E_{\text{cc}}^{\text{ccs}} \times EF_{\text{p}} + E_{\text{ct}}^{\text{ccs}} \times d_{\text{ct}} \times EF_{\text{p}} + E_{\text{cs}}^{\text{ccs}} \times EF_{\text{p}}, \tag{5}$$

Table 1 Main parameters of carbon footprint assessment of coal transportation

Parameters	Parameter description	Value	Unit	Data source
R_r	Percentage of railway transportation of coal	70.1%	–	Refs. [17,23,24]
R_s	Percentage of waterway transportation of coal	11.75%	–	Refs. [17,23,24]
R_h	Percentage of highway transportation of coal	18.15%	–	Refs. [17,23,24]
D_r	Average transportation distance of coal by railway	696.27	km	Ref. [25]
D_s	Average transportation distance of coal by waterway	1402.69	km	Ref. [25]
D_h	Average transportation distance of coal by highway	176.52	km	Ref. [25]
E_r	Carbon emission factor of railway transportation	101.78	kg/(10^4 t·km)	Ref. [26]
E_s	Carbon emission factor of highway transportation	1406.16	kg/(10^4 t·km)	Ref. [27]
E_h	Carbon emission factor of waterway transportation	58.92	kg/(10^4 t·km)	Ref. [28]

where E_{cc}^{ccs} and E_{cs}^{ccs} (kWh/t) represent the electricity consumed by the capture and storage of per unit CO_2, respectively. Since the technology of pipeline transportation of CO_2 is mature and the future transportation cost reduction requires the establishment of large-scale pipeline transportation, therefore, this paper assumes that CO_2 is transported by pipeline. E_{ct}^{ccs} (kWh·(t·km)$^{-1}$) represents the electricity consumed to compress one unit of CO_2 and transport one unit distance. d_{ccs} denotes the transport distance of CO_2 (km). Table 3 shows the parameters of the capture, transport, and storage of CO_2. It should be noted that the energy consumption of CO_2 capture and compression of coal chemical synthesis ammonia projects is approximately 219–222 kWh/t [30]. Thus, 220 kWh/t is selected as the energy consumption of per unit capture of process capture O_2. The main CO_2 capture method of coal-fired power plants is post-combustion capture with the capture energy consumption of about 2.35 GJ/t for heat consumption and 70 kWh/t for power consumption [30]. Thus, 720 kWh/t is selected as the energy consumption of per unit capture of public capture O_2.

2.3 Lifecycle levelized cost assessment for CTL coupled with the CCUS technology

Levelized cost is a significant indication for measuring the economic benefits and competitiveness of a particular technology, as well as the feasibility of a certain project [33]. The levelized cost of coal to liquid refers to the ratio of the current price after discounting the cost of the whole life cycle of the coal to liquid project to the present value after discounting the volume of oil, reflecting the unit oil price when achieving the balance of payments. The formula of levelized cost is shown in Eq. (6).

$$\sum_{t=1}^{N}\sum_{s=1}^{n}\frac{P_t^s\times Q_t^s}{(1+r)^t}=\sum_{t=1}^{N}\frac{\mathrm{COST}_{tn}}{(1+r)^t},\tag{6}$$

where s refers to the products which generated in the CTL project, with n types in total; t indicates the year in which the project is operated, and the life of the project is N years; P_t^s refers to the price of S product in the year t; Q_t^s refers to the output of S product in the year t, COST_{tn} is the cost of the CTL project in year t; and r represents the discount rate.

When P_t^s remains constant, Eq. (6) can be obtained by converting Eq. (7).

$$\mathrm{LCOL}=P_t=\frac{\mathrm{COST}_{\mathrm{Initial}}+\sum_{t=1}^{N}\frac{\mathrm{COST}_t}{(1+r)^t}}{\sum_{s=1}^{n}\sum_{t=1}^{N}\frac{Q_t^s}{(1+r)^t}}.\tag{7}$$

As shown in Eq. (7), LCOL is the levelized cost per unit liquid product for the CTL project, which equals to the ratio of the present value of the sum of all costs over the lifecycle of the project and the present value of oil output volume. The discount of oil output volume here refers to the discounted value of oil output, not to its physical quantity [34], which is the result of the mathematical transformation of Eq. (6), where P_t refers to the weighted average price of the oil production; $\mathrm{COST}_{\mathrm{Initial}}$ denotes the initial investment cost of the oil production project, which includes equipment, land, and construction costs; and COST_t represents variable costs, including the operation and maintenance costs of the project.

It can be seen from Eq. (7) that the cost of LCOL includes two parts, the initial investment cost and the annual variable cost. In this paper, the initial investment cost refers to the total investment of the CTL project from the beginning of construction to the beginning of operation (equipment, land, installation, and civil construction cost). The life-cycle variable cost of the CTL coupled with CCUS technology mainly includes the cost of coal transportation, the variable cost of coal-to-liquid, and the cost of CCUS. In specific, the lifecycle cost of CTL coupled with the CCUS technology (COST_t) can be expressed by Eq. (8).

$$\mathrm{COST}_t=\mathrm{COST}_{\mathrm{trans}}+\mathrm{COST}_{\mathrm{CTL}}+\mathrm{COST}_{\mathrm{ccus}},\tag{8}$$

where $\mathrm{COST}_{\mathrm{trans}}$, $\mathrm{COST}_{\mathrm{CTL}}$, $\mathrm{COST}_{\mathrm{ccus}}$ ($) denote the cost of coal transportation, the variable cost of coal to liquid process, and the cost of CCUS.

Table 2 Carbon balance sheet

DCL

Carbon input/(10^4 t·a^{-1})				Carbon output/(10^4 t·a^{-1})											
Coal for liquefaction	Coal for gasification	Thermal power coal	Total	Liquid gas	Naphtha	Diesel oil	Coarse powder	Liquefied oil residue	Gasification ash	Thermoelectric ash	Gasification methanol washing tail gas	Gasification filter exhaust	Flue gas and flare of various industrial furnaces	Thermoelectric flue gas	Total
150.3	89.3	70.4	310	8.3	22.3	64.5	0.3	45.2	0.8	0.5	80.7	1.1	16.3	69.9	310

ICL

Carbon input/(10^4 t·a^{-1})			Carbon output/(10^4 t·a^{-1})								
Raw coal	Fuel coal	Total	Light diesel	Naphtha	Dissolved gas	By-product	Process high concentration and unit tail gas CO_2	Coal gasification ash	Flue gas from coal-fired boiler	Wish coal boiler ash	Total
890.49	197.31	1087.8	239.6	73.03	27.77	7.6	538.4	3.95	191.5	5.8	1087.8

Table 3 Main parameters of carbon footprint assessment for the CCUS technology

Parameters	Parameter description	Value	Unit	Data source
E_{cc1}^{ccs}	Energy consumption of per unit CO_2 of process capture	220	kWh/t	Refs. [20,31]
E_{cc2}^{ccs}	Energy consumption of per unit CO_2 of public capture	720	kWh/t	Refs. [20,31]
E_{ct}^{ccs}	CO_2 energy consumption of per unit transportation	1.3	kWh/(t·km)	Ref. [32]
E_{csE}^{ccs}	Oilfield CO_2 storage energy consumption	15.6	kWh/t	Ref. [16]
E_{cs}^{ccs}	Brackish water layer CO_2 sequestration energy consumption	12	kWh/t	Ref. [32]

2.3.1 Transportation cost of coal

In this paper, only the cost of coal transportation is considered when calculating the transportation costs without considering the consumption during the transportation process. The total cost of coal transportation is determined based on the transportation method, transportation distance, proportion of transportation method in Table 2, and the unit cost of different transportation methods in Table 4. $COST_{trans}$ is calculated by Eq. (9).

$$COST_{trans} = C_r \times D_r \times R_r + C_s \times D_s \times R_s + C_h \times D_h \times R_h, \quad (9)$$

where C_r, C_s, and C_h (\$/t·km) denote the unit cost of coal transportation by railway, waterway, and highway, respectively. D_r, D_s and D_h (km) denote the average distance of coal transportation by railway, waterway, and highway, and R_r, R_s and R_h (%) denote the proportion of coal transportation by railway, waterway, and highway respectively.

Table 4 Unit transportation cost of coal

Parameters	Description	Value /(\$·(10^4 t·km)$^{-1}$)	Data source
C_r	Unit transportation cost by railway	13.46	Ref. [35]
C_s	Unit transportation cost by waterway	31.22	Ref. [36]
C_h	Unit transportation cost by highway	460.89	Ref. [37]

2.3.2 Cost of coal-to-liquid

The initial investment cost and operating cost of the project are determined based on the largest DCL and ICL projects that can be put into production after researching the currently invested CTL projects and related literatures. The relevant data are shown in Table 5 and the initial investment cost is calculated by Eq. (10).

$$COST_{initial} = CAPEX_{CTL} \times CAP_{CTL}, \quad (10)$$

where $CAPEX_{CTL}$ (\$/t of oil) represents the unit initial investment and construction cost of the CTL project, and CAP_{CTL} (t/a) indicates the scale of the CTL project.

Variable costs of CTL include operation and maintenance costs and fuel costs. The fuel cost is determined based on the amount of fuel used to produce 1 t oil and the price per unit of fuel for the CTL projects above. In terms of coal types, the coal for liquefaction has high requirements, the coal for cogeneration has relatively low requirements, while the coal for gasification has a wide range of types but also has certain requirements. Therefore, the price of coal for liquefaction is the highest and the price of coal for thermal power is the lowest. In this paper, coal prices are set by referring to the National Bureau of Statistics [23], Bohai Sea Power Coal Price Index [39], China Coal Index (CCI) [40], China Coal Price Index (CCPI) [41], and references about coal prices in the literature, which means each coal price has a corresponding low (L), middle (M), and high (H) price [42,43]. In addition to the coal price, the price of other raw materials including the transportation price, and the data are obtained from Ref. [44] and physical stores from Ref. [45]. The specific values are shown in Table 6 [19] and the available investment cost is calculated by Eq. (11).

$$COST_{CTL} = \sum_{i=1}^{n} P_i \times Q_i + OM_{CTL}, \quad (11)$$

where P_i (\$/t) indicates the price of the material i consumed by the CTL project; Q_i (t/t·oil) indicates the quantity of the material i consumed; and OM_{CTL} indicates the operation and maintenance cost of the CTL project.

2.3.3 Cost of capture, transport, and storage of CO_2

The calculation method of CCUS cost refers to the calculation method in Ref. [37], which converts the fixed cost and operation and maintenance cost into the unit capture cost, transportation cost, and storage cost. First, the cost of capture and storage varies according to the concentration of CO_2. Therefore, the high concentration of CO_2 emitted by the process leads to a lower capture cost, while the low concentration of CO_2 emitted by public use leads to a higher capture cost [36]. Next, the transportation cost is mainly related to the transportation

Table 5 Cost parameters of CTL projects

Parameters	Parameter description	Numerical value	Unit	Data source
$CAPEX_{DCL}$	DCL unit initial investment cost	2149.04	\$/t	Ref. [3]
CAP_{DCL}	Size of DCL	16.06	10^4 t/a	Ref. [3]
OM_{DCL}	DCL operation and maintenance costs	3%CAP	\$/t	Ref. [47]
$CAPEX_{ICL}$	ICL unit initial investment cost	2007.11	\$/t	Ref. [13]
CAP_{ICL}	Size of ICL	400	10^4 t/a	Ref. [13]
OM_{ICL}	ICL operation and maintenance costs	3%CAP	\$/t	Ref. [36]
T	Project operation period	20	a	Assumed in this paper
n	Project load	90%	–	Ref. [16]
r	Discount rate	0.08	–	Ref. [11]

Table 6 Feedstock consumption of CTL

	Feedstocks	Numerical value/kg	Unit price/($\$\cdot t^{-1}$)
DCL feedstocks	Coal for liquefaction	2018.19	68.39/111.13/153.88
	Coal for gasification	1198.67	65.42/106.30/147.19
	Coal for cogeneration	1460.73	59.47/96.64/133.81
	Sulfur	1.04	29.73
	Carbon disulfide	1.03	780.54
	Liquid ammonia	0.36	408.86
	Ferrous sulfate	335.91	32.71
	Steam, water	2536.02	0.30
ICL feedstocks	Coal for gasification	4074.4	65.41/106.30/147.19
	Coal for cogeneration	1059.58	59.47/96.64/133.81
	Steam, water	1314.69	0.30
	Desalinated water	589.71	10.11
	Lime	2.65	104.07

distance, and the larger the transportation distance, the higher the cost. According to the existing CCUS demonstration projects in China, the transportation distance is less than 100 km [37], but 250 km is the upper limit of CO_2 transportation distance in China [48]. To compare, 0 km (D1), 100 km (D2), and 250 km (D3) are set as the distance of CO_2 transportation in this paper. Finally, the cost of storage is mainly related to the storage method. According to the existing projects, enhanced oil recovery (EOR) and deep saline formation (DSF) are considered, corresponding to certified emission reduction benefits and oil drive benefits in the carbon market, respectively, both of which can offset part of the costs. The carbon price in the carbon market is taken from the average trading price of the national carbon market in the first half of 2022 [49], and the oil price is derived from the average futures price of West Texas Intermediate (WTI) for the last ten years (2002–2021) [50]. Specific cost parameters are shown in Table 7, and the cost of CCUS can be calculated by Eq. (12).

$$\mathrm{COST}_{\mathrm{ccus}} = \sum_{a=1}^{n} C_a \times Q_a + C_\mathrm{T} \times D + C_\mathrm{F} \times Q - C_{\mathrm{income}}, \quad (12)$$

where C_a (\$/t) represents unit capture cost of CO_2 with a concentration; Q_a (\$/t) represents the capture amount of CO_2 with a concentration; C_T (\$/(t·km)) represents the cost of unit transportation distance; D (km) represents the transportation distance; C_F (\$/t) indicates the unit sealing cost; Q indicates CO_2 storage capacity; and C_{income} represents the generated income, which is the product of carbon price and capture amount under DSF storage, and oil price, oil change rate, and capture amount under EOR storage.

2.4 Scenarios setting

Three scenarios are set based on different CO_2 sources

Table 7 CCUS-related cost parameters

Parameters	Description	Data	Unit	Data source
C_w	Capture cost of process emission source	18.58	\$/t	Ref. [51]
C_b	Capture cost of Boiler emission source	51.30	\$/t	Ref. [46]
C_T	Transportation cost	0.15	\$/(t·km)	Ref. [46]
C_{DSF}	DSF cost	8.92	\$/t	Ref. [46]
C_{EOR}	EOR cost	11.15	\$/t	Ref. [52]
P_{CO_2}	Carbon price	6.68	\$/t	National average carbon price
e	Oil change rate	0.04	t oil/t CO_2	Ref. [53]
P_{oil}	Oil price	459.51	\$/t	Ref. [44]

throughout the CTL process: no capture scenario (S1), process capture scenario (S2), and all capture scenarios (S3). S1 denotes no CO_2 capture, corresponding to the CTL without coupling with CCUS; S2 denotes CO_2 capture from the process CO_2 emissions; and S3 denotes CO_2 capture from both the process and public CO_2 emissions. In this case, pre-combustion capture is utilized to capture process emissions, while post-combustion capture is employed to capture public emissions. In principle, the higher the CO_2 concentration, the easier it is to capture, resulting in a higher capture rate. According to recent studies, the capture rate of process capture in coal chemical projects can reach 90% or even higher [53–55]. Capturing CO_2 from public sources is the same as capturing CO_2 from coal-fired power plants, which has been proved in certain tests to have a capture rate of 90% [54,56]. In addition, the synthetic flue gas capture in both the double-bubbling fluidized bed of Tsinghua University (2019) and the synthetic flue gas capture in the double-bubbling fluidized bed of Southeast University (2012) reached 90%, as did many other world-wide CCUS retrofitted power plants [30]. Given the reality, the capture rate in this study is set at 90%, as indicated in Table 8 [29].

3 Results and discussion

3.1 Comparative analysis of DCL and ICL

A medium coal price (M) and a medium CO_2 transport distance (D2) are chosen in this section for comparing the carbon footprint and LCOL of DCL and ICL under different scenarios. According to Fig. 3, in the S1 scenario, the carbon footprint of ICL is 1.20 times larger than that of DCL, and the LCOL of ICL is 881 \$/t of oil, which is 1.05 times of DCL. As shown in Fig. 3(b), the cost of raw materials is where the two differ most in terms of cost composition. The main reason is that the coal consumption per unit oil of ICL is 0.46 t higher than that of DCL. Obviously, DCL offers more benefits in terms of carbon emissions and costs. In the S2 scenario,

Table 8 CO_2 capture by coal-to-liquid coupled CCUS technology

Capture scenarios	Type	Capture unit	Concentration of CO_2/%	Capture rate
Foundation (S1)	DCL	None	–	–
	ICL	None	–	–
Process capture (S2)	DCL	Low temperature methanol washing	87.6	90
	ICL	Low temperature methanol washing	> 98	90
		F-T synthesis	90	90
		Coal gasification pulverized coal bunker	99	90
		Sulfur recovery	40	90
Full capture (S3)	DCL	Low temperature methanol washing	87.6	90
		Coal-fired boilers	15.1	90
	ICL	Low temperature methanol washing	> 98	90
		Coal gasification pulverized coal bunker	99	90
		F-T synthesis	90	90
		Sulfur recovery	40	90
		Coal-fired boilers	9	90

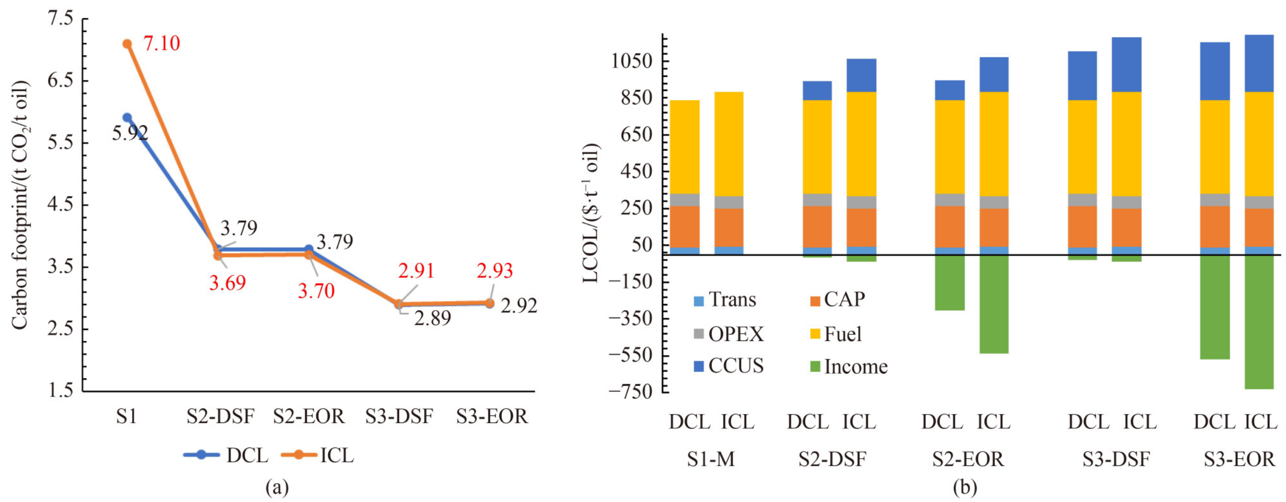

Fig. 3 (a) Carbon footprint and (b) cost of DCL and ICL (Trans representing the cost of coal transportation, CAP representing initial investment cost, OPEX representing operation and maintenance costs, Fuel representing raw material cost, CCUS representing CCUS cost, and Income representing carbon market revenue or oil displacement revenue).

ICL captures more CO_2, resulting in a slightly lower carbon footprint than DCL. As the revenue from DSF storage is insufficient to balance the CCUS cost, the increasing CO_2 capture incurs additional costs. In the S2-DSF scenario, the LCOL of ICL is 1025 $/t of oil, being 1.11 times that of DCL. In contrast to DSF storage, EOR storage means more revenue. In the S2-EOR scenario, the LCOL of ICL is 538 $/t of oil, which is 0.84 times of DCL. More CO_2 is captured from S2 to S3 due to higher CO_2 emissions from DCL than ICL. In S3, the CO_2 emissions/t·oil from ICL are 0.02 t more than those from DCL. In the S3-DSF scenario, the LCOL of ICL is 1141 $/t of oil, which is 1.06 times that of DCL, and the LCOL of ICL in the S3-EOR scenario is 648 $/t of oil, which is 0.86 times that of DCL. At the same time, since the ICL process emissions are greater than DCL and the public emissions are lower than DCL, the average emission reduction cost of the S3 scenario is lower than DCL. In summary, ICL generates more CO_2 emissions than DCL while having no competitive advantage in DSF storage. On the contrary, in the case of EOR storage, more CO_2 capture means a higher revenue, and ICL has more advantages.

To verify the reliability of this study, the results were compared with the study conducted by Zhang et al. [17] with a similar research boundary. The results show that the carbon footprint of DCL and ICL of Zhang are 24.30% and 24.89% higher than that of this study, respectively, because Zhang has considered CH_4 and N_2O emissions according to certain conversion coefficients.

3.2 Results for DCL coupled with the CCUS technology

3.2.1 Carbon footprint of DCL coupled with the CCUS technology

The carbon footprint of the entire DCL process is 5.92 t of CO_2/t·oil in the no capture scenario, of which 0.15 t CO_2 comes from coal mining and washing, 0.07 t CO_2 comes from coal transportation, and 5.7 t CO_2 comes from the coal to oil production process. The 5.7 t CO_2 generated during the coal to liquid production process includes 2.74 t CO_2 of process emissions, 2.37 t CO_2 of public emissions, and 0.59 t CO_2 of other emissions. From the perspective of the entire life cycle, the oil production process has the largest emissions, accounting for 96.33%. In the process capture scenario, as shown in Fig. 4(a), when the CO_2 transportation distance increases from 0 to 250 km, the average carbon emissions generated by CCUS are 0.52 t CO_2. The total process carbon footprint in S2 is 3.79−4.26 t CO_2/t·oil with a decrease of 28.15%−36.01% compared to the S1 scenario. It should be noted that because the EOR storage consumes slightly more energy than DSF, the carbon footprint of the EOR storage is slightly greater than that of DSF. For the “total” column in Fig. 4, the maximum carbon footprint is calculated based on the EOR storage, and the minimum carbon footprint is calculated based on the DSF storage. In the full capture scenario, CCUS emits an averagely 1.59 t of CO_2 emissions in Fig. 4(b), and the entire carbon footprint under the S3 scenario is 2.55−3.41 t CO_2/t·oil, which is 42.29%−56.96% lower than that under the S1 scenario.

3.2.2 Levelized cost of DCL coupled with the CCUS technology

As shown in Fig. 5, the S1 scenario shows that the LCOL of traditional DCL production has increased from 648 to 838 \$/t, and then to 1027 \$/t of oil, as the coal price has changed from low price (L) to middle price (M) to high price (H) (see Table 6 for the low, medium, and high coal prices). When CO_2 transportation distance increases from

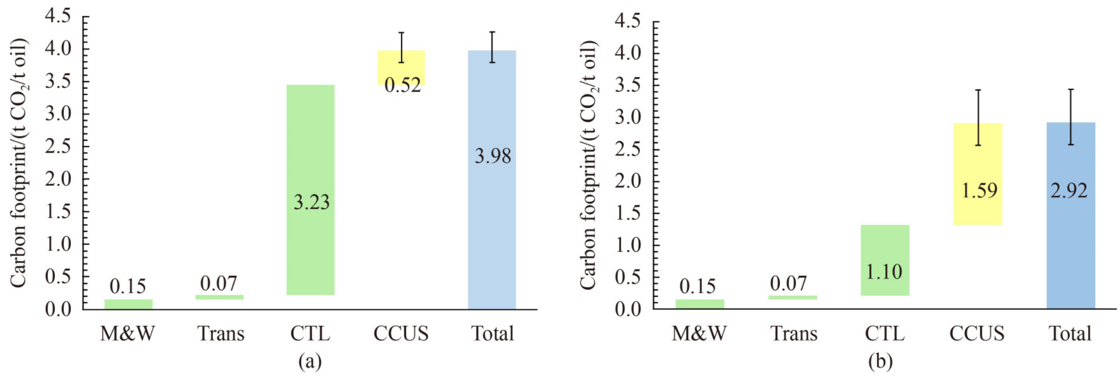

Fig. 4 Carbon footprint of DCL coupled CCUS under (a) S2 and (b) S3 scenarios (M&W representing coal mining and washing process emissions, Trans representing the coal transportation process emissions, and CTL representing coal to oil process emissions).

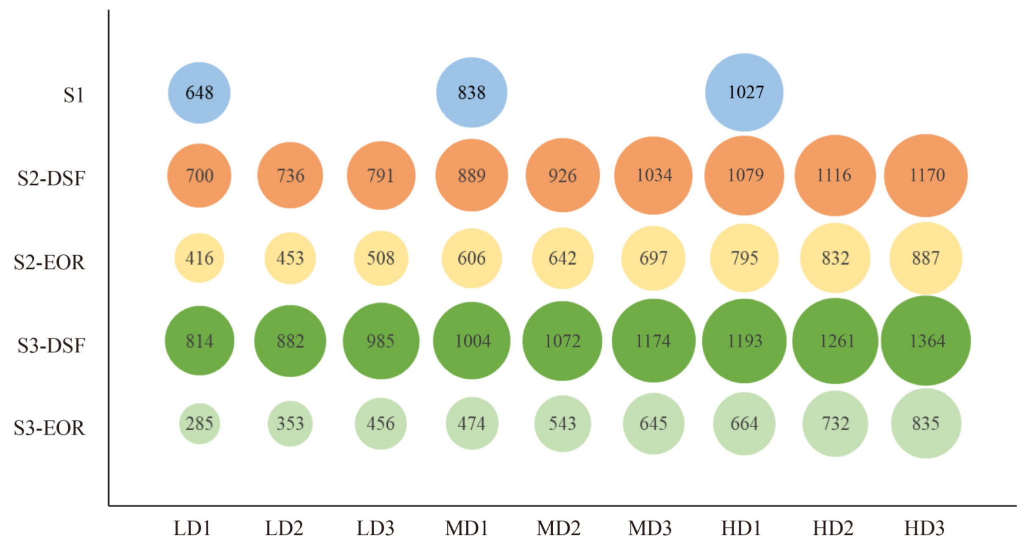

Fig. 5 LCOL of DCL in different conditions (unit: \$/t of oil; L/M/H respectively representing the low/middle/high price of coal, and D1/D2/D3 respectively representing the CO_2 transportation distance of 0/100/250 km).

0 to 100 km and then to 250 km, the LCOLs in the S2-DSF scenario increase by 51, 88, and 143 \$/t of oil, while those in the S2-EOR scenario decrease by 232, 196, and 141 \$/t of oil. Under the S3-DSF scenario, the change of transportation distance increases the LCOL by 165, 234, and 336 \$/t of oil, while under the S3-EOR scenario, the LCOL decreases by 193, 295, and 364 \$/t of oil. It can be found that the highest LCOL is in the S3-DSF scenario and the lowest cost is in the S3-EOR scenario. The results illustrate that the factor that has the greatest impact on cost is the method of sequestration, and the high revenue generated by EOR in any capture conditions cannot only compensate for the cost of CCUS but also partially cover the cost of oil production. In contrast, the certified emission reduction benefits do not offset the high costs of CCUS.

As shown in Fig. 6, first, feedstock cost has the largest proportion in LCOL, and as the coal prices increase from L to H, the feedstock cost (fuel) respectively accounts for an increasingly large proportion of 48.73%, 60.33%, and 67.65% in the S1-L, S1-M, and S1-H scenario. After coupling with CCUS, the feedstock cost still accounts for the largest proportion in LCOL, which varies from 39.94% to 64.44%. Due to the reduction in total costs, the ratio of raw material cost to LCOL ranges from 0.62 to 0.87 in the S2-EOR scenario and from 0.69 to 1.11 in the S3-DSF scenario. The initial investment cost (CAP), which accounts 21.48% to 34.04% in the S1 scenario, is the largest proportion in LCOL in the S3-EOR scenario. In the case of the DSF storage, similar to the cost of raw materials, the proportion of capital cost will decrease due to the increase in total cost caused by the increase in the CCUS cost, while the EOR storage is the contrary. The third largest proportion of LCOL is the cost of CCUS (CCUS), which increases as the CO_2 transportation distance increases. In the S2-DSF scenario, the cost of CCUS increases from 6.27% to 20.13%, and from 16.18% to 25.02% in the S3-DSF scenario. In addition, there are some minor costs for operation (OPEX) and maintenance, and coal transportation (Trans).

3.3 Results for ICL coupled with CCUS technology

3.3.1 Carbon footprint of ICL coupled with the CCUS technology

The carbon footprint of ICL is 7.10 t CO_2/t·oil in the no capture scenario, of which the process of coal mining and washing, coal transportation, and coal to liquid production emits 0.17, 0.07, and 6.86 t CO_2, respectively.

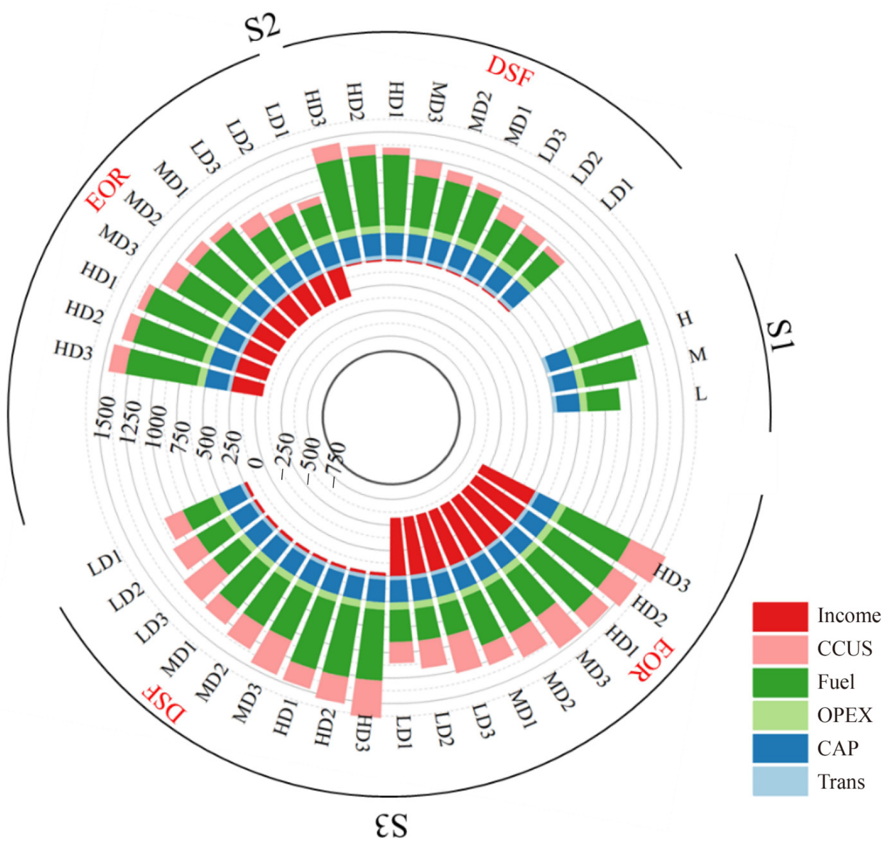

Fig. 6 Cost components of DCL (Trans representing the cost of coal transportation, CAP representing initial investment cost, OPEX representing operation and maintenance costs, Fuel representing raw material cost, CCUS representing CCUS cost, and Income representing carbon market revenue or oil displacement revenue).

4.8 t of process emissions, 1.72 t of public emissions and 0.34 t of other emissions are produced during the oil production. The capture capacity under the S2 scenario is 4.32 t, and that under the S3 scenario is 5.87 t. As is shown in Fig. 7(a), the lifecycle carbon footprint of ICL coupled with the CCUS technology in the S2 scenario is 3.36−4.19 t CO_2/t·oil with a reduction of 41.10%−52.63% compared to the no capture scenario, while the CCUS emission is 0.58−1.41 t CO_2/t·oil. In Fig. 7(b), the lifecycle carbon footprint is 2.47−3.60 t CO_2/t·oil under the S3 scenario with a reduction of 49.29%−65.21% compared to no capture scenario, while the CCUS emission is 1.23−2.36 t CO_2/t·oil.

3.3.2 Levelized cost of ICL coupled with the CCUS technology

Similar to DCL, the storage method has the greatest impact on cost (Fig. 8). At the lowest coal price, the minimum LCOL for the EOR storage is 150 $/t of oil, which is much lower than the oil price. Due to the need to consume more coal per unit of oil produced by ICL, the rise in LCOL caused by the rise in coal prices is more evident. In the S1 scenario, the cost increases by 228 $/t and 412 $/t of oil with the coal price changing from low price (L) to middle price (M) to high price (H) (see Table 6 for the low, medium, and high coal prices), respectively. In the S2-DSF scenario, the transportation distance from 0 to 100 km and then to 250 km increases the LCOL by 80145, and 241 $/t of oil, respectively, while in the S3-DSF scenario, it is 173, 260, and 391 $/t. Due to the change in transportation distance, the LCOL was decreased by 408, 344, and 247 $/t of oil in the S2-EOR scenario, and by 489, 416, and 285 $/t in the S3-EOR scenario.

As shown in Fig. 9, in the S1 scenario, the cost of raw materials accounts for the largest proportion in the LCOL of ICL for 51.47%, 64.01%, and 70.24% in the low, middle, and high coal price, respectively. The second is the initial investment cost accounting for 31.56%, 23.40%, and 19.35%, respectively. In the S2-DSF scenario, the raw material costs also account for the largest proportion, ranging from 37.60% to 65.32% when the coal price changing from the coal price has changed

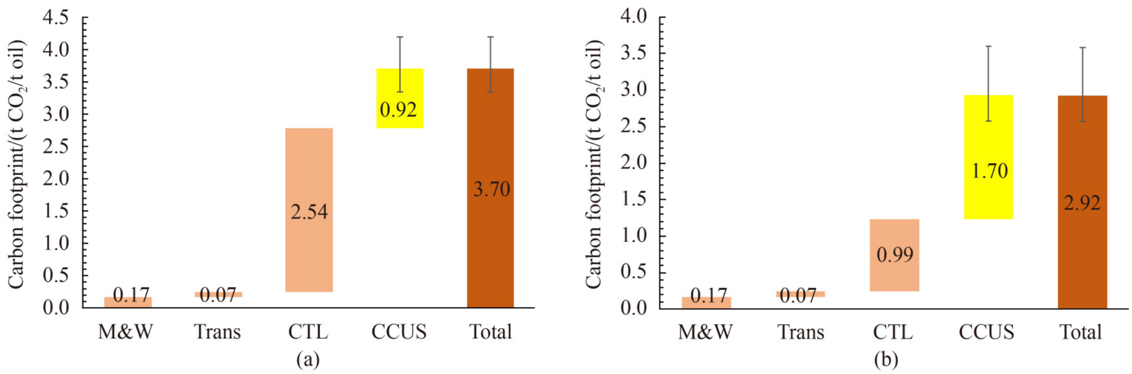

Fig. 7 Carbon footprint of ICL coupled CCUS under (a) S2 and (b) S3 scenarios.

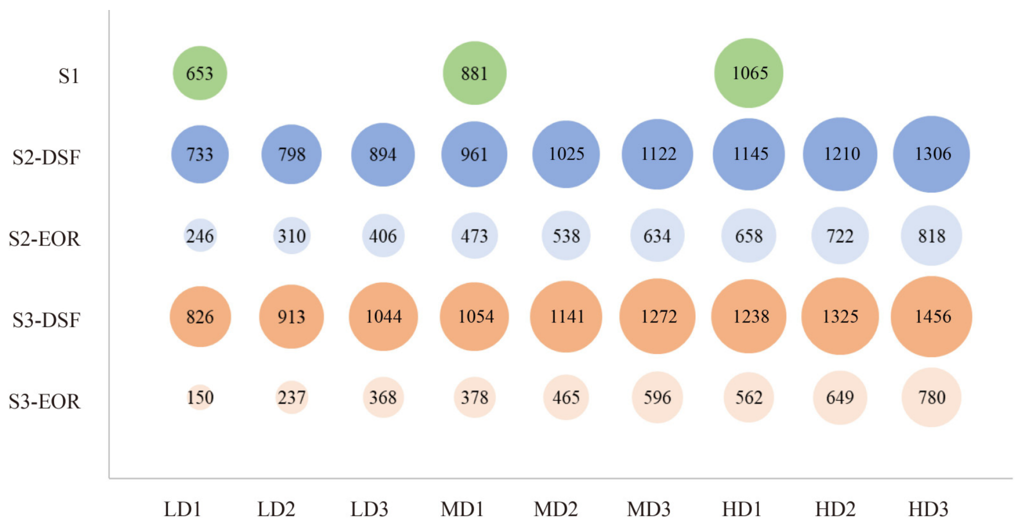

Fig. 8 LCOL of ICL in different conditions (unit: $/t of oil; L/M/H respectively representing the low/middle/high price of coal, and D1/D2/D3 respectively representing the CO_2 transportation distance of 0/100/250 km).

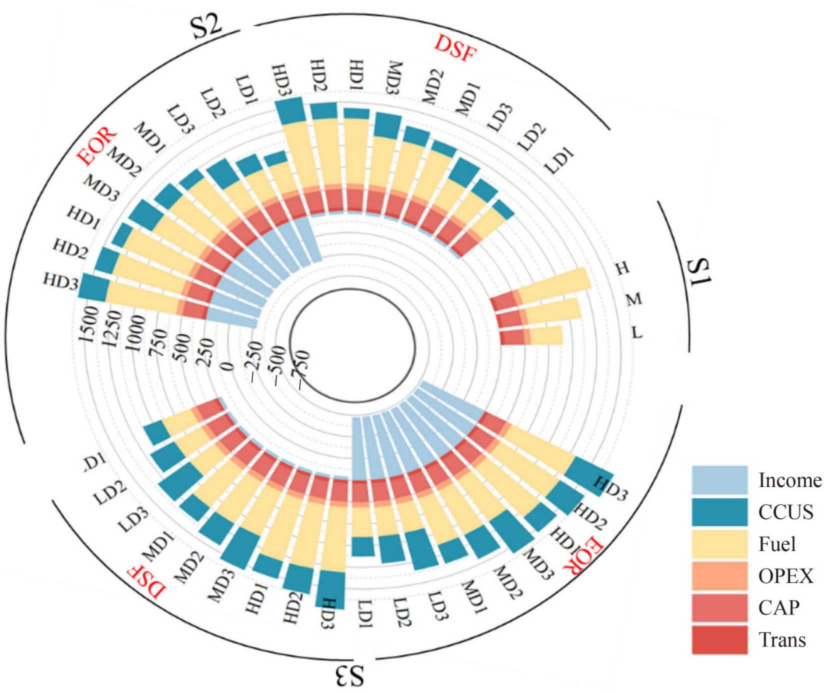

Fig. 9 Cost components of ICL (Trans represents the cost of coal transportation, CAP represents initial investment cost, OPEX represents operation and maintenance costs, Fuel represents raw material cost, CCUS represents CCUS cost, Income represents carbon market revenue or oil displacement revenue).

from low price (L) to high price (H) (see Table 6 for the low, medium and high coal prices) and CO_2 transportation distance changed from 0 to 250 km. The initial investment costs account for 15.78% to 28.11%, and the CCUS costs account for 10.37% to 31.25%, respectively. In the S2-EOR scenario, LCOL significantly decreases due to oil displacement benefits. Therefore, the ratios of various costs to LCOL rapidly increase, such as the ratio of raw material costs to LCOL ranging from 0.83 to 1.36. In the S3-DSF scenario, due to the increase in capture capacity, the increase in the CCUS costs leads to an increase in LCOL. Therefore, the proportion of CCUS costs also increase, from 17.12% to 41.19%. In the S3-EOR scenario, the increase in revenue further reduces LCOL.

3.4 Sensitivity analysis

3.4.1 Sensitivity analysis of carbon footprint to CO_2 transportation distance

The carbon footprint of coal to oil, coal mining and washing, and coal transportation are calculated at the national level, and are relatively stable. The transport distance of CO_2 presents a certain degree of uncertainty, and thus, the carbon footprint of CTL-DSF among different transportation distances are discussed, as shown in Fig. 10.

The actual emission reduction of CCUS is the amount of capture minus the emissions of CCUS itself. The amount of capture is certain in each scenario, but the emissions of CCUS are affected by the amount of capture and the transportation distance. The greater the capture amount or the greater the transportation distance, the more the CCUS emissions. It can be seen that there is more CO_2 captured and the carbon footprint is more sensitive to transportation distance in the S3 scenario. Both the total emissions for the S2 and S3 scenarios of DCL (Fig. 10(a)) and ICL (Fig. 10(b)) contain an intersection point. The DCL intersect is in 544 km, and the ICL intersect is in 761 km. This means that when the CO_2 transportation distance of DCL is greater than 544 km, and the ICL is greater than 761 km, the carbon footprint of the S3 scenario is greater than that of the S2 scenario.

3.4.2 Sensitivity analysis of LCOL to various parameters

As shown in Fig. 11, the most influential factor on the LCOL of DCL and ICL is the coal price, followed by initial investment cost (CAP). When the coal price rises by 10%, the LCOL of DCL and ICL increases by 5.46% and 5.83%, respectively. When the CAP increases by 10%, the LCOL of DCL and ICL increases by 2.38% and 2.04%. The cost of CCUS also has a significant impact on LCOL. Because ICL traps more CO_2, the cost of CCUS is greater, and the impact on total cost is also more significant. Moreover, the impact of carbon prices on LCOL is minimal, with carbon prices increasing by 10%

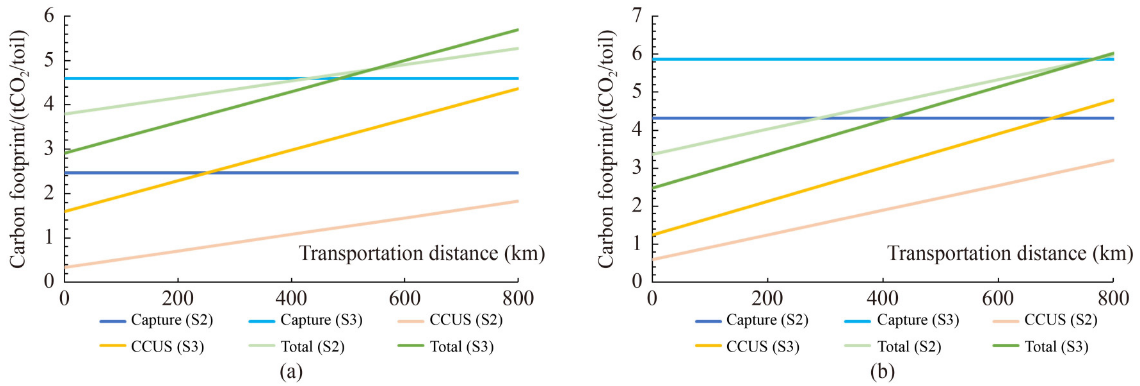

Fig. 10 Sensitivity of carbon footprint to CO_2 transportation distance of CTL.
(a) Sensitivity analysis of DCL; (b) sensitivity analysis of ICL.

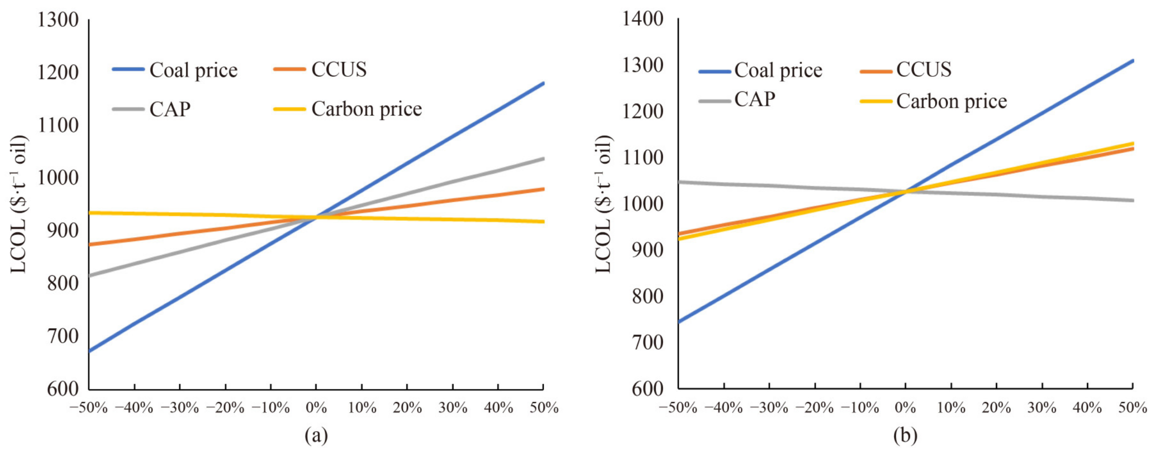

Fig. 11 Sensitivity of LCOL to various factors under the S2 scenario.
(a) Sensitivity analysis of DCL; (b) sensitivity analysis of ICL.

and DCL and ICL, LCOL decreasing by 0.18% and 0.38%. This also indicates that the current carbon price in the carbon market is extremely low and does not provide incentives for enterprises to reduce emissions.

4 Conclusions and policy implications

This study evaluates the carbon footprint and LCOL of the whole life-cycle process of CTL coupled with the CCUS technology in China based on the materials and energy consumption at each stage, with coal mining as the starting point and oil output as the endpoint. Three scenarios, i.e., no capture scenario, process capture scenario, and all capture scenario, are set in accordance with the actual production process of CTL. Three types of coal prices are considered in the light of the fluctuation of coal market price, while the CO_2 transportation distances of 0, 100, and 250 km are set in line with the existing CCUS operation projects. The conclusions of this paper are as follows.

(1) The carbon footprints of DCL and ICL in the no capture scenario are 5.92 t CO_2/t·oil and 7.10 t CO_2/t·oil, respectively. After coupling with CCUS, the carbon footprints of DCL and ICL are 2.55–4.62 t CO_2/t·oil and 2.67–4.19 t CO_2/t·oil. Overall, DCL can achieve an emission reduction of 28.15%–56.96%, and ICL can reach an emission reduction of 41.10%–65.29%.

(2) The LCOL of conventional DCL and ICL are 648–1027 \$/t and 653–1065 \$/t of oil respectively when the price of coal for liquefaction ranges from 68 to 154 \$/t, for gasification ranges from 65 to 147 \$/t, and for thermal power ranges from 59 to 134 \$/t. After coupling with the CCUS technology, LCOL increases as the amount of CO_2 captured, the transportation distance of CO_2, and the price of coal increase. The LCOL of DCL is 700–1364 \$/t of oil, while those of ICL is 733–1456 \$/t of oil in the DSF scenario. The LCOL of DCL is 284–887 \$/t of oil, while those of ICL is 150–818 \$/t of oil in the EOR scenario. The greater the amount of CO_2 captured, the greater the impact of CO_2 transport distance on emission reduction. Therefore, in the case of complete capture, excessive CO_2 transport distance will significantly weaken emission reduction and increase

costs. In addition, coal price is the main influencing factor of the CTL cost, and thus special consideration should be given in making CTL investment decisions by enterprises.

(3) Compared with ICL, DCL has more advantages in terms of emissions and costs, but its requirements for coal quality are not as broad as ICL. After coupling with CCUS, the carbon footprint generated by ICL is close to DCL and the unit capture cost is less than DCL. At the same time, because of more CO_2 capture of ICL, higher CCUS costs are generated in the DSF scenario. Therefore, LCOL is far greater than DCL. On the contrary, in the EOR scenario, the LCOL of ICL is smaller than that of DCL.

Synergistic utilization of coal and other energy sources is the key to low-carbon development in China [53]. Leveraging China's energy advantages, the safe, efficient, clean, and sustainable characteristics of CTL can control the external dependence of oil at a certain level [54] and contribute to the achievement of carbon neutrality. This paper proposes some relevant policy recommendations to promote the development of CTL coupled with CCUS in China. For example, a comprehensive national layout of the CTL industry is extremely necessary from a comprehensive perspective of considering oil consumption and CCUS abatement effectiveness. Meanwhile, the investment in research and development should be increased to reduce CTL costs by promoting technological advances and developing CO_2 utilization pathways. In addition, the national energy sector should encourage the policies such as clean oil price subsidies and coal reduction tax credits.

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Competing interests The authors declare that they have no competing interests.

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