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Carbon Footprint and Economic Analysis of Classic Coal-to-Hydrogen Retrofit Planning with CCUS

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ABSTRACT

As a clean, efficient, and safe new energy carrier, hydrogen is widely utilized in the construction, transportation, and power industries, and it is also one of the critical directions of the world energy transition. China produces about 2/3 of hydrogen through coal-to-hydrogen as the world's largest hydrogen producer and significant consumer. However, "grey hydrogen" generates lots of carbon dioxide (CO_2) emissions through the combustion of fossil fuels. As an effective way to achieve rapid carbon reduction in the future, Carbon Capture, Utilization and Storage (CCUS) technology is regarded by the IEA as a bottom-up technology to achieve carbon neutrality. This study presents a CCUS retrofit planning method based on the classic coal-to-hydrogen process and CCUS technology. Carbon capture devices capture CO_2 through the electricity supplied by the hydrogen power generation unit, the remaining electricity can be sold for revenue; meanwhile, captured CO_2 can be further utilized to profit. The cases discuss the effectiveness and economy of the planning model from the perspectives of full-chain carbon footprint and the levelized cost of hydrogen (LCOH) production. The simulation results show that the LCOH in the proposed retrofit planning method is 9.65￥/kg. Compared with the unretrofitted scenario, the full-chain carbon footprint is reduced by 79.7%, and the LCOH is increased by 36.5%.

Keywords: CCUS, Coal-to-Hydrogen, Retrofit Planning, Carbon Footprint, Economic Analysis

1. INTRODUCTION

As a clean, efficient and safe new energy carrier, hydrogen energy is conducive to reducing the proportion of fossil energy and improving energy utilization. It is an essential approach to cope with climate change and optimize the energy structure. China is rich in coal resources, and coal is its primary raw material for hydrogen production. Currently, nearly 2/3 of hydrogen (about 21 million tons) is produced through coal gasification in China. However, the "grey hydrogen" produced by fossil fuels has the characteristics of high carbon emissions, which seriously restricts the realization of "carbon naturality." Carbon Capture, Utilization and Storage (CCUS) technology is one of the key technologies to achieve efficient and rapid carbon reduction in the future and has been highly valued by countries worldwide, reaching “carbon naturality” will be virtually impossible without CCUS[1].

The development of hydrogen production from fossil fuels and CCUS has gradually attracted attention worldwide. On March 17, 2023, at the 7th International Forum on Carbon Capture, Utilization and Storage, the International Energy Agency (IEA) report " Opportunities for Hydrogen Production with CCUS in China" was released in Beijing [2]. The report pointed out that hydrogen energy and CCUS technology will complement each other and play an important role in the process of China's carbon peaking by 2030 and neutrality by 2060.

2. COAL-TO-HYDROGEN RETROFIT FRAMEWORK

Figure 1 shows the flow chart of the proposed coal-to-hydrogen CCUS retrofit. The first step of classic coal-to-hydrogen production is to generate syngas ($C+H_2O \rightleftharpoons CO+H_2$), and the second step is to react CO with water vapor further to generate more H_2 through shift reaction ($CO+H_2O \rightleftharpoons CO_2+H_2$). Most of the CO_2 emission (66-78%) in the classic coal-to-hydrogen process occurs in the deacidification unit, which has a high purity and can be directly captured before combustion; a small amount of CO_2 emission occurs in the purification unit (22-34%), with relatively low purity and need to be captured by post-combustion capture technology. Therefore, the deacidification and purification units should be equipped with different types of carbon capture devices, respectively.

The captured CO_2 is compressed from a gaseous state to a supercritical state by a compressor and then transported through a pipeline for utilization. Utilization methods are usually divided into four types: geological utilization, chemical utilization, biological utilization and geological storage: geological utilization is often used to

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strengthen the exploitation of resources such as oil, natural gas, geothermal, deep salt water, and uranium ore; chemical utilization is often used to synthesize energy chemicals and high value-added chemicals, etc.; the main products of biological utilization include food, feed, bio-fertilizer, etc.; geological storage refers to the storage of captured CO_2 in the ground or seabed nearby through engineering approaches.

The deacidification unit produces high-purity hydrogen after carbon capture and pressure swing adsorption, which the hydrogen power generation unit uses to produce electricity. In addition to the use of internal carbon capture device, the remaining electricity can be sold to the external grid for revenue.

3. COAL-TO-HYDROGEN RETROFIT MODEL

The section reveals the carbon footprint composition of classic coal-to-hydrogen and its CCUS retrofit, and analyzes the carbon reduction pathways in the process of coal-to-hydrogen from the root. The coal-to-hydrogen CCUS retrofit planning model is also illustrated .

3.1 Carbon Footprint Analysis

The carbon footprint analysis consists of four parts: coal mining and washing, coal transportation, coal hydrogen production, and CO_2 transportation and storage. The upstream CO_2 emissions, such as plant construction and equipment manufacturing, are outside the scope of this study.

The carbon footprint of coal mining and washing is the summation of the carbon emissions of all kinds of consumed energy, and the calculation method is shown in (1). $CF^{m\&w}$ indicates the carbon footprint of the mining and washing process (kg/t), in which γ is the C-CO_2 molecular weight conversion coefficient and its value is 44/12, $D^{m\&w\_i}$ indicates the demand of the ith consumed energy for mining and washing per unit mass coal (kg/t or m^3/t), i =1,...,19 is the serial number of 19 consumed energy categories (see reference [3] for details), LHV^i indicates the low calorific value of the i*th* energy categories (MJ/kg or MJ/m^3), CC^i indicates the carbon content per unit calorific value of the i*th* energy categories (kg/MJ), OF^i indicates the oxidation rate of the i*th* energy categories, $D^{m\&w\_e} / D^{m\&w\_h}$ indicates the electricity/ thermal energy consumed for mining and washing per unit mass coal (kWh·t^{-1}/GJ·t^{-1}), EF^e / EF^h indicates the carbon emission factor of electricity/thermal energy (kg·kWh^{-1}/kg·GJ^{-1}).

$$CF^{m\&w} = \begin{pmatrix} \gamma \sum_{i=1}^{19} D^{m\&w\_i} LHV^i CC^i OF^i + \\ D^{m\&w\_e} EF^e + D^{m\&w\_h} EF^h \end{pmatrix} \tag{1}$$

There are three modes of coal transportation in China: railway, waterway and road transportation. The formula of carbon footprint of coal transportation is shown in (2). Among them, CF^{ct} represents the carbon footprint of coal transportation (kg/t), ω^R , ω^W and ω^H respectively represent the proportions of the three modes in coal transportation, d^R , d^W and d^H represent the distances of the three transportation modes, EF^R , EF^W and EF^H represent the carbon emission factors of the three transportation modes.

$$CF^{ct} = \sum_{j \in \{R,W,H\}} \omega^j d^j EF^j \tag{2}$$

The carbon footprint calculation formula of per unit mass coal in the coal-to-hydrogen process is shown in (3), and the corner mark "1" indicates the energy category index of the raw coal.

$$CF^{cth} = \gamma LHV^1 CC^1 OF^1 \tag{3}$$

After the coal-to-hydrogen CCUS retrofit, the carbon capture device can effectively capture CO2. However, operating carbon capture devices may also consume energy and contribute to carbon emissions. In the retrofit model, the hydrogen power generation unit provides the electricity supplied for the carbon capture devices. Hydrogen does not contain carbon atoms, so electricity generated from hydrogen does not generate any carbon emissions, nor does the operation of the carbon capture devices create a carbon footprint.

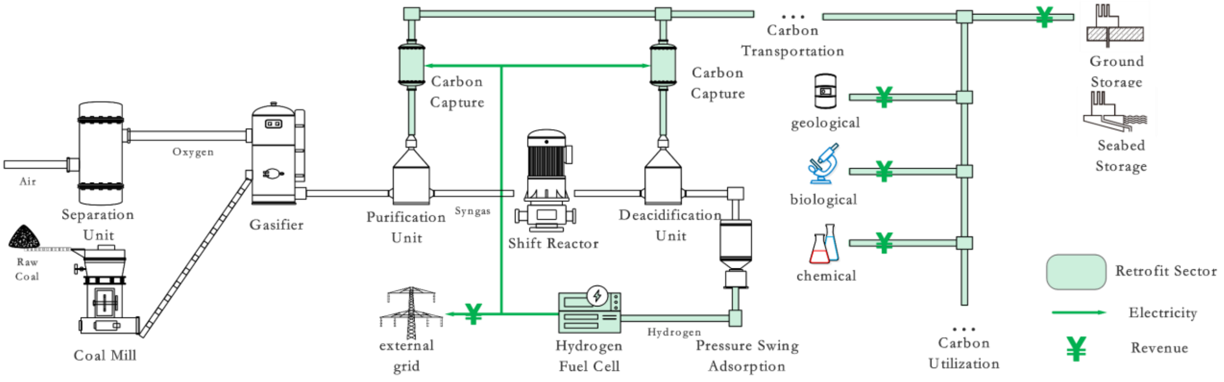


Fig. 1 Flow Chart of Coal-to-Hydrogen Retrofit with CCUS

For captured CO_2, the transportation and storage process mainly consume electricity, and their carbon footprint can be calculated according to formulas (4)-(5). Where CF^{CCUS_ct} / CF^{cs} represents the carbon footprint of CO_2 transportation/storage (kg/t), d^{CCUS_ct} represents the CO_2 transportation distance (km), D^{CCUS_ct} represents the electricity demand for compressing unit CO_2 to transport unit distance ($\mathrm{kWh \cdot t^{-1} \cdot km^{-1}}$), D^{cs} represents the electricity demand (kWh/t) of injecting unit CO_2 into the storage site, η_{cc} indicating the capture efficiency.

$$CF^{CCUS\_ct} = d^{CCUS\_ct} D^{CCUS\_ct} EF_e \eta_{cc} CF^{cth} \tag{4}$$

$$CF^{cs} = D^{cs} EF_e \eta_{cc} CF^{cth} \tag{5}$$

The ratio of carbon emissions in the full-chain coal-to-hydrogen is the unit carbon emissions of producing unit mass hydrogen, and the calculation method is shown in (6). Among them, Q_t^1 represents the mass of raw coal used in the full-chain coal-to-hydrogen at time DUt, LHV^{H_2} represents the average low calorific value of hydrogen (MJ/kg), and η^{cth} represents the efficiency of coal-to-hydrogen. It can be seen from formula (6) that the term Q_t^1 can be eliminated, so the full-chain carbon footprint without retrofit depends on objective factors such as coal-to-hydrogen conversion efficiency.

$$\begin{aligned} CF_{H_2} &= \frac{(CF^{m\&w} + CF^{ct} + CF^{cth}) Q_t^1}{\eta^{cth} \dfrac{LHV^1}{LHV^{H_2}} Q_t^1} \\ &= \frac{CF^{m\&w} + CF^{ct} + CF^{cth}}{\eta^{cth} \dfrac{LHV^1}{LHV^{H_2}}} \end{aligned} \tag{6}$$

After the coal-to-hydrogen CCUS retrofit, the upstream carbon footprint i.e., coal mining, washing and coal transportation will not be affected. Equation (7) represents the full-chain carbon footprint after CCUS retrofit, and the hydrogen production needs to remove the consumption of carbon capture devices.

$$CF_{H_2}^{CCUS} = \frac{\begin{bmatrix} CF^{m\&w} + CF^{ct} + (1-\eta^{cc}) CF^{cth} \\ CF^{CCUS\_ct} + CF^{cs} \end{bmatrix} Q_t^1}{\eta^{cth} \dfrac{LHV^1}{LHV^{H_2}} Q_t^1 - Q_t^{cc\_H_2}} \tag{7}$$

3.2 Economic Analysis

The sources of CO_2 emissions in the coal-to-hydrogen process are different, so the carbon capture devices need to be invested separately. The CO_2 produced by the deacidification unit (Deacidification Unit, DU) has a high purity and can be captured by the pre-combustion capture system; the purification unit (Purification Unit, PU) produces low purity CO_2, which needs to be captured by an amine-based adsorption post-combustion capture system. Formula (8) indicates that the sum of the hourly coal consumption Q_t^1 is the annual coal consumption Q_y^1. Equation (9) represents the real-time carbon emissions of the coal-to-hydrogen process without retrofit. Formulas (10)-(11) indicate that the real-time operation power of the carbon capture device is determined by the captured CO_2 mass (t) and the energy consumption coefficient ω (MWh/t). Generally, the higher the CO_2 concentration, the lower the capture energy consumption coefficient, and the α^{DU} represents the carbon emission ratio of the deacidification unit. Formulas (12)-(13) are the upper and lower limits of the operation power of the carbon capture device. $x_{cc}^{DU} / x_{cc}^{PU}$ is a non-negative integer variable representing the planned carbon capture device capacity (MW) of the DU/PU. This study adopts modular processing, the capacity of a single module is set to 1MW.

$$\sum_{t=1}^{8760} Q_t^1 = Q_y^1 \tag{8}$$

$$Q_t^{CO_2} = CF^{cth} Q_t^1 \tag{9}$$

$$P_t^{DU} = \omega^{DU} \eta^{cc} \alpha^{DU} Q_t^{CO_2} \tag{10}$$

$$P_t^{PU} = \omega^{PU} \eta^{cc} \left(1 - \alpha^{DU}\right) Q_t^{CO_2} \tag{11}$$

$$0 \le P_t^{DU} \le x^{DU} \tag{12}$$

$$0 \le P_t^{PU} \le x^{PU} \tag{13}$$

Till now hydrogen power generation device is mainly based on hydrogen fuel cell (HFC). Equation (14) is the power supply balance equation of hydrogen power generation units. Equation (15) is the energy conversion equation of HFC, indicating that hydrogen electricity is obtained from raw coal through two energy conversion processes (coal-to-hydrogen and hydrogen power generation), and η_{HFC} is the conversion efficiency of HFC. Equation (16) is the energy conversion equation between the electricity consumption of the carbon capture unit and its corresponding hydrogen consumption $Q_t^{cc\_H_2}$. Equation (17) guarantees that the operation power of HFC will never exceed the planned capacity (MW) and is a non-negative integer variable. Similar to carbon capture devices, it also adopts modular processing.

$$P_t^{HFC} = P_t^{DU} + P_t^{PU} + P_t^{grid} \tag{14}$$

$$P_t^{HFC} = \eta^{HFC} \eta^{cth} LHV^1 Q_t^1 \tag{15}$$

$$P_t^{DU} + P_t^{PU} = \eta^{HFC} LHV^{H_2} Q_t^{cc\_H_2} \tag{16}$$

$$0 \le P_t^{HFC} \le x^{HFC} \tag{17}$$

The revenue from coal-to-hydrogen CCUS retrofit includes electricity and carbon revenue. Formula (18) is the electricity revenue of surplus electricity after internal use, in which Pr^e is the electricity price (￥/MWh). Although CO_2 is utilized differently, the revenue can be processed according to formula (19), Pr^c the revenue of per unit mass CO_2 (￥/t). Although geological storage has no direct benefits, the saved carbon allowances can be sold in the carbon market in the form of carbon prices.

$$\mathrm{REV}^e = Pr^e \sum_{t=1}^{8760} P_t^{grid} \tag{18}$$

$$\mathrm{REV}^c = Pr^c \sum_{t=1}^{8760} \eta^{\mathrm{cc}} Q_t^{CO_2} \tag{19}$$

3.3 Objective function

The objective function of economic analysis is to minimize the levelized cost of hydrogen production (LCOH). The total cost comprises the CCUS Retrofit Sector Expenditure (RSE) and Original Sector Expenditure (OSE). OSE (21) is the product of the unretrofitted levelized cost of hydrogen production LCOH^* and the unretrofitted annual hydrogen production. RSE (22) includes investment cost (Capital Expenditure, CAPEX) and operation cost (OPEX). CAPEX (23) represents the annualized investment costs of each device, dr is the annual interest rate, L^k is the life cycle of device *k*, *k* Indicates the planned device type. OPEX (24) include annual CO_2 capture costs, CO_2 compression transportation costs and comprehensive benefits. c^k is the unit investment cost of device k (￥/MW), λ^{DU} / λ^{PU} is the unit operation and maintenance cost of the DU/PU carbon capture device (￥/MWh), and λ^{ct} is the unit compression transportation cost of CO_2 ($￥\cdot t^{-1} \cdot km^{-1}$). THT is the annual hydrogen production after removing the hydrogen consumed by the carbon capture sector (25).

$$\min \quad \mathrm{LCOH} = \frac{\mathrm{OSE+RSE}}{\mathrm{THT}} \tag{20}$$

$$\mathrm{OSE} = \mathrm{LCOH}^* \cdot \eta^{cth} \frac{LHV^1}{LHV^{H_2}} D^{cth-1} \tag{21}$$

$$\mathrm{RSE} = \mathrm{CAPEX+OPEX} \tag{22}$$

$$\mathrm{CAPEX} = \sum_{k \in \{DU,PU,HFC\}} \frac{dr((1+dr)^{L^k})}{(1+dr)^{L^k}-1} c^k x^k \tag{23}$$

$$\mathrm{OPEX} = \left(\begin{array}{l} \lambda^{DU} \sum_{t=1}^{8760} P_t^{DU} + \lambda^{PU} \sum_{t=1}^{8760} P_t^{PU} \\ + d^{CCUS\_ct} \sum_{t=1}^{8760} \lambda^{ct} \eta^{cc} Q_t^{CO_2} \\ - \mathrm{REV}^c - \mathrm{REV}^e \end{array} \right) \tag{24}$$

$$\mathrm{THT} = \sum_{t=1}^{8760} \left(\eta^{cth} \frac{LHV^1}{LHV^{H_2}} Q_t^1 - Q_t^{cc\_H_2} \right) \tag{25}$$

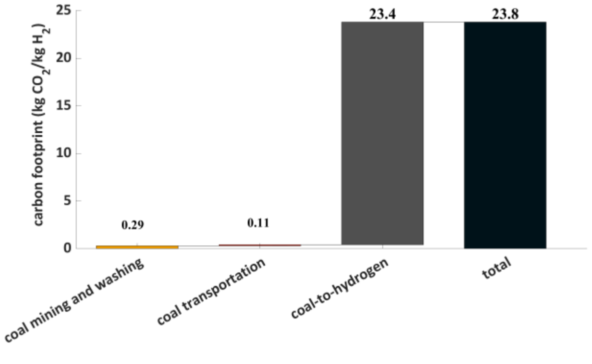
4. CASE STUDIES

In terms of economic analysis, the coal-to-hydrogen plant adopts the appendix case data of the IEA report [2], the annual coal consumption is 180,000 tons, and the conversion efficiency of coal-to-hydrogen is assumed to be 55%.

The proportion of CO_2 produced by the DU is assumed to be 66%, which is captured by the pre-combustion capture system; the unit investment cost is 246\$/kW, the unit operation cost is 1.6\$/MWh, and the capture energy consumption coefficient is 0.21MWh/t. The proportion of CO_2 produced by the PU is assumed to be 34%, which is captured by the amine-based adsorption post-combustion capture system; the unit investment cost is 218\$/kW, the unit operation cost is 2.4\$/MWh, and the capture energy consumption coefficient is 0.269MWh/t. The investment cost of HFC is assumed to be 4000￥/kW. The compression and transportation cost of CO_2 is 0.8 yuan/t • km. The electricity price adopts the 110 kV industrial electricity price in Ningxia, China, and the unit carbon revenue adopts 60￥/t. The case studies are simulated based on MATLAB R2022a and solved by IBM CPLEX 12.10.0.

4.1 Carbon Footprint Analysis

While CCUS retrofit is not considered, from the perspective of covering coal mining and washing (1), coal transportation (2), and coal-to-hydrogen (3), the full-chain carbon footprint of the coal-to-hydrogen technology (6) decreases with the conversion efficiency of coal-to-hydrogen (45%-70%) increases, about 18.70-29.09kg CO_2/kg H_2, i.e., producing 1kg of hydrogen emits 18.70-29.09kg CO_2, which is consistent with the IEA's conclusion. When the coal-to-hydrogen conversion efficiency is 55%, the carbon footprints of coal mining and washing, coal transportation, and coal-to-hydrogen links (unit: kg CO_2/kg H_2) are 0.29, 0.11, and 23.40, accounting for 1.23%, 1.44%, 97.42%, respectively. Figure 2 shows the full-chain carbon footprint and its formulation of coal-to-hydrogen production. It can be seen from Figure 2 that carbon emissions in the coal-to-hydrogen process account for the highest proportion, reaching more than 98%, which shows the importance and urgency of the retrofit of coal-to-hydrogen CCUS.



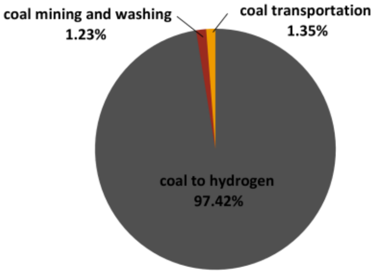
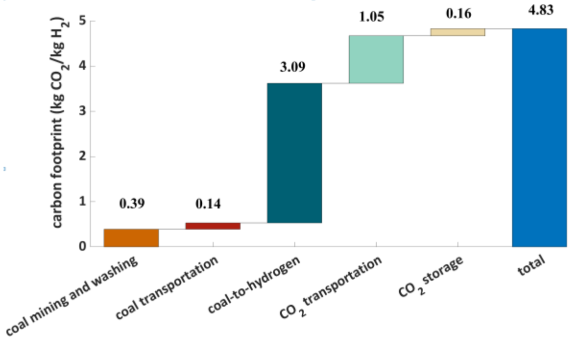


Fig. 2 Carbon Footprint and Its Formulation of the Full-Chain Coal-to-Hydrogen

While considering the coal-to-hydrogen CCUS retrofit, the full-chain carbon footprint covers coal mining and washing (1), coal transportation (2), coal-to-hydrogen (3), CO_2 transportation (4), and CO_2 storage (5). From (7), (9), (10), (11), and (16), it can be obtained that the full-chain carbon footprint of coal-to-hydrogen CCUS retrofit can be simplified into the following form.

$$CF_{H_2}^{CCUS}=\frac{CF^{m\&w}+CF^{ct}+(1-\eta^{cc})CF^{cth}+CF^{CCUS\_ct}+CF^{cs}}{\dfrac{\eta^{cth}LHV^{1}}{LHV^{H_2}}-\dfrac{\left[\omega^{DU}\alpha^{DU}+\omega^{PU}\left(1-\alpha^{DU}\right)\right]\eta^{cc}CF^{cth}}{\eta^{HFC}LHV^{H_2}}} \tag{26}$$

Assuming that the CO_2 transportation distance is 50km, the full-chain carbon footprint after the coal-to-hydrogen CCUS retrofit will fluctuate with the conversion efficiency (45%-70%), about 3.55~6.37 kg CO_2/kg H_2. The carbon footprints (unit: kg CO_2/kg H_2) of coal mining and washing, coal transportation, coal hydrogen production, CO_2 transportation, and CO_2 storage are 0.39, 0.14, 3.09, 1.05, and 0.16, accounting for 8.05%, 2.91% , 63.94%, 21.73%, and 3.34%, respectively. Figure 3 is the full-chain carbon footprint and its formulation after the coal-to-hydrogen CCUS retrofit. It can be seen from Figure 3 that compared with the unretrofitted state, the carbon footprint is only 20.29% of the original, and the carbon footprint and its proportion in the coal-to-hydrogen link decreased significantly (98% → 64%), followed by CO_2 transportation, coal mining and washing, which shows the effectiveness of CCUS retrofit.



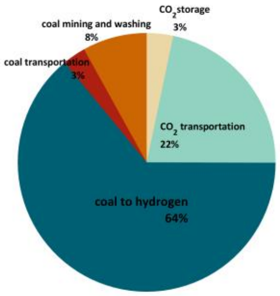


Fig. 3 Full-Chain Carbon Footprint and Its Formulation of the Coal-to-Hydrogen Retrofit with CCUS

4.2 Economic Analysis

This section analyzes the economics of the coal-to-hydrogen CCUS retrofit planning model in four different scenarios, as follows:

Scenario ①: Coal-to-hydrogen without retrofit

Scenario ② : Coal-to-hydrogen CCUS retrofit plan without considering benefits

Scenario ③ : Coal-to-hydrogen CCUS retrofit plan considering carbon benefits

Scenario ④ : Coal-to-hydrogen CCUS retrofit plan considering electricity revenue

Tab.1 Planning Results of Coal-to-Hydrogen Retrofit Planning with CCUS in Different Scenarios

Planning Result		①	②	③	④
Capacity (MW)	Pre-Combustion Capture	-	4.83	4.83	4.83
	Post-Combustion Capture	-	3.18	3.18	3.18
	HFC	-	32.81	32.81	98.45
Investment Cost (×10⁴￥)	Pre-Combustion Capture		47.89	47.89	47.89
	Post-Combustion Capture		35.66	35.66	35.66
	HFC		853.9	853.9	2561
O&M Cost (×10⁴￥)	Pre-Combustion Capture	-	70.99	70.99	70.99
	Post-Combustion Capture	-	31.23	31.23	31.23
	CO_2 Transportation	-	1219	1219	1219
	Carbon Revenue	-	-	1829	1829
	Electricity Revenue	-	-	-	13455
LCOH(￥/kg)		7 [2]	11.32	9.65	-0.93

Table 1 compares the planning results in different scenarios. It can be seen from the table that the carbon capture device planning and O&M results in different scenarios are consistent. This is because once the annual coal consumption of a coal-to-hydrogen plant is determined, its total annual carbon emissions are also determined; since the carbon capture device captures 90% of carbon emissions, the amount of captured, utilized, transported CO_2 and O&M cost are also determined accordingly.

If the benefits are not considered, taking the unretrofitted LCOH is 7￥/kg H_2 as the benchmark, it can be seen from the comparison of ① and ② that the LCOH after the coal-to-hydrogen CCUS retrofit is 11.32

￥/kg H_2, and the cost of producing 1kg H_2 An increase of 4.32 yuan (61.7%). In terms of carbon footprint, the production of 1 kg of H_2 reduces 18.96 kg of CO_2 emissions (23.8 kg→4.83 kg), and the CO_2 avoided cost is 227.72 ¥/t CO_2.

If carbon revenue is taken into account, it can be seen from the comparison of ① and ③ that the retrofitted LCOH is 9.65 ￥/kg H_2, and the cost of producing 1 kg of H_2, increasing 2.65 yuan (29.44%), and the CO_2 avoided cost is 139.69 ￥/t CO_2. Suppose electricity revenue is further taken into account. In that case, the planned capacity of the hydrogen power system will be tripled (98.45/32.81). The LCOH will be -0.93￥/kg H_2, which means that after the retrofit of the coal-to-hydrogen CCUS, in the case of using hydrogen fuel cells to supply energy and selling the remaining hydrogen electricity, profits can be realized while covering the cost of hydrogen production.

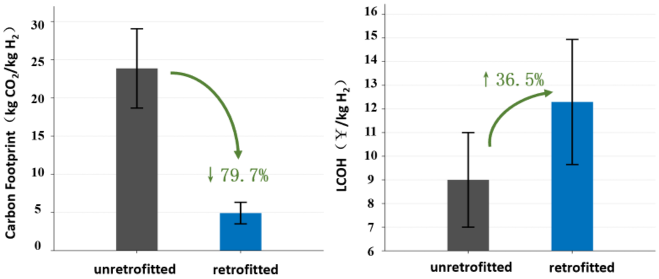


Fig. 4 Comparison chart of carbon footprint and economic analysis of Coal-to-Hydrogen Retrofit with CCUS

Figure 4 compares the carbon footprint and the economics of the coal-to-hydrogen CCUS retrofit. The full-chain carbon footprint has been reduced from 18.70-29.09kg CO_2/kg H_2 before retrofit to 3.55-6.37kg CO_2/kg H_2, and the carbon reduction rate has reached 79.7%. Compared with the LCOH range of 7~11￥/kg H_2 in the unretrofitted state, the LCOH considering carbon benefits is 9.65~14.94￥/kg H_2, increasing about 36.5%.

5. CONCLUSIONS

In this paper, a CCUS retrofit planning is carried out for the coal-to-hydrogen process, the full-chain carbon footprint is systematically analyzed, and the impact of the retrofit of each process is pointed out, with the optimization goal of minimizing the levelized hydrogen production cost, different scenarios are designed to verify the effectiveness of the planning model.

The simulation results show that compared with the unretrofitted scenario, the full-chain carbon footprint is only 20.29% of the original, and the levelized cost of hydrogen production, including carbon benefits after the retrofit increases by about 36.5%; the cost of producing hydrogen is negative after considering the hydrogen electricity revenue.

The research results can provide a technical basis for the low-carbon retrofit of China's coal-to-hydrogen industry, thereby helping to accelerate the implementation of demonstration projects and the realization of carbon neutrality goals. Future work will combine the actual road network, coal mines and coal-to-hydrogen plant geographical information and analyze regional and even nationwide coal-to-hydrogen CCUS retrofit costs and emission reduction potentials according to local conditions.

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