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Carbon emission and economic analysis of hydrogen integrated energy system for carbon neutrality

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ABSTRACT

The application of integrated energy system can effectively realize the complementary advantages of various energy sources, better meet the various load demands of users, and improve the energy utilization rate. With the aim of carbon neutralization and the development of hydrogen gas turbine technology, considering the low carbon characteristics of hydrogen fuel and renewable energy hydrogen production technology's advantage, it is significant for the integrated energy system develops towards using low carbon emission fuel like hydrogen to achieve the goal of carbon neutralization. In this paper, we construct an integrated energy system considering multiple types of energy sources, and build the system performance analysis model to analyze the impact of different combinations of renewable energy input directly to the power grid and conversion to hydrogen on system operating costs and carbon emissions. The result shows that determining an appropriate ratio of renewable energy input directly to the system internal power grid and conversion to hydrogen by the system operating conditions will help the system to achieve carbon neutrality with maximum emission reduction capability, while paying a small cost.

Keywords: hydrogen integrated energy system; carbon neutralization; renewable energy hydrogen production; carbon capture and utilization technology; operation analysis

NONMENCLATURE

Abbreviations	
CCHP	Combined cooling, heating and power system
CCUS	Carbon capture, utilization and storage
CTH	Coal to hydrogen
GTH	Natural gas to hydrogen
IES	Integrated energy system
IBH	Industrial by-product hydrogen
PTH	Electric to hydrogen
RTH	Renewable energy to hydrogen
EES	Electrical energy storage
TES	Thermal energy storage
CES	Cold energy storage
Symbols	
L_{lbr}	The capacity of lithium bromide refrigerator
L_{ec}、P_{ec}	The cooling capacity and input power of electric chiller
L_c、L_d	The charging and discharging power of cold storage equipment
L_{load}、H_{load}、E_{load}	The cold, heat and electricity load
H_{hrb}	The heating power of heat recovery boiler
H_{eb}、P_{eb}	The heating power and input power of electric boiler
H_c、H_d	The charging and discharging power of heat storage equipment
H_{ccus}、P_{ccus}	The input thermal power and electrical power of CCUS
P_{epg}	The external power grid input
E_c、E_d	The charging and discharging power of electric storage equipment
P_{pv}、P_{wt}	The photovoltaic power and wind power input

1. INTRODUCTION

For sustainable development, China has proposed " the 14th Five-Year Plan" to achieve carbon neutrality by 2060. Carbon neutrality means that the CO_2 emissions is equal to the amount treated by absorption, storage and other technical in a given period of time [1].

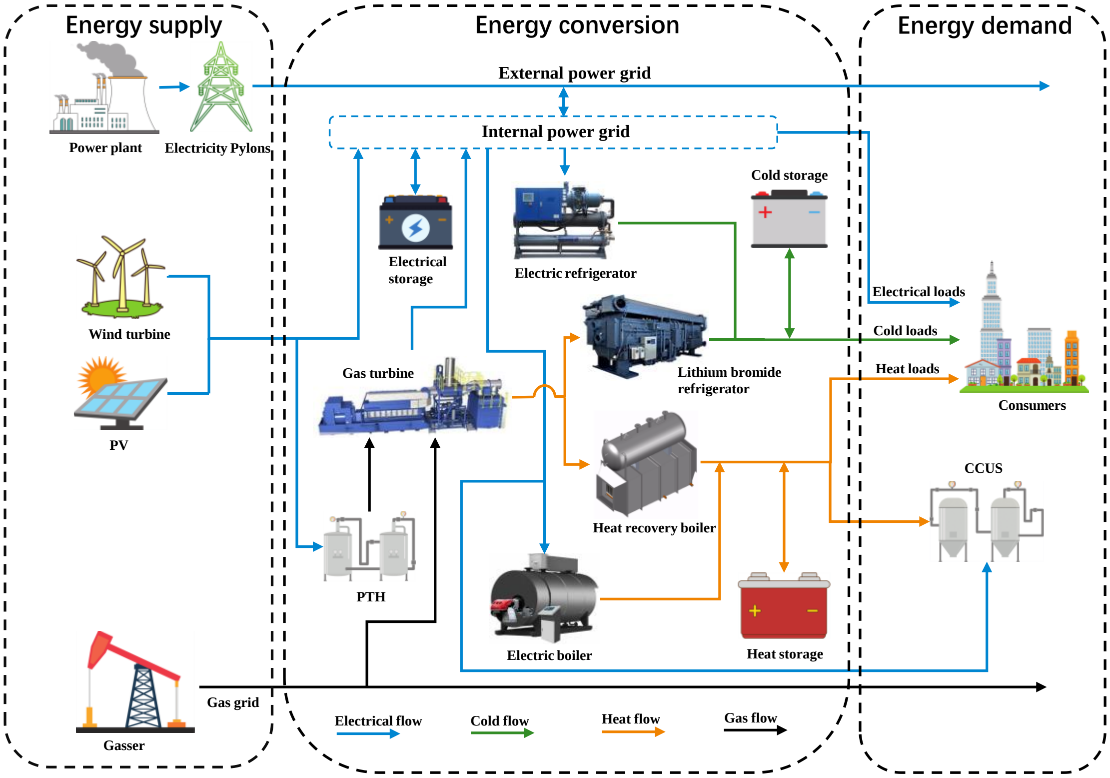

Fig. 1. Schematic diagram of the carbon neutral energy systems

Integrated energy system (IES) is a multi-energy complementary clean and efficient operation system. It is composed of a variety of energy supply equipment, constraints of energy conversion and energy storage equipment. It is an effective way to reduce the ratio of traditional thermal power supply in energy consumption and carbon emissions by incorporating photovoltaic, wind power and other renewable energy generation technologies into the IES [2,3]. In recent years, hydrogen has been recognized as an important clean fuel to achieve carbon neutrality [4]. It can be mixed with other fuels such as natural gas and biogas to enrich its application in various power generation systems. For a gas turbine using mixture fuel of hydrogen and natural gas, its operation CO_2 emissions will be reduced [5,6]. Using hydrogen and natural gas mix fuel in integrated energy systems is an important trend towards achieving carbon neutrality. Considering the carbon emission and cost of different hydrogen production processes, as well as the cost of hydrogen storage and transportation, it is a reasonable solution to reduce the cost and carbon emission by using renewable energy sources located near to the system to produce hydrogen [7,8]. Locating RTH equipment nearby the system energy utilization equipment can reduce the limiting effect of gas pipeline on hydrogen transportation [9]. Otherwise, in order to achieve carbon neutrality, CCUS technology also needs to play an important guarantee role [10].

Most of the previous studies have focused on distributed renewable energy directly connected to the power grid, and converting electricity to natural gas with carbon capture technology [11,12]. Under the carbon neutrality, there are few studies considering the impact of power distribution between distributed renewable power generation and hydrogen production on the operating costs and carbon emissions of IES using hydrogen and natural gas mixtures.

In this paper, we construct an integrated energy system considering multiple types of energy sources, and build the system performance analysis model, taking the minimum daily operating cost as the objective function, considering various load balance constraints, equipment operation constraints and carbon neutralization constraints. This mathematical model is designed based on Yalmip toolbox of MATLAB applying Cplex business planning software to solve it.

2. METHODOLOGY

2.1. Mathematical model of IES components

- CCHP system

CCHP system is generally composed of gas turbine, lithium bromide refrigerator and heat recovery boiler equipment, which can respectively supply electricity, cold and heat energy. Generally, the power generation efficiency of micro gas turbine is only about 30%, while the energy utilization efficiency can reach more than 70%

by using heat recovery boiler and lithium bromide refrigerator for energy cascade utilization of gas turbine waste heat flue gas. The energy conversion relationship in the CCHP system is calculated as follows:

$$P_{gt}(t) = [P_{egn}(t) + P_{h2}(t)] \cdot \eta_{gt}^{e} \quad (1)$$

$$H_{gt}(t) = \frac{P_{gt}(t)\cdot(1-\eta_{gt}^{e}-\eta_{gt}^{w})}{\eta_{gt}^{e}} \quad (2)$$

$$H_{hrb}(t) = H_{hrb}^{gt}(t) \cdot \eta_{hrb} \quad (3)$$

$$L_{lbr}(t) = \left[H_{gt}(t) - H_{hrb}^{gt}(t)\right] \cdot COP_{lbr} \quad (4)$$

where t refers to any hour in 24 hours, P_{gt} refers to the electricity generated by the gas turbine, P_{egn} refers to the natural gas energy consumed by the gas turbine, P_{h2} refers to the hydrogen energy consumed by the gas turbine, η_{gt}^{e} is the power generation efficiency of gas turbine, H_{gt} refers to the gas turbine exhaust gas waste heat, η_{gt}^{w} is the heat loss power of gas turbine, H_{hrb} refers to the heat generated by the heat recovery boiler, H_{hrb}^{gt} refers to the natural gas energy consumed by the heat recovery boiler, H_{hrb}^{gt} refers to the exhaust gas waste heat energy consumed by the heat recovery boiler, η_{hrb} is the heating coefficient of the heat recovery boiler, L_{lbr} refers to the cold produced by the lithium bromide refrigerator, COP_{lbr} is the refrigerating efficiency of the lithium bromide refrigerator.

- The electric boiler

Electric heating boiler is a heating device used to convert electric energy into heat energy, which has the advantages of pollution-free heat production process, convenient installation and high thermal efficiency. Electric heating boiler can realize thermoelectric decoupling of cogeneration unit and meet the residential heat load. The heat supply is calculated as follows:

$$H_{eb}(t) = P_{eb}(t) \cdot \eta_{eb} \quad (5)$$

where H_{eb} refers to the heat generated by the electric boiler, and P_{eb} refers to the electric energy consumed by the electric boiler, η_{eb} is the heating coefficient of the electric boiler.

- The electric chiller

The electric chiller has higher energy efficiency than the lithium bromide refrigerator. Under using the combination of electric chiller and lithium bromide refrigerator in IES, the output thermoelectric ratio of the CCHP system can be adjusted in a certain range.

$$L_{ec}(t) = P_{ec}(t) \cdot COP_{ec} \quad (6)$$

where L_{ec} refers to the cold produced by the electric chiller, P_{ec} refers to the electric energy consumed by the electric chiller, COP_{ec} is the refrigerating efficiency of the electric chiller.

- The PTH equipment

There are approximately three types of water electrolysis: alkaline water electrolysis (AWE), polymer electrolyte membrane electrolysis (PEM), and solid oxide electrolysis (SOE). The PEM electrolysis has many advantages, such as small size and lightweight, no lye corrosion [13]. This method has an electrolytic efficiency of 70-90% and can operate at 0-100% of its rated power. The hydrogen production is calculated as follows:

$$P_{h2}(t) = \alpha \cdot [P_{pv}(t) + P_{wt}(t)] \cdot \eta_{pth} \quad (7)$$

$$M_{h2}(t) = P_{h2}(t)/Q_{h2} \quad (8)$$

where P_{h2} refers to the hydrogen production power of PTH device, α is the proportion of renewable energy generation used to produce hydrogen, P_{pv} refers to the electricity generated by the photovoltaic module, P_{wt} refers to the electricity generated by the wind power module, η_{pth} is the hydrogen production efficiency,M_{h2} is the amount of hydrogen produced by the PTH device, Q_{h2} is the calorific value of hydrogen.

- The CCUS equipment

CCUS technology is a new trend in the development of Carbon Capture and Storage technology (CCS). CCUS system will consume a certain amount of electric energy and heat energy in the operation process, among which carbon capture process is the most part of energy consumption in the whole process. The carbon capture energy consumption is calculated as follow:

$$M_{CCUS}(t) = \frac{P_{egn}(t)}{Q_{ch4}} \cdot \beta - P_{gt}(t) \cdot \varepsilon_{gas} + P_{epn}(t) \cdot (\varepsilon_h - \varepsilon_l) \quad (9)$$

$$P_{ccus}(t) = M_{ccus}(t) \cdot P_{ccus-unit} \quad (10)$$

$$H_{ccus}(t) = M_{ccus}(t) \cdot H_{ccus-unit} \quad (11)$$

where M_{CCUS} refers to the amount of carbon capture system, Q_{ch4} is the calorific value of natural gas, β is the amount of CO_2 of per kilogram natural gas combustion, ε_{gas} is the amount of CO_2 of per kilowatt hour gas power generation in 2060,ε_h is the amount of CO_2 of per kilowatt hour electricity in 2019, ε_l is the amount of CO_2 of per kilowatt hour electricity in 2060, P_{CCUS} refers to the electric energy consumed by the CCUS device, $P_{ccus-unit}$ power consumption to capture one kilogram of CO_2, H_{CCUS} refers to the heat energy consumed by the CCUS device, $H_{ccus-unit}$ heat consumption to capture one kilogram of CO_2.

- The energy storage equipment

The continuous development of energy storage technology can play an increasingly good effect in load shifting of energy using, and has a good application prospect in the IES. Storage battery usually use the state of charge (SOC) to express energy storage state, which is the ratio of the battery's actual capacity to its rated capacity. The mathematical models of cold and thermal energy storage device can be established by analogy with the mathematical model of storage battery. Their mathematical models are established as follows:

$$SOC_i(t) = (1 - \varepsilon_i) \cdot SOC_i(t-1)$$

$$+\left(\frac{P_i^c\cdot\eta_i^c}{E_i^r}-\frac{P_i^d}{E_i^r\cdot\eta_i^d}\right)\cdot\Delta t \qquad (12)$$

where SOC_i refers to the energy storage states of each energy storage device, ε_i is the energy storage loss efficiency, P_i^c is the energy storage power, η_i^c is the efficiency of energy storage, E_i^r is the rated capacity of energy storage device, P_i^d is the energy discharge power, which is the same value as P_i^c, η_i^d is the discharge efficiency of energy storage equipment, which is the same value as η_i^c.

2.2. IES design and the optimization object

A typical industrial park in Shanghai is taken as the research object in this paper and the design of IES for this industrial park is shown in Fig.1. The situation of local renewable energy output power and various energy usage load in the park showing in Fig.2. In this example, the system operation period is set to 24h, and the unit operation time is 1h.

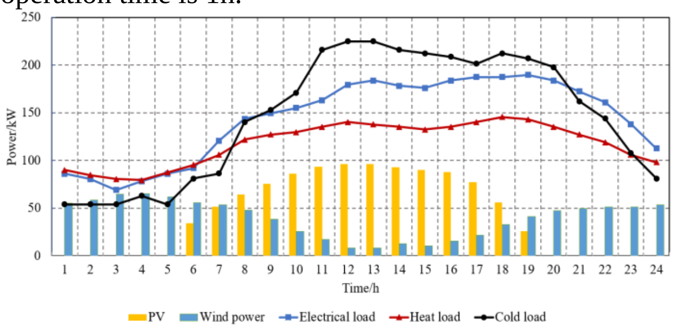

Fig.2. Energy usage load and renewable energy output in IES

2.3. Objective function

In this paper, the IES mainly studies considering hydrogen utilization and CCUS technology to achieve carbon neutrality at a small cost, so the mathematical model of the system takes the minimum daily operating cost C_{all} as the objective function. The system daily operation cost includes three parts: the interaction cost with the external power supply network C_{net}, the initial investment cost of equipment C_{set} and the operation and maintenance cost of C_{run} equipment.

$$C_{all}=C_{net}+C_{set}+C_{run} \qquad (13)$$

$$C_{net}=\sum_{t=1}^{24}\left[P_{epg}(t)\cdot C_e+P_{egn}(t)\cdot C_g-P_{sell}(t)\cdot C_e^{sell}\right] \qquad (14)$$

$$C_{set}=\sum\frac{R_i\cdot C_i^{set}}{8760}\cdot\frac{r\cdot(1+r)^{n_i}}{(1+r)^{n_i}-1} \qquad (15)$$

$$C_{run}=\sum_{t=1}^{24}P_i(t)\cdot C_i^{op}+\sum N_j\cdot C_j^{st} \qquad (16)$$

where P_{epg} refers to the amount of the internal grid purchasing power from the external grid, C_e is the power purchase price, C_g is the natural gas purchase price, P_{sell} refers to the amount of the internal grid selling power to the external grid, C_e is the power sell price, R_i refers to the installed capacity of each equipment, C_i^{set} is the unit capacity cost of each piece of equipment, r is the is the bank loan interest rate, which is taken as 5% in this paper [6], n_i is the service life of all the equipment, P_i refers to the output power of each equipment, C_i^{op} is the operation and maintenance cost per unit power of each equipment, N_j is the number of each equipment starts and stops, which CCHP, EB and EC are considered here, C_j^{st} is the cost of a single starts and stops.

2.4. Constraint condition

During the operation process of IES, the output power constraints of energy supply network and each equipment should be considered.

(1) energy supply network:

$$P_{epg}^{min}\le P_{epg}(t)\le P_{epg}^{max} \qquad (17)$$

$$P_{egn}^{min}\le P_{egn}(t)\le P_{egn}^{max} \qquad (18)$$

where P_{epg}^{min} refers to the lower limit of the external power grid output power, P_{epg}^{max} refers to the upper limit of the external power grid output power, P_{egn}^{min} refers to the lower limit of the natural gas network output power, P_{egn}^{max} refers to the upper limit of the natural gas network output power.

(2) energy conversion equipment:

$$u_{cchp}(t)\cdot P_{gt}^{min}\le P_{gt}(t)\le u_{cchp}(t)\cdot P_{gt}^{max} \qquad (19)$$

$$u_{cchp}(t)\cdot H_{hrb}^{min}\le H_{hrb}(t)\le u_{cchp}(t)\cdot H_{hrb}^{max} \qquad (20)$$

$$u_{cchp}(t)\cdot L_{lbr}^{min}\le L_{lbr}(t)\le u_{cchp}(t)\cdot L_{lbr}^{max} \qquad (21)$$

$$u_{eb}(t)\cdot P_{eb}^{min}\le P_{eb}(t)\le u_{eb}(t)\cdot P_{eb}^{max} \qquad (22)$$

$$u_{ec}(t)\cdot P_{ec}^{min}\le P_{ec}(t)\le u_{ec}(t)\cdot P_{ec}^{max} \qquad (23)$$

$$M_{ccus,min}\le M_{ccus}(t)\le M_{ccus,max} \qquad (24)$$

where the superscript 'min' means the lower limit of each equipment output, the superscript 'max' means the upper limit of each equipment output, u_i is the 0-1 variable, which 0 indicates shutdown, and 1 indicates startup.

(3) energy storage equipment:

$$SOC_{i,min}\le SOC_i(t)\le SOC_{i,max} \qquad (25)$$

$$SOC_i^{start}=SOC_i^{end} \qquad (26)$$

$$u_c^i(t)\cdot P_{c,min}^i\le P_c^i(t)\le u_c^i(t)\cdot P_{c,max}^i \qquad (27)$$

$$u_d^i(t)\cdot P_{d,min}^i\le P_d^i(t)\le u_d^i(t)\cdot P_{d,max}^i \qquad (28)$$

$$0\le u_c^i(t)+u_d^i(t)\le 1 \qquad (29)$$

where $SOC_{i,min}$ refers to the lower limit of energy storage, $SOC_{i,max}$ refers to the upper limit of energy storage, SOC_i^{start} refers to the initial energy storage state in one day, SOC_i^{end} refers to the final energy storage state in one day, $P_{c,min}^i$ refers to the lower limit of energy storage power, $P_{c,min}^i$ refers to the lower limit of energy storage power, $P_{c,max}^i$ refers to the upper limit of energy storage power, $P_{d,min}^i$ refers to the lower limit of energy discharge power, $P_{d,max}^i$ refers to the upper limit of energy discharge power, u_c^i is the 0-1 variable, which 1 indicates energy storage, u_d^i is the 0-1 variable, which 1 indicates energy discharge. Due to simultaneous charging and discharging will affect the service life of the energy storage equipment, u_c^i and u_d^i are not equal to 1 at the same time.

In addition to considering all kinds of equipment output power constraints, system operation constrains need to include user load balance constraints and carbon neutrality constraints. The user load balance constraints mainly include cold, heat and electricity load balance. Carbon neutrality constraint means that the CO_2 emission generated by gas turbine and the power plant operation will be equal to the predicted allowable carbon emissions of the system in 2060.

(1) cooling load:

$$L_{lbr} + L_{er} + L_d = L_{load} + L_c \tag{30}$$

(2) heat load:

$$H_{hrb} + H_{eb} + H_d = H_{load} + H_c + H_{ccus} \tag{31}$$

(3) electric load:

$$P_{epg} + P_{gt} + E_d + (1-\alpha)\cdot\left(P_{pv} + P_{wt}\right) = E_{load} + E_c + P_{eb} + P_{ec} + P_{ccus} \tag{32}$$

Where α means the ratio of PTH power in renewable energy output power.

(4) carbon neutrality:

$$P_{gt}\cdot\varepsilon'_{gas} + P_{epn}\cdot\varepsilon'_e + M_{CCUS} = P_{gt}\cdot\varepsilon_{gas} + P_{epg}\cdot\varepsilon_e \tag{33}$$

Where ε_{gas} and ε_e are the amount of CO_2 actually produced by gas turbine and external power grid per unit of electricity. ε'_{gas} and ε'_e are the predicted CO_2 emission amount per unit of electricity produced by gas turbines and external power grids at carbon neutralization. M_{CCUS} means the amount of CO_2 needed to be captured by CCUS equipment.

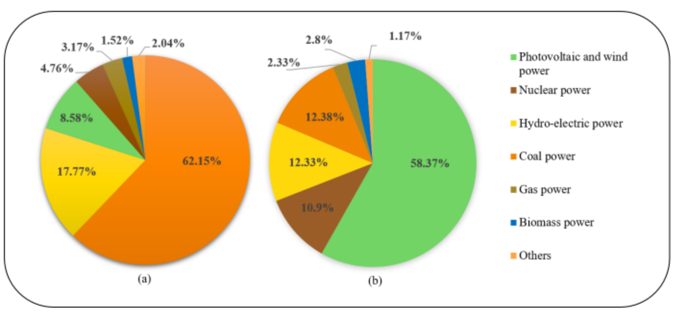

Fig.3. China's power grid structure in 2019(a) and 2060(b)

For China's external power grid, the actual CO_2 emission in 2019 is 0.577 kg/(kW·h). Based on the comprehensive analysis of various energy current situation, the growth trend of user energy consumption and carbon absorption capacity in China, it is predicted that the allowable CO_2 emission of China's external power grid will be 0.118 kg/(kW·h) and the gas turbine power generation will be 0.375 kg/(kW·h) in 2060. China's power grid structure in 2019 and 2060 is shown in Fig.3.

2.5. Configuration plan

The relevant parameters of the system mathematical model in the calculation process are shown in Table 1, Table 2, Table 3 and Table 4.

Table 1 Economic parameters of equipment for the IES

Parameter	Value	Unit
The unit price of natural gas	2.5	CNY/Nm^3
The unit price of photovoltaic power	0.44	CNY/kW
The unit price of wind power	0.393	CNY/kW
The unit price of photovoltaic hydrogen production	27.1	CNY/kW
The unit price of wind power hydrogen production	30.75	CNY/kW

Table 2 Technical parameters of equipment for the IES

Equipment	R_i /kW	n_i /year	P_i /kW	c_i^{set} /(CNY/kW)	c_i^{op} /(CNY/kW)
GT	200	20	[10,200]	6400	0.025
LBR	285	20	[10,400]	1500	0.015
HRB	250	20	[10,200]	850	0.01
EC	25	15	[5,100]	600	0.02
EB	125	15	[5,100]	140	0.016
EPG	—	—	[-60,60]	—	—

Table 3 Technical parameters of energy storage equipment for the IES

Equipment	R_i/kW	SOC_i	ε_i /%	P_c^i/kW	c_i^{set} /(CNY/kW)	c_i^{op} /(CNY/kW)	η_i^c	n_i /year
EES	150	[0.1,0.9]	0.1	80	600	0.0018	0.9	10
TES	100	[0.1,0.85]	1	50	300	0.0016	0.9	10
CES	100	[0.1,0.8]	1	50	400	0.0016	0.6	10

Table 4 Periodic electricity price

Time period	C_e/(CNY/kW)	C_e^{sell}/(CNY/kW)
6:00~22:00	0.977	0.75
22:00~6:00	0.487	0.45

In order to analyze the IES operation characteristics in different scenarios, this paper sets three schemes. Table 5 lists the different components in the three schemes, the rest components are the same as shown in Fig.1. Cost and CO_2 emission of different hydrogen source are shown in Table 6. Scheme1 mainly studies the influence of four typical hydrogen production methods on IES system operating cost and carbon emission. Scheme2 mainly studies the operation characteristics of IES to achieve carbon neutralization through CCUS without considering hydrogen utilization. Scheme3 adds distributed wind power and photovoltaic power on the basis of Scheme2.It means to study the influence of different proportions of renewable energy into the internal power grid and PTH device on system operating costs and carbon emissions.

Table 5 Configuration plan of IES

Scheme	PV&WT	PTH	CCUS
Scheme1	X	X	X
Scheme2	X	X	√
Scheme3	√	√	√

Table 6 Cost and CO_2 emission of different hydrogen source

Hydrogen source	Cost[1] /(CNY/kg H_2)	CO_2 emission /(kg CO_2/kg H_2)
CTH	10	20.9
GTH	12.83	11
IBH[2]	5.6	——
RTH	28.9	0

[1] Cost doesn't include hydrogen storage and transportation cost.
[2] Cost and carbon emission of relevant chemical industry of IBH are not considered.

3. RESULTS AND DISSCUSIONS

In scheme1, the operation cost calculation only considers the hydrogen production cost. Fig.4 shows that although the operating cost of CTH and GTH is low, the carbon emission of these methods is high. These methods are not conducive to achieving carbon neutralization. If IES hydrogen comes from IBH, although the operating cost and carbon emission of the system are low, this method has complex hydrogen purification process and high initial investment. If the hydrogen production plant is far away from IES, it may not have good economy after including high hydrogen storage and transportation cost. The way of RTH not only has low carbon emission, but also can be located nearby IES and has low initial investment cost, which has good adaptability with distributed energy supply system.

In scheme2, IES minimum typical daily operating cost is 5197.6\$, total CO_2 production is 2841.7kg, allowable CO_2 emission to achieve carbon neutrality is 1416.8 kg, power grid power consumption is 859.4kW·h, and natural gas consumption is 11686.6kW·h.

Fig.5 shows that when the PTH device power accounts for 2% and 31% of the total output power of renewable energy, the power grid power consumption and natural gas consumption reach the minimum values of 39.6kW·h and 8848.1kW·h. Compare to the scheme 2, these two figures decreased by 95.4% and 24.3% respectively.

Fig.6 shows that when the PTH equipment power accounts for 2% of the total output power of renewable energy, system total CO_2 production and carbon neutral allowable emissions reaches the minimum values of 1847.7kg and 1031.1kg. Compare to the scheme 2, these two data decreased by 35% and 27% respectively. Fig.6 shows that when all renewable energy output power is supplied to the power grid, IES achieves carbon neutralization at the lowest cost.

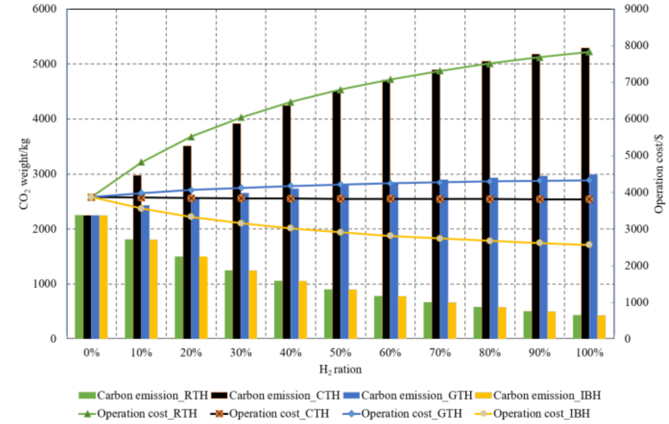

Fig.4. Comparative analysis of different hydrogen production methods in IES

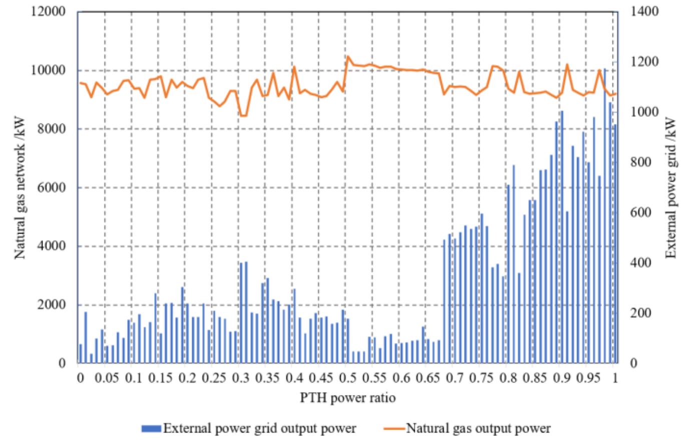

Fig.5. Energy supply network output power under different PTH power ratio

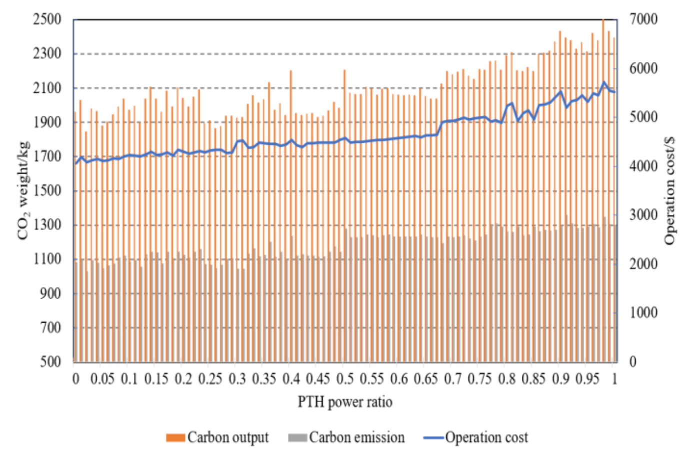

Fig.6. Operation cost and carbon emission under different PTH power ratio in IES

Fig.7 shows the operating cost and carbon emission of the scheme3 under different PTH power ratio when the efficiency of electric hydrogen production and carbon capture energy consumption change. Combined with IES mathematical model, it can be seen that the PTH power ratio with minimum carbon emission under carbon neutralization is mainly affected by these two factors.

From Fig.7, the operating cost of the system of both cases has an overall upward trend with the increase of the PTH power ratio. In both cases, the allowable CO_2 emissions under carbon neutralization of the IES are reduced in different degrees compared with Fig. 6, and the PTH power ratio to achieve the minimum carbon emission is increased. For reducing CCUS energy consumption, the allowable carbon emission of the IES is the lowest when the PTH power ratio is 23%, which is 1000.3kg and 29.4% lower than that of scheme 2. For increasing the efficiency of PTH equipment, the allowable carbon emission of the IES is the lowest when the PTH power ratio is 30%, which is 1044.1kg and 26.3% lower than that of scheme 2.

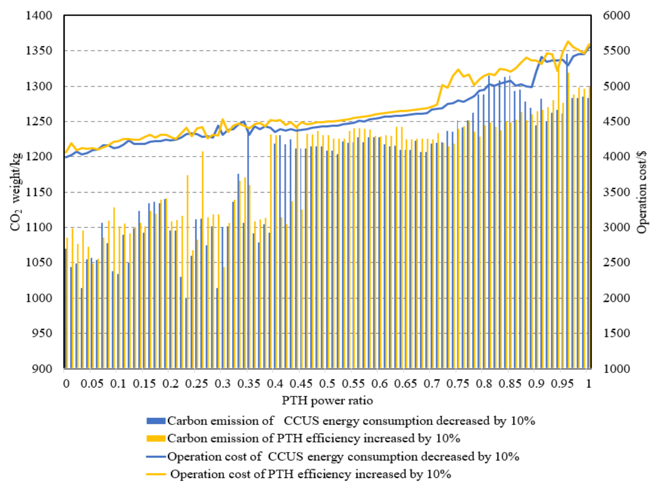

Fig.7. Operation cost and carbon emission under different PTH efficiency and CCUS energy consumption

4. CONCLUSIONS

Using renewable energy located near to IES to produce hydrogen can help to reduce system carbon emissions. For the example in this paper, all renewable output power supplied directly to the IPG in the IES can achieve carbon neutrality at the lowest cost, using 2% of renewable output power to produce hydrogen can achieve carbon neutrality at the minimal carbon emissions. With the development of PTH and CCUS technology, RTH will play an increasingly important role in achieving carbon neutrality and have a lower use cost, which will have a broader application prospect.

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