Article:

Zhao, Y.-J., Duan, Y.-Y., Liu, Q. et al. (8 more authors) (2021) Life cycle energy-economy-environmental evaluation of coal-based CLC power plant vs. IGCC, USC and oxy-combustion power plants with/without CO2 capture. Journal of Environmental Chemical Engineering, 9 (5). 106121. ISSN 2213-3437

https://doi.org/10.1016/j.jece.2021.106121

Life Cycle Energy-Economy-Environmental Evaluation of Coal-based CLC Power Plant vs. IGCC, USC and Oxy-combustion Power Plants with/without CO_2 Capture

Ying-jie Zhao[a,c]*, Yuan-yuan Duan*[a,c]*, Qian Liu*[a]*, Yang Cui*[a,c]*, Usama Mohamed*[d]*, Yu-ke Zhang*[a,c]*, Zhi-li Ren*[a]*, Yi-feng Shao*[a]*, Qun Yi*[a,b]**, Li-juan Shi*[c*]*, William Nimmo*[d]

[a]*State Key Laboratory of Clean and Efficient Coal Utilization, Taiyuan University of Technology, Taiyuan 030024, PR China*

[b]*School of Chemical Engineering and Pharmacy, Wuhan Institute of Technology, Wuhan, 430205, P. R. China.*

[c]*College of Environmental Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, P. R. China.*

[d]*Energy 2050 Group, Faculty of Engineering, University of Sheffield, S10 2TN, UK*

Corresponding author: *E-mail address*: yiqun@tyut.edu.cn (Q. Yi)

[*]**Corresponding author,** Fax & Tel.: +86 3513176580. *E-mail address*: yiqun@tyut.edu.cn (Q, Yi)

Abstract: Coal-based chemical looping combustion (CLC) power plant presents itself as a promising technology due to its low energy penalty which is associated with its inherent CO_2 capture process. However, most evaluations and comparisons (energy efficiency, economic, and environmental aspects) of the CLC power plant generally were focused on the power plant operation stage. Life cycle assessment (LCA) method with a "cradle to gate" model involving power plant construction, operation, and decommissioning stage,of coal-based power plants was established. Following that the resource consumption, energy consumption, environmental impact potential, and economic performance in the life cycle, were comprehensively compared between the coal-based CLC power plant and other plants such as IGCC, USC and oxy-combustion power plants with and without (w/o) CO_2 capture, to find out the potential and deficiency of the coal-based CLC power plant in a life cycle perspective. Results showed that energy resource consumption accounts for the largest proportion of the total resource consumption (81.88-91.89%) in six coal-fired power plants. Among the environmental impact potentials, smoke and dust potential (SAP) has the highest value while eutrophication potential (EP) resulted in the lowest in six coal-based power plants. CLC presented resource depletion indicator, energy payback ratio and the total life cycle costs, at 4.79×10^{-6} kWh/person/day, 3.22, and 0.138 $/kWh, respectively. These power plants were ranked from highest to lowest according to their sustainability as the following USC, CLC, IGCC, oxy-CCS, USC-CCS, and IGCC-CCS. However, CLC presents the best sustainability in all coal-based power plants with CO_2 capture. The CLC power plant will be one of the most attractive options for carbon reduction in coal-based power systems, as the development of CLC technology further improves energy efficiency and economic performance. The results further demonstrated that the coal-based CLC power plant can solve the issues involving CO_2 emission reduction and energy utilization in coal to power generation process from lifecycle viewpoint.

Keywords: chemical looping combustion, power plant, life cycle assessment, CO_2 capture

1. Introduction

There are increasing pressure and concern in regards to global warming (GW), requiring nations to seek lower-carbon energy sources in view of the Paris Agreement commitment. Carbon dioxide emission causes a major environmental (GW) [1, 2] and political concern. To further mitigate climate change and better achieve the goals of the Paris Agreement, the goal of achieving "carbon neutrality" of anthropogenic greenhouse gases (GHGs) (mainly CO_2) has been proposed in many nations. Last decades, coal and natural gas combined power plants have exceeded 63% of global electricity generation [3], which accounted for 59% CO_2 emission of whole CO_2 emission in the world. Over 80% CO_2 emissions is from coal-based power plants. The CO_2 emissions reduction of coal-based power plants has become one of the significant tasks of countries to achieve carbon neutrality. Despite the global push for “carbon neutrality”, the path in coal-based power plants is unclear. To reducing GHG emissions and achieve carbon neutrality in coal-based power plants, some technological options have been outlined to mitigate global warming: turning to lower-carbon intensive fuels in power plants, improving energy efficiency in power plants, deployment of promising power generation technology, and carbon capture and storage (CCS) technologies.

The most significant measurement in power plants (for example: Ultra-supercritical (USC) power plant [4-8], Integrated Coal Gasification Combined Cycle (IGCC) power plant [9, 10] and oxy-combustion power plants [11, 12]) for reducing CO_2 emission is to improve energy efficiency, especially in coal-fired power plants. The most effective method to reduce carbon emissions is to capture and store the emitted CO_2 to prevent accelerating global warming in a short period. However, the CCS system provides a significant increase in energy consumption and costs in power plants. Amongst CCS technologies, the post-combustion CO_2 capture (using amine solvent) is the most technologically and commercially-matured technology. The electricity generation efficiency of the USC-CCS power plant is reduced by approximately 9.5% compared to the USC-power plant (45.5%) [8]. The cost of electricity (COE) of the USC-CCS power plant would be increased by 44% compared with the USC-power plant [13]. IGCC power plant with CO_2 capture uses pre-combustion capture technology, in which CO_2 is removed from the syngas (water gas shift reaction is required: $CO+H_2O=CO_2+H_2$) before combustion. The electricity generation efficiency of the IGCC-CCS power plant is reduced by 9.3% compared with that of the IGCC-power plant (~44.3%) [14]. COE of an IGCC-CCS power plant is increased by 33 ~ 44% compared to an IGCC power plant [15]. USC-CCS and IGCC-CCS power plants can support reducing CO_2 emissions using CCS technology, however, this will result in a reduced power generation efficiency and increased COE. Oxy-combustion with CO_2 capture and storage (Oxy-CCS) power plant is another promising technology enable to reduces CO_2 emission for coal-fired power plants. CO_2-rich flue gas in oxy-combustion power plants avoided relatively expensive CO_2 capture compared to that of the conventional coal-fired power plant. However, using ASU for oxygen separation from air to obtain nearly pure oxygen, which makes the power generation costly and inefficient. Electricity generation efficiency and COE of the Oxy-CCS power plant is reduced by 10.0 ~ 12.0 % (due to O_2 generation from ASU, and CO_2 compression) [11, 16, 17] and increased by 29.5 ~ 31.4% compared to that of typical traditional power plant without CCS (42 ~ 45%).

Therefore, it is imperative to find a carbon capture technology with low energy consumption for power plants to gain high electricity generation efficiency. Chemical looping combustion (CLC) presents itself as a promising technology due to its low energy penalty which is associated with its inherent CO_2 capture process [18, 19]. Therefore, coal-based CLC power plants with CO_2 capture could be suggested as an alternative power generation technology compared to USC power plants with CO_2 capture (Amine-based), IGCC power plants with CO_2 capture (chemical/physical processes such as MEA, Selexol and Rectisol, etc.), and oxy-combustion power plant with CO_2 capture. Compared with these coal-based power plants with energy-intensive CCS systems, the CLC power plant has the advantage in power generation efficiency and COE due to the lower energy penalty in the CCS process. With different fuel-based (coal, natural gas, biomass, syngas, etc.) CLC power plants, power generation efficiency ranged from 35% to 46% with nearly zero CO_2 emission [19-22]. It was estimated that the COE of the coal-based CLC power plant is approximately 0.088-0.127$ /kWh [23, 24], which is more favorable than the advanced coal-based power plants mentioned above. Due to the low carbon emission and high electricity generation efficiency of the CLC power plant [25, 26], it attracts extensive research focus.

However, most evaluations and comparisons (energy efficiency, economic, and environmental aspects) of the CLC power plant generally were focused on the power plant operation stage. For example, the efficiency performance of chemical looping combustion power generation systems is estimated by using energy and exergy analysis approaches[27-29], and to improve the system techno-economic performance by optimizing CLC unit or heat exchange network. Moreover, the environmental performance evaluation only considers the CO_2 emission in the power generation section [24, 30, 31]. Considering only the operational stage of power plants when analyzing the potentiality of economic, energy and CO_2 emissions reduction ignore additional impacts in other processes (such as coal and OC (coal/OC) mining/washing, raw material transportation, waste transportation, etc.) of the whole life cycle, especially in new promoted technology. A quantitative assessment of the potential energy consumptions and CO_2 emission reduction to better understand the application of CLC power plants is crucial for future carbon-neutral power plants. Life cycle assessment (LCA) has proven to be an effective tool on the environmental impacts measuring of various conventional and advanced power plants, which was applied to comprehensively analyze the advantage and disadvantages of coal-based advanced power plants. Nevertheless, there is very little focus on the life cycle assessment of lower-carbon coal-based CLC power plants in current research. Navajas [32] evaluated the environmental impact of CLC-based natural gas combined cycles (GCLC-CC) power plant and compared it to that of gas turbine combined cycle (GTCC) and GTCC-Amine in the whole lifecycle, results presented that GCLC-CC did not add negative environmental impact to those in current natural gas combustion. Fan [33] reveals the relationship between global warming impact (GWI) of CLC and four factors (the types of oxygen carrier (OC), the lifetime of OC, the global warming potential (GWP) of OC, and thermodynamic performances of CLC power facility) to investigate the environmental sustainability of this technology, showing that integrating CLC with more-efficiency power plant system can contribute to lower GWI.

In this study, a life cycle assessment model of coal-based power plants was established. The resource consumption, energy consumption, environmental impact potential and economic performance in the life cycle, were comprehensively compared between coal-based CLC power plant and other five power plants, IGCC, USC and oxy-combustion power plants with and without (w/o) CO_2 capture, from which it can reveal the development potential and technologic bottleneck of the CLC power plant in the life cycle. The significance of this work is to comprehensively evaluate coal-based power plants, including the life cycle energy-economy-environmental associated with any given industrial activity (from the initial gathering of raw materials to the electricity production) of power plants. And to provide targeted solutions and research direction to promote the development and application of the CLC power plant.

2. Methodology

To completely evaluate the resource use, energy consumption, economic costs, and environmental burden associated with coal-based CLC power plants. This study analyzes these impacts based on sub-stages (Fig. 1) of coal-based CLC power plants by using the LCA method. After a holistic evaluation of the coal-based CLC power plant, it is then compared to the other five coal-based power plants (IGCC, IGCC-CCS, USC, USC-CCS, and Oxy-CCS).

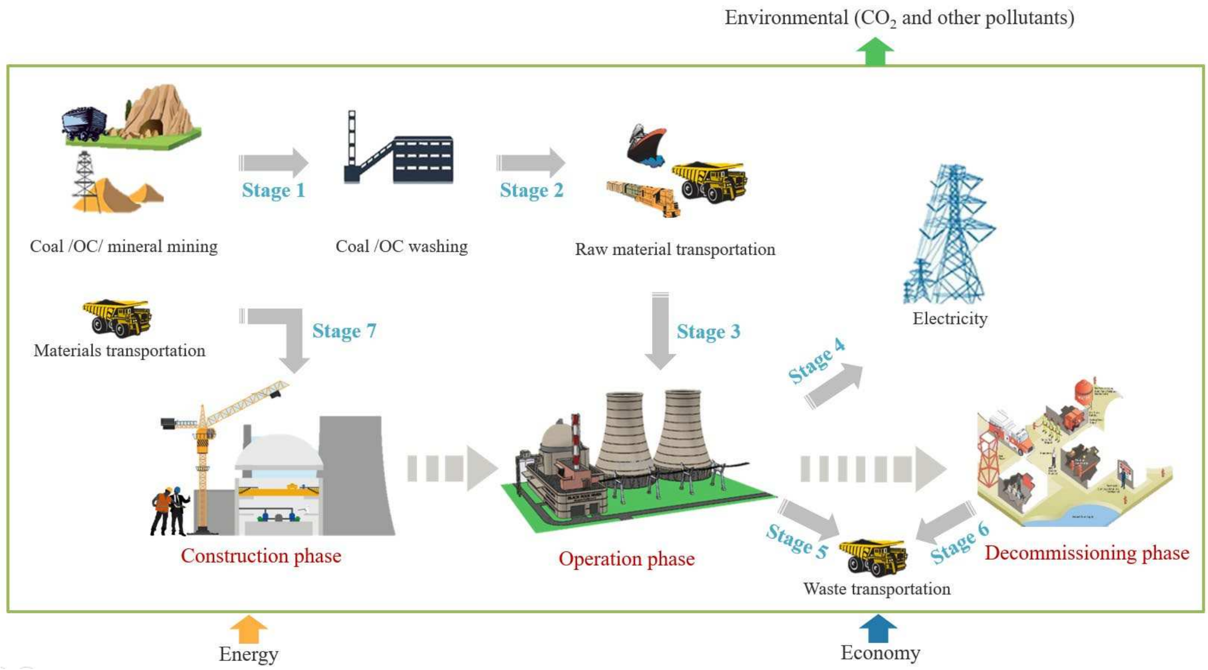


Fig. 1 Sub-stages of a coal-based CLC power plant

2.1 Description of power plants

A simplified block diagram of CLC power plant with CO_2 capture, coal-based USC power plant with/without CO_2 capture, IGCC power plant with/without CO_2 capture and Oxy-CCS power plant is depicted in Fig. 2(a) to (e). Table 1 shows the main operating parameters of these power plants. Especially, levelized cost of electricity (LCOE) of different net power out power plants are estimated by using the cost-to-capacity method [34] (scale factor, 0.82) for adapting the same net power plant size (550 MW). In addition, the key components in each stream (based on Fig.2) for each process are presented in Table S1. CLC is an innovative and leading-edge energy conversion technology that utilizes oxygen carriers to oxidize the fuel instead of atmospheric air [35-37]. Fig. 2(a) shows the whole conceptual diagram of a 600 MW coal-based CLC power plant, in which the combustion section is replaced by a CLC process with two reactors. Flue gases from the fuel and air reactors are sent to the HRSG unit to produce steam for power generation using a steam turbine. Exhaust gas 1 mostly containing N_2, and exhaust gas 2 containing CO_2 and H_2O generated from the FR, with CO_2 easily separated by condensation.

As shown by Fig. 2(b), a USC power plant (550 MW net power output) without CO_2 works based on a reheated Rankine Cycle, in which eight regenerative steam extractions and three steam turbines were considered [38]. There are mainly three primary inputs (coal, air, and water) given to a USC power plant. Coal creates required heat energy by combustion with air in the combustion chamber, the heat energy is transferred to steam in a steam boiler unit, and steam with higher parameters is sent to a steam turbine for electricity generation. The high-pressure (HP) steam (24.1 MPa and 593°C), intermediate-pressure (IP) steam (4.8 MPa and 593°C), and low-pressure (LP) are considered for three steam turbines to achieve higher efficiency and lower CO_2 emission. The exhaust gas purification unit is based on the SNOX™ Topsoe technology [39] for NO_X and SO_X simultaneous cleaning. Chemical absorption with MEA (methyl-ethanolamine) solvents was considered for the USC power plant with the CCS process. CO_2 capture (90% capture ratio) and compression (compressed to 11 MPa) units are presented [40] in Fig. 2(c) with a dotted box. Other configurations are the same as the 550 MW USC power plant.

IGCC power plant is an environmentally benign technology with greater power generation efficiency. Simplified process flow of a 500 ~ 650 MW (net power output) class IGCC power plant [41] system with/without CO_2 recovery is shown in Fig. 2 (d-e). IGCC power plant makes up technologies of coal gasification (Shell gasifier), raw fuel gas cooling and scrubbing, gas cleaning, gas turbine, heat recovery steam generator, steam turbine, sulfur byproduct recovery together. In the IGCC power plant, coal is converted to syngas in the gasifier, composed mainly of H_2 and CO, using a gasification process with higher purity O_2 from an ASU. Raw fuel gas is sent to a cleanup system where soluble gases and particles are initially removed by wet scrubbing, followed by sulfur as a by-product being removed and recovered via a removal and recovery process. Clean syngas is utilized in a combined cycle power generation process, in which syngas is sent to a Gas turbine unit, and HP, IP, and LP steam generated from the heat exchange network (HRSG) are sent to steam turbines. Thereby generating combined electricity. The integration of CO_2 capture systems (the process of water gas shift, CO_2 removal, and CO_2 compression) in IGCC can further improve environmental performance. Here, the Selexol absorption processes were applied to achieve 90% CO_2 capture.

An oxyfuel power plant retrofitted from a typical traditional power plant is selected as a base power plant [42]. As presented in Fig. 2(f), the oxy-combustion power plant (550 net power output MW) is divided into four subsystems including pulverized coal (PC) boiler, ASU, flue gas desulphurization (FGD), CO_2 removal, and compression. O_2 from the ASU and coal are feed into PC boiler, in which coal is combusted and steam is produced. Steam is sent to a steam turbine to generate electricity. Then, the flue gas is taken to the flue gas desulphurization (FGD) unit, after flue gas clean up, CO_2 is distilled and compressed.

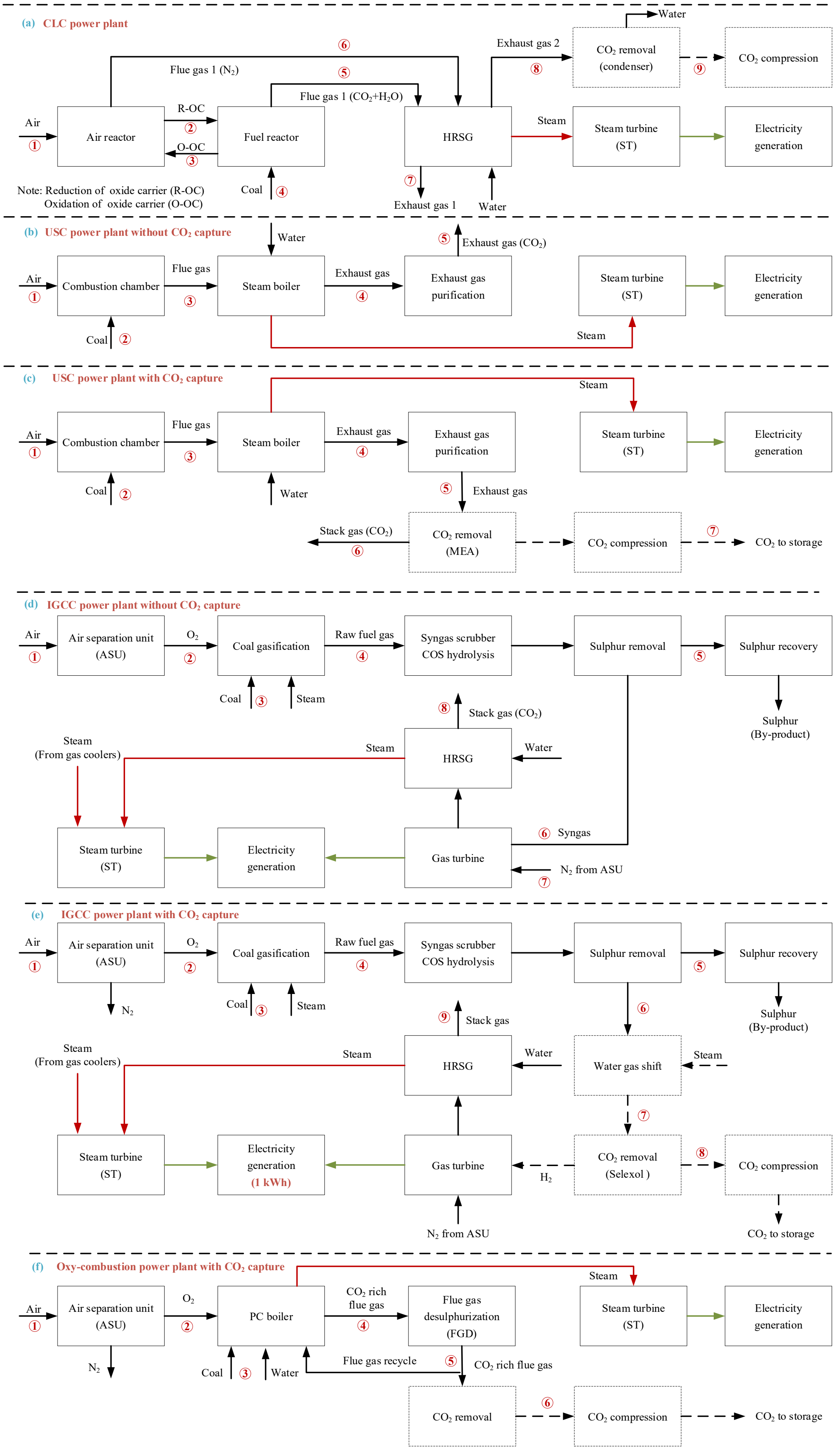


Fig. 2 Process flow of the six coal-based power plants

Table 1 Primary technical parameters of the power plants

Parameters	USC [38]	IGCC [41]	USC-CCS[38]	IGCC-CCS [41]	Oxy-CCS [42, 43]	CLC
Gross power output (MW)	580	765	642	696	-	674
Net power output (MW)	550	640	550	519	550	600
Net power generation HHV efficiency (%)	40.7	43.0	32.5	32.5	30.1	34.8
Operation capacity (%)	85	85	85	85	85	85
CO_2 capture efficiency (%)	0	0	90	90	90	90
Capital cost ($/MWh)	45.17	48.13*	83.62	93.23*	91.02	42.92*
Fixed costs($/MWh)	11.12	17.66*	17.83	33.45*	19.54	17.90*
Variable costs ($/MWh)	10.54	12.01*	17.02	23.39*	11.38	12.72*
Fuel Cost ($/MWh)	28.49	17.7	35.79	23.4	41.30	48.69*
LCOE ($/MWh)*	95.31	95.50*	154.26	173.47*	163.23	122.22*
Coal	Illinois No.6	Illinois No.6	Illinois No.6	Illinois No.6	Illinois No.6	Illinois No.6
Gasification technology	-	Shell	-	Shell	-	-
Gasifier pressure, MPa	-	4.2	-	4.2	-	-
Oxidant	-	95 vol% O_2	-	95 vol% O_2	-	-
Excess Air, %	20.9	-	20.9	-	-	-
O_2: coal ratio, kg O_2/kg as-received coal	-	0.72	-	0.72	-	-
Carbon conversion, %	99.4	99.5	99.4	99.5	99.5	99.5
WGS	No	No	Yes	Yes	No	No

Parameters	USC [38]	IGCC [41]	USC-CCS[38]	IGCC-CCS [41]	Oxy-CCS [42, 43]	CLC
Boiler efficiency, %	88.1	89	88.1	89	93.5	90
Main steam pressure, MPa	24.1	12.4	24.1	12.4	24.1	24.1
Main steam temperature, °C	593	562-566	593	533-536	599	593
Reheat steam pressure, MPa	4.8	3.3	4.8	3.3	4.8	4.8
Reheat steam temperature, °C	593	562-566	593	533-536	621	593
CO_2 separation	No	No	MEA-based	selexol	distillation	condenser

* Due to the economic performance being significantly affected by the scale of power plants, the data of economic indicators (capital cost, fixed costs, variable costs) are normalized to the same net power output (550MW) based on that of IGCC (640 MW), IGCC-CCS (519 MW) and CLC (600 MW) by using cost-to-capacity method [34], in which the equation: $\frac{C_2}{C_1} = (\frac{Q_2}{Q_1})^x$, is used to estimate economic indicators of IGCC, IGCC-CCS and CLC power plants. C_2 represents the estimated cost of power plant 2, with net power output Q_2, C_1 is the known cost of power plant 1, with net power output Q_1, x is the scale factor (0.82) for power plants of 2 and 1.

2.2 Life cycle assessment

The framework of the LCA methodology has been defined by the International Standard 14040 and 14044 [44], which is divided into four inter-related phases as presented in Fig. 3. The details are shown in the following sections.

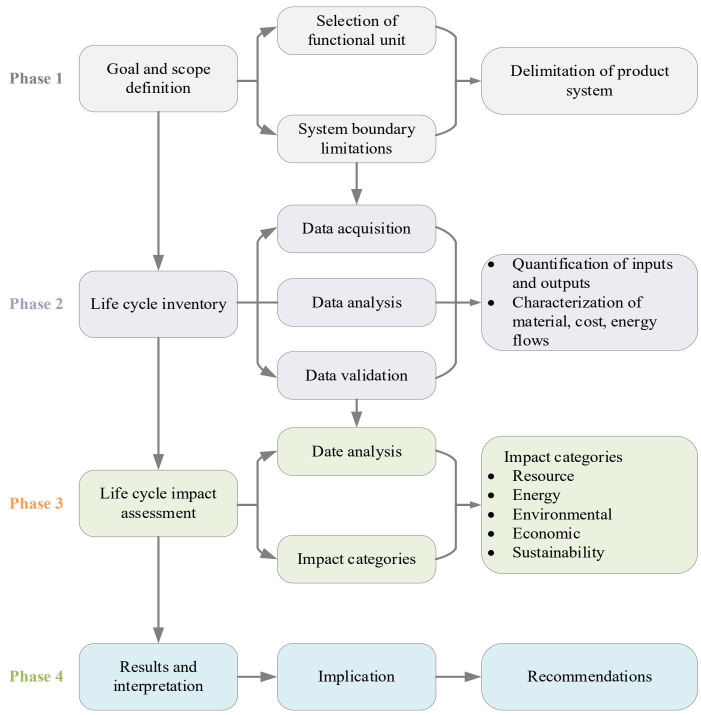


Fig. 3 Diagram of the LCA method

2.2.1 Goal and scope definition

Goal and scope definition phase is delimited by the electricity production of a coal-based power plant system. The main goal of this LCA study is to investigate resource use, energy consumption, emissions, and the overall environmental impact of power plants that use CLC technology to produce low-carbon energy from a high-carbon resource (coal), and to compare with that of other coal-based power plants. A functional unit (1 kWh) was used in six power plants with the same coal (Illinois #6 coal). The LCA of coal-based power plants has common functions that can be compared.

The flow diagram of a power plant is divided into three stages: power plant construction, operation, and decommissioning. The power plant construction phase includes the mining, processing, transportation of raw materials (steel, concrete, aluminum, etc.), as well as the construction and installation of the power plant. The operation stage of the power plant includes the extraction, processing, and transportation of resources needed for power production, discharge of pollutants (CO_2, NO_X, SO_X, chemical oxygen demand (COD)), as well as control, treatment, and transportation of solid waste and dust. In the decommissioning stage of the power plant, the data of the power plant demolition and waste recycling process is lacking, and only the waste transport process is considered. The life cycle assessment boundary of the six coal-based power generation systems established in this paper does not include the electric power transmission, which belongs to the study of "cradle to gate", as shown in Fig. 4. The different units in the system are composed of energy and raw materials as inputs and emissions as outputs.

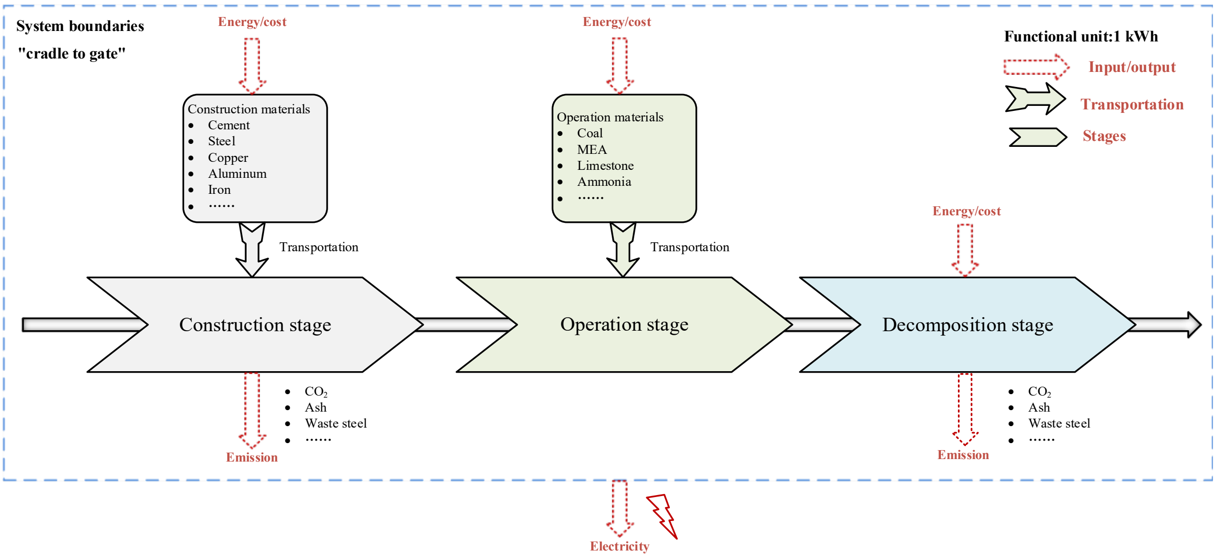


Fig. 4 System boundary of the six coal-based power plants for life cycle assessment

2.2.2 Life cycle inventory analysis

The data contained in the inventory mostly includes the input and output of materials and energy in the whole system. Life cycle inventory is divided into energy consumption inventory, resource consumption inventory, and emission inventory. The environmental emission inventory includes CO_2, SO_2, NO_X, CO, CH_4, chemical oxygen demand (COD), solid waste and dust. The collection of coal-based power plant system life cycle inventory is also divided into three stages: power plant construction, power plant operation, and power plant decommissioning. The construction phase of a power plant involves the extraction, processing, transportation, and installation of the materials needed to build the power plant facility. The detailed process of the life cycle inventory data collection is shown in Fig. 5.

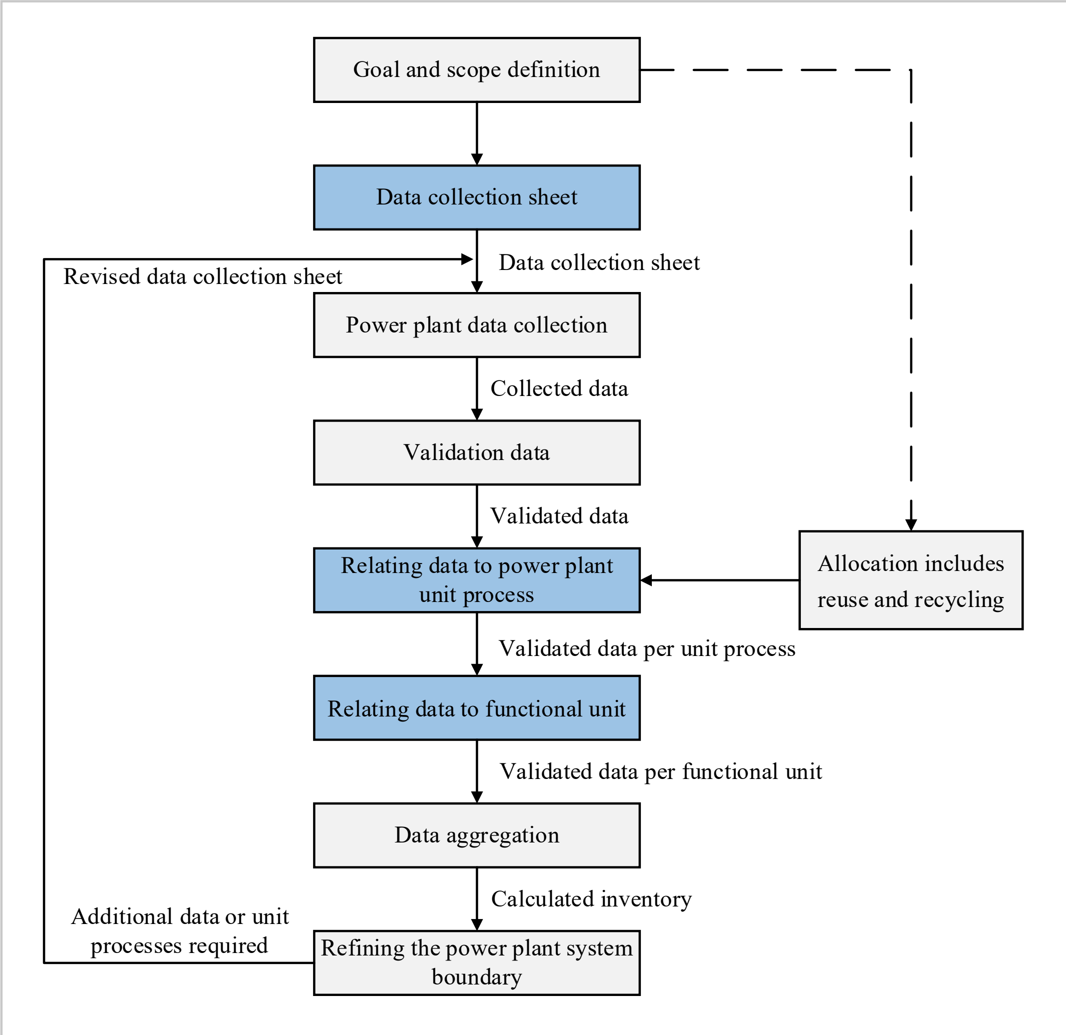


Fig. 5 Data collection and calculation process [45]

The calculation method of energy consumption in the construction stage [46] is shown in Eqn. 1. m_i (kg), E_{ei} (kJ/kg), E_{mi} (kJ/kg), E_{ti} (kJ/kg·km), and L_i (km) represent the quality, energy consumption per unit of mining, energy consumption per unit of processing energy consumption per unit of mass, energy consumption per unit of transport length, and transport distance of type i raw materials, respectively.

$$E_{con} = \sum_i m_i \times (E_{ei} + E_{mi} + E_{ti} L_i) \tag{1}$$

Resource consumption includes consumption of energy resources (coal, petroleum, and natural gas) and consumption of non-energy resources (steel, iron, cement, copper, and aluminum). The non-energy resource consumption is calculated by Eqn. 2, in which m_i (kg), R_{ei} (1/kWh), R_{mi} (1/kWh), R_{ti} (1/km·kWh), and L_i (km) represent the quality of the i_{th} raw material, the energy resources consumed by unit quality mining, the energy resources consumed by unit quality processing, and the energy resources consumed and transported from unit quality unit to transport, respectively.

$$R_{i,con} = m_i \times (R_{ei} + R_{mi} + R_{ti} L_i) \quad (2)$$

Pollutants in the construction stage include CO_2, SO_2, NOx, CO, CH_4, COD, solid waste, smoke, and dust. The emission of pollutants consists of the emission from the production process of energy resources (P_{pi}) and the emission of pollutants from the production of non-energy resources (see Eqn. 3). The pollutants of non-energy resources can be divided into three sections: emissions from the production of energy, non-energy resources (P_{ei}), emissions from the transport of non-energy resources (P_{ti}), and emissions from the use of energy resources (P_{ui}) during the exploitation and processing of non-energy resources. Energy-related CO_2 emissions can be calculated by multiplying the total amount of energy by its CO_2 emission factor. Electricity-related CO_2 emissions are calculated by referring to the CO_2 emission coefficient published by the Ministry of Environment [47].

$$P_{i,con} = P_{pi} + P_{ei} + P_{ti} + P_{ui} \quad (3)$$

Eqn. 4 is used to calculate the energy consumption in the operation stage of the power plant [46], including the energy consumption in the mining, processing, and transportation process of the raw materials (coal and oxygen carrier, etc.) required in the operation stage of the power plant (E_{ri}) (kJ), the energy generated in the power production process (E_{op}) (kJ) and the energy consumption in the transportation of solid waste (E_t) (kJ).

$$E_{opa} = \sum_i E_{ri} + E_{op} + E_t \quad (4)$$

The resource consumption in the operation stage is mainly coal, petroleum, natural gas, limestone, and ammonia, and the calculation of resource consumption in the operation stage is similar to that of in the construction stage of the power plant. The calculation of pollutant emissions in the operation stage is presented in Eqn. 5, which increases the quality (P_{gi}) of emissions generated during the generation of the power plant compared with the calculation of pollutant emissions in the construction stage. Since there is no measured data of the coal-based CLC power plant, the pollutants generated in the power generation process are calculated by the material balance analysis and method of pollutant producing coefficient (PPC) and pollutant discharge coefficient (PDC) [46]. The calculation formula is shown in Eqn. 6 to Eqn. 10 [48], Where, B_g is fuel consumption, q_4 is the incomplete combustion loss of boiler, $S_{t,ar}$ is the total sulfur content of the fuel received, K is the share of the fuel oxidized to SO_2 after combustion, $Q_{ar, LHV}$ is the lower heating value of the coal received, β is the CO_2 removal rate, β_g is the pollution production coefficient, and α_i is the emission factor.

$$P_{i,ope} = P_{pi} + P_{ei} + P_{ti} + P_{ui} + P_{gi} \tag{5}$$

$$E_{SO_2} = 2B_g \times (1 - \frac{q_4}{100}) \times \frac{S_{t,ar}}{100} \times K \times (1-\beta) \tag{6}$$

$$E_{CO_2} = B_g \times (0.201 + 0.087 \times Q_{ar,LHV}) \times (1-\beta) \tag{7}$$

$$E_{exhaust\ gas,NO_X} = B_g \times \beta_g \times 10^{-3} \tag{8}$$

$$E_{COD} = B_g \times \beta_g \times 10^{-6} \tag{9}$$

$$E_{CO,CH_4} = B_g \times Q_{ar,LHV} \times \alpha_i \tag{10}$$

Due to the lack of data on power plant demolition and waste recycling process, the energy consumption and emission in the decommissioning stage of the power plant is 10% of the power plant construction[16]. The calculation method of total energy consumption, resource consumption, and environmental emission in the decommissioning stage is consistent with the other two stages. In the decommissioning stage, only energy consumption, resource consumption, and environmental emission in waste transportation are considered.

Assumptions

The boundary demarcation and LCA calculation methods of the coal-based CLC power plant (600 MW) are the same as the other three coal-based power generation technologies (IGCC, USC, Oxy-combustion). According to the current state of coal-based CLC power plant, to simplify the data collection and calculation at different stages of the power plant, the following assumptions are proposed:

1) The CLC coal-based power plant is similar to the circulating fluidized bed combustion coal-based power plant in power plant construction. The data of non-energy resource consumption and energy resource consumption are the same in power plant construction.
2) On the CLC power plant operation stage, the data include the extraction, processing, transportation, and disposal of oxygen carriers.
3) Coal, concrete, steel, aluminum, limestone, oxygen carrier (Fe_2O_3), and ammonia are

produced in China and transported to the site of the power plant by rail or truck.

4) Due to the lack of data on equipment installation and plant construction, the impact of mining, processing, and transportation of raw materials is considered only during the construction phase.
5) Energy consumption in the decommissioning stage of the coal-based CLC power plant refers to the calculation of energy consumption of the CFBC power plant in the decommissioning stage.
6) The coal-based CLC power plant and the circulating fluidized bed power plant (CFBC) adopt the same limestone desulfurization technology [49], the molar ratio of Ca and S is 2, and the desulfurization efficiency is 90%.

2.2.3 Life cycle impact assessment

Based on the results of inventory analysis, Life Cycle Impact Assessment (LCIA) is divided into life cycle energy consumption assessment, life cycle resource consumption assessment, life cycle environmental impact assessment, and life cycle cost assessment.

Life cycle energy and resource consumption assessment

The energy payback ratio (EPR) is adopted as the evaluation index of energy consumption in the life cycle and is the ratio of total electric energy output to total energy consumption in the life cycle. It can be calculated by Eqn. 11, in which E_{con}, E_{ope}, and E_{dec} represent the energy consumed by the power plant during construction, operation, and decommissioning, respectively, and E_e (kWh) represents the electricity generated by the plant during its life cycle. Life cycle resource consumption assessment has two indicators: life cycle resource consumption and resource depletion indicators (RDI). RDI is obtained by standardized and weighted assessment of resource consumption [45]. Life cycle resource consumption is calculated by Eqn. 12, including life cycle energy resource consumption and non-energy resource consumption. R_{con} (kJ), R_{ope} (kJ), and R_{dec} (kJ) represent the energy resource consumption in the construction, operation, and decommissioning stages of the power plant, respectively. U_{con}, U_{ope}, and U_{dec} characterize the three phases of non-energy resource consumption, respectively.

$$EPR=\frac{E_e}{E_{con}+E_{ope}+E_{dec}} \quad (11)$$

$$REC=R_{con}+R_{ope}+R_{dec}+U_{con}+U_{ope}+U_{dec} \quad (12)$$

Life cycle environmental impact assessment

For the assessment of environmental impact, the Centre For Environment Studies (CML) method [50] was selected in this study. The CML method includes three steps: classification, characterization, and normalization. Impact categories chosen for this study are nutrient enrichment, acidification, human toxicity, global warming, solid waste, and dust. According to the life cycle inventory, different emission data are classified into different impact types. For example, CO_2, NO_X, and CH_4 are classified as global warming, SO_2 and NO_X as acidification, NO_X, and COD as nutrient enrichment, SO_2, NO_X, and CO as human toxicity, solid waste as solid waste, and dust as soot and dust. The environmental impact potential value is calculated based on pollutant discharge and equivalent factors, and the specific parameters are shown in Table 2.

The environmental impact potential value is defined as the total amount of similar environmental impact emissions in the whole system, which is calculated in Eqn. 12. EP(m) represents the m_{th} environmental impact potential value in the product life cycle, $EP(m)_n$ represents the m_{th} environmental impact potential value of the n_{th} emission, Q(m)n represents the emissions of the n_{th} substance, and $EF(m)_n$ represents the equivalent factor of the m_{th} environmental impact of the n_{th} emission. Data standardization is required after the calculation of the environmental impact potential. The purpose is to provide a standard for comparing the relative size of the various types of impacts. The impact potential value of standardization can reflect the size of the potential environmental impact amount. The data of 1990 is used as the standard benchmark, and the calculation process is shown in Eqn. 13. Where NEP(m) represents the value after the standardization of the potential value of the m_{th} environmental impact, and ER(m) represents the standardized benchmark. The unit of environmental impact potential after standardization is the standard human equivalent. Different scale benchmarks are used for the types of environmental impacts in different impact regions. For example, global scale benchmarks are used for the environmental impact potential value of a global environmental impact region; Use regional or national benchmarks for regional environmental impacts; Use national or regional benchmarks for local environmental impacts. To compare the relative severity of different environmental impact types, the standardized environmental impact potential value was weighed and the weight factor was calculated in Eqn. 13. WF(m) is the weight factor of the m_{th} environmental impact type can be calculated by Eqn. 14, and the current social level of the m_{th} environmental impact ($ER(m)_{base}$) is divided by the target level of the environmental impact ($ER(m)_{aim}$). Through the weight assessment of different environmental impact types, the impact of the production (electricity, heat, and so on) system on the environment can be carried out more reasonably.

$$EP(m)=\sum EP(m)_n=\sum[Q(m)_n \cdot EF(m)_n] \tag{12}$$

$$NEP(m)=\frac{EP(m)}{ER(m)} \tag{13}$$

$$WF(m)=\frac{ER(m)_{base}}{ER(m)_{aim}} \tag{14}$$

Table 2 Impact categories and equivalent factors

Impact categories	Matters	Equivalent factor [46]
Global Warming Potential (GWP)	CO_2, CH_4, NO_X	1, 21, 320
eutrophication potential (EP)	NO_X, COD	1, 1
acidification Potentials (AP)	SO_2, NO_X	1, 0.7
human Toxicity Potential (HTP)	CO, SO_2, NO_X	0.012, 1.2, 0.78
solid Waste Potential (SWP)	coal gangue, waste and residues, blast furnace slag, depleted OC	1, 1, 1, 1
smoke and dust potential (SAP)	smoke, coal ash, dust and mud	1, 1, 1

Life cycle cost assessment

To realize the comparison of different coal-based power plants, the same index function (1 kWh) was used to compare the performance of power plants with similar net power output. Nevertheless, the economic performance is significantly affected by the scale of power plants, as result, for economic assessment in the life cycle, economic data from different sizes (500~650 MW net power output) of power plants mentioned above are normalized to the same size (550 MW net power output) by using the cost-to-capacity method (scale factor is 0.82) [34]. While the economic performance of CLC is calculated from the data of the economic evaluation model (**Supporting Information**), and estimated by using the same method (cost-to-capacity) mentioned above[34].

Total life cycle costs (TLCC) are divided into internal and external costs. Internal cost refers to the unit cost of power plant construction, daily operation of power plant maintenance, treatment cost of decommissioning and residual cost within the life cycle of the power plant, namely, LCOE. Internal cost consists of capital costs, fixed operation and maintenance (O&M), variable O&M, fuel cost and CO_2 transport and storage (T&S). External cost refers to the cost unit of environmental impact during the construction, operation, and decommissioning of the plant. The internal cost of CLC is calculated from the data of the economic evaluation model (Supporting Information), and estimated by using the same method (cost-to-capacity) mentioned above. The external cost is calculated from the environmental impact index and the corresponding environmental cost factor [46]. The environmental cost factor of environmental impact categories including GWP, AP, EP, HTP, SWP and SAP are 0.06, 0.74, 0.58, 0.76, 0.06 and 0.31, respectively.

Power plant sustainability assessment

Power plant sustainability assessment (SIPP) is related to energy rate of return, resource depletion indicators, environmental impact potential, and life cycle cost, as shown in Eqn. 15. ε, β, χ, and δ are the weights of the four evaluation indexes[46]. The values are 0.214, 0.095, 0.214, and 0.477, respectively. The higher the SIPP, the better the plant will be for resources, the environment, and the economy.

$$SIPP = \frac{\varepsilon \times EPR}{\beta \times RDI + \chi \times NEP + \delta \times TLCC} \tag{15}$$

2.3 Life cycle inventory analysis

2.3.1 Data collection

The total energy consumption in the construction stage is calculated by Eqn. 1, neglecting the energy consumption in the process of plant construction and equipment installation, and only considering the energy consumption in the process of material mining, processing, and transportation to the power plant. The materials used for the construction of the power plant are transported by road. According to the national average distance of road cargo transportation, the value is 69 km [51]. The energy consumption in the process of raw material mining, processing, and transportation is calculated by unit energy consumption and amount of raw material [46]. The pollutant emission in the construction stage of the power plant is calculated by Eqn. 3, in which the pollutant emission in the energy production process is calculated by the emission of unit energy production [45] and the amount of energy consumption. Pollutants produced by the production, processing and transportation of non-energy resources are calculated by unit pollutant discharge[45] and consumption of non-energy resources.

The total energy consumption in the operation stage of the power plant is calculated according to Eqn. 4, including direct and indirect energy consumption. Direct energy consumption is the energy consumption generated by fuel consumption within the whole life cycle, and indirect energy consumption refers to the energy consumption caused by the mining, processing, and transportation of raw materials, materials needed for power plant operation, and the transportation of solid wastes generated by power plant operation.

In the calculation process, it is assumed that the fuel and raw materials (limestone, oxygen carrier, and ammonia water) are transported by railway and road. In which railway transportation accounts for 70%, and the transportation distance [51] is 757 km. Road transportation accounts for 30% and the transportation distance is 69 km [51]. The solid waste generated from the power plant in the operation stage is transported by road with a transportation distance of 5 km. The pollutant emission during the transportation process is based on the following reference [52]. The emission of pollutants in the operation stage of the power plant is calculated by Eqn. 5. The calculation process of the first four items in the formula is the same as that in the construction stage of the power plant, in which the pollutant emission process in the mining and transportation of oxygen carrier Fe_2O_3 is calculated by reference [53]. CH_4 emissions during coal mining are about 0.262 kg/GJ coal [54].

2.3.2 Inventory analysis

Based on the above assumptions and data collection, a life cycle assessment inventory of the three stages of the coal-based power plants (CLC, IGCC, IGCC-CCS, USC, USC-CCS, Oxy-CCS) are established as shown in Table S2.

3. Results and discussions

3.1 Life cycle assessment of coal-based CLC power plant

Based on the established inventory of the coal-based CLC power plant, life cycle resource consumption, life cycle energy consumption, life cycle environmental impact, and life cycle cost of the coal-based CLC power plant are evaluated. The details are presented in the next section.

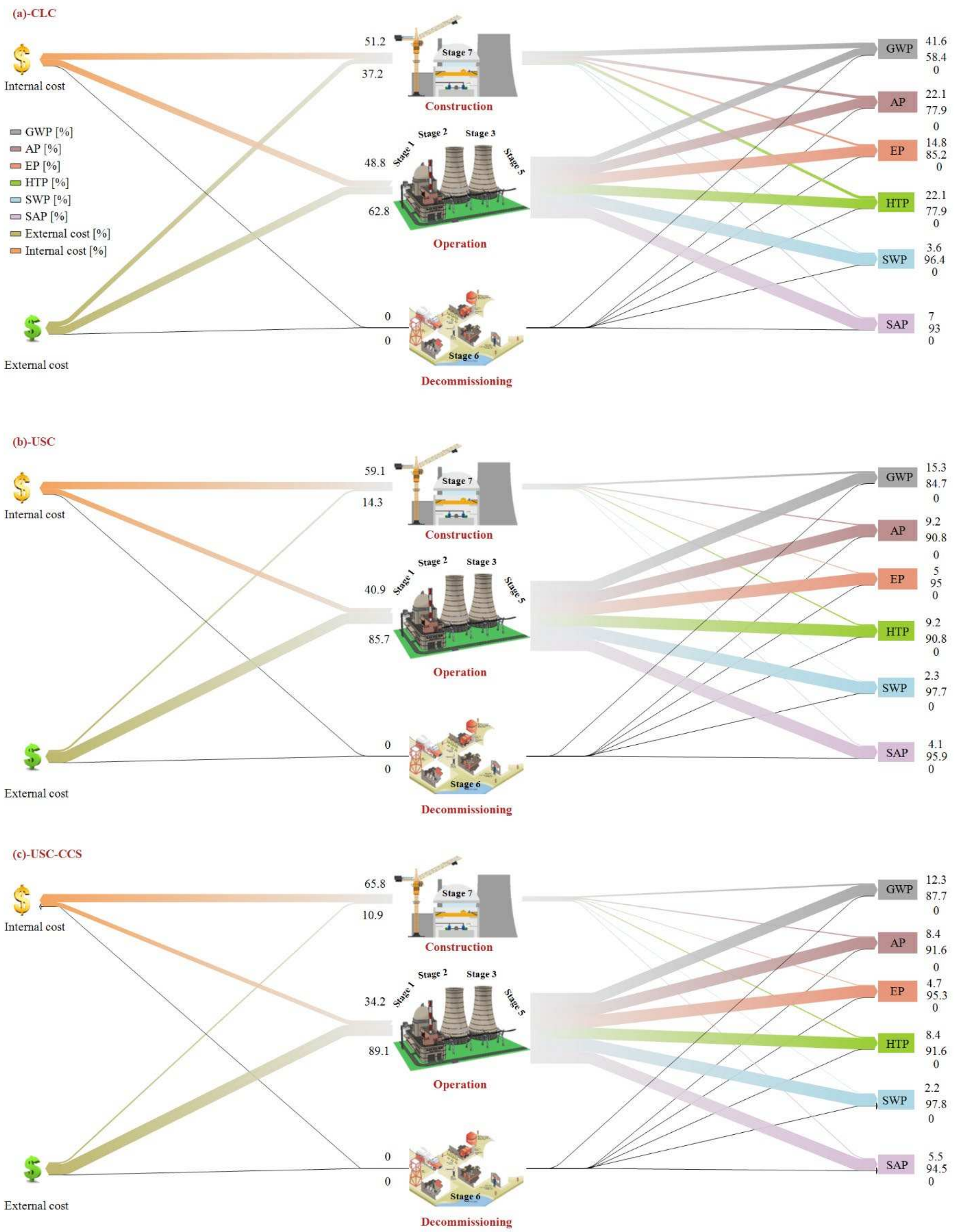
3.1.1 Life cycle resource consumption assessment

The life cycle resource consumption of power plants is carried out from two aspects of resource consumption and resource depletion indicators. The total resource consumed of coal-based CLC power plant is obtained by adding the energy consumption in the three stages of construction, operation, and decommissioning, giving a value of 461.87 g /kWh. Coal, limestone, and oxygen carriers accounted for 83.60%, 9.67%, and 3.44% respectively. However, resource consumption reflects the absolute resource consumption in the life cycle assessment of power plants and does not reflect the relative value of resource consumption. Resource consumption is standardized and weighted [45] to obtain the resource depletion indicators, which can be used to compare the relative value of the power plant resource consumption. Coal is the main component, accounting for 81%, followed by natural gas, accounting for 15%, and metal mineral resources account for less than 3%. Therefore, reducing power plant resource consumption should start from energy resources, coal, petroleum, and natural gas.

3.1.2 Life cycle environmental impact assessment

Based on the impact categories and equivalent factors, and the amount of different environmental pollutants shown in Table S2, the potential value of environmental impact is calculated, and is shown in Table 3. CO_2, NO_X, CO, and CH_4 contribute to the GWP. As presented in Fig. 6, among the construction (including materials transportation in construction), operation (including coal/OC/ mineral mining, coal/OC washing; raw material transportation, and waste transportation in operation), operation and decommissioning (including waste transportation in decommissioning) stages of the power plant, the operation stage accounts for a maximum proportion of GWP (58.4%). GWP of the construction stage and the decommissioning stage is 41.6% of the total. NO_X and SO_2 gases contribute to the potential value of acidification. The AP of the construction and decommissioning stage is 22.1% of the total AP in the coal-based CLC life cycle assessment, and AP of the power plant operation stage accounts for 77.9%. According to the calculation of nutrient enrichment potential value by using the Chemical Oxygen Demand (COD) index, the power plant operation stage contributes the most to EP, accounting for 85.2%, while the EP produced by the power plant construction and decommissioning stages only account for 14.8%. The main gases that contribute to the potential of human toxicity are SO_2, CO, and NO_X. Among the three stages of the whole life cycle of the power plant, the operation of the power plant contributes the most to HTP, accounting for 77.9%, while the construction and decommissioning stage of the power plant only account for 22.1%. The materials that contribute to the potential value of solid waste mainly include power plant waste slag, furnace slag, and waste oxygen carrier. The potential value of solid waste in the power plant operation stage is the largest, accounting for more than 96.4%, while the contribution of the power plant construction and decommissioning stage is less than 3.6%. The largest contributor to soot and dust emission during the life cycle of the power plant is the construction and decommissioning stage, which accounts for 93.0%, while the operation stage only accounts for 7.0%.

According to the data (Table 3) analysis, it can be concluded that to reduce AP, EP, HTP, and SWP, we need to start by reducing the construction and operation stage of the power plant. Since the power plant itself can reduce CO_2, for this power generation technology, further reducing GWP should start from the construction and operation of the power plant at the same time, and the impact on soot and dust should be mainly considered from the construction and decommissioning of the power plant.



(a)-CLC
Internal cost
External cost
GWP [%]
AP [%]
EP [%]
HTP [%]
SWP [%]
SAP [%]
External cost [%]
Internal cost [%]
51.2
37.2
Stage 7
Construction
Stage 1
Stage 2
Stage 3
Stage 5
48.8
62.8
Operation
0
0
Stage 6
Decommissioning
GWP
41.6
58.4
0
AP
22.1
77.9
0
EP
14.8
85.2
0
HTP
22.1
77.9
0
SWP
3.6
96.4
0
SAP
7
93
0
(b)-USC
Internal cost
External cost
59.1
14.3
Stage 7
Construction
Stage 1
Stage 2
Stage 3
Stage 5
40.9
85.7
Operation
0
0
Stage 6
Decommissioning
GWP
15.3
84.7
0
AP
9.2
90.8
0
EP
5
95
0
HTP
9.2
90.8
0
SWP
2.3
97.7
0
SAP
4.1
95.9
0
(c)-USC-CCS
Internal cost
External cost
65.8
10.9
Stage 7
Construction
Stage 1
Stage 2
Stage 3
Stage 5
34.2
89.1
Operation
0
0
Stage 6
Decommissioning
GWP
12.3
87.7
0
AP
8.4
91.6
0
EP
4.7
95.3
0
HTP
8.4
91.6
0
SWP
2.2
97.8
0
SAP
5.5
94.5
0

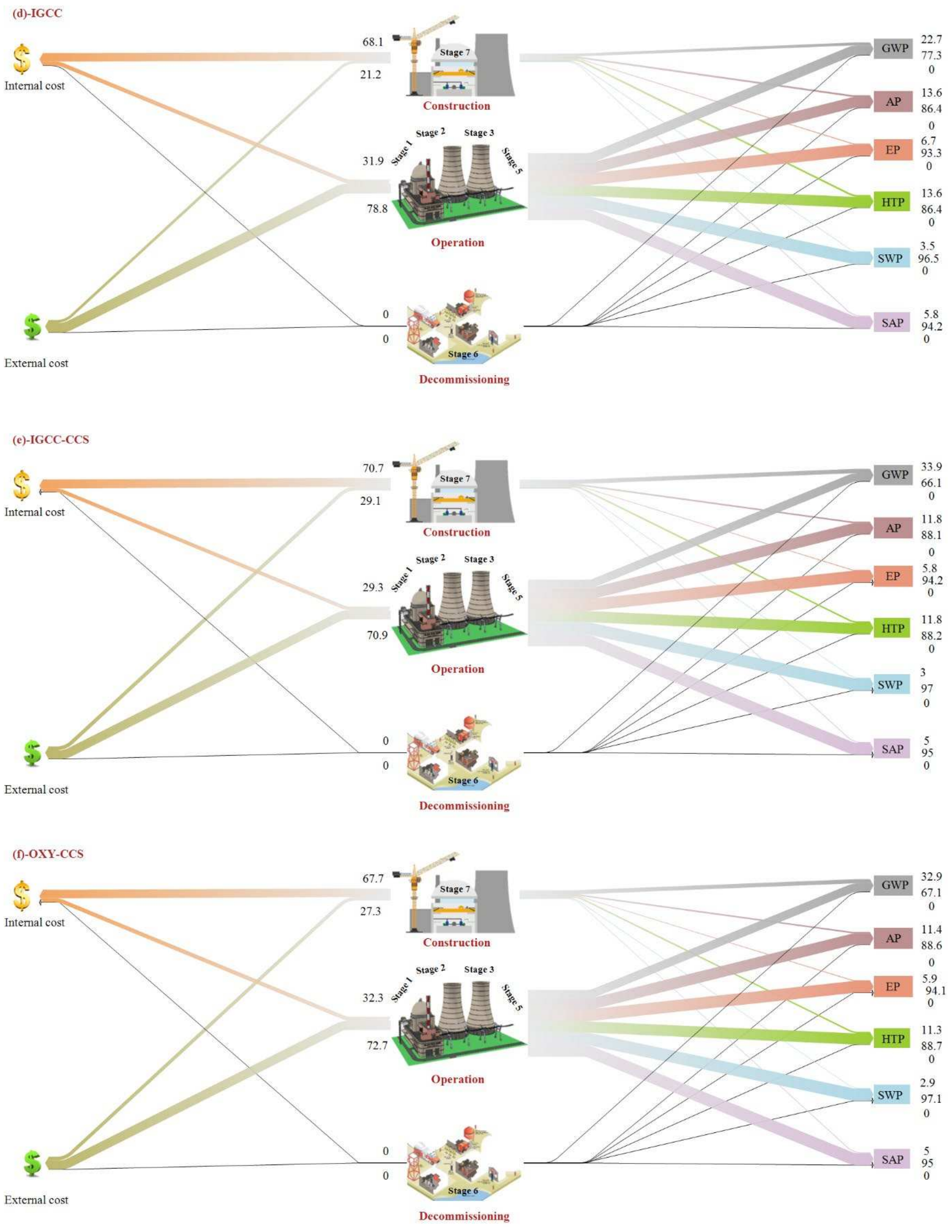


Fig. 6 Grassmann diagram of life cycle assessment (environmental and economic) of coal-based power plants (stage 1: coal/OC/ mineral mining; Stage 2: coal/OC washing; Stage 3: raw material transportation; Stage 5: waste transportation; Stage 6: waste transportation in decommissioning; Stage 7: materials transportation in construction)

Table 3 Environmental effect potential of coal-based power plants

Power plants	Environmental impact potential	Construction	Operation	Decommissioning	Total
CLC	GWP/ (kg CO_2 eq/ (kW h))	6.52×10^{-1}	8.50×10^{-1}	4.42×10^{-5}	1.50
	AP/ (kg SO_2 eq/ (kW h))	1.11×10^{-3}	3.86×10^{-3}	6.29×10^{-8}	4.98×10^{-3}
	EP/ (kg NO_3 eq/ (kW h))	5.24×10^{-7}	3.01×10^{-6}	0	3.53×10^{-6}
	HTP/ (kg / (kW h))	1.31×10^{-3}	4.55×10^{-3}	7.21×10^{-8}	5.68×10^{-3}
	SWP/ (kg / (kW h))	3.54×10^{-3}	9.10×10^{-2}	0	9.45×10^{-2}
	SAP/ (kg / (kW h))	7.15×10^{-4}	9.46×10^{-3}	0	1.02×10^{-2}
USC	GWP/ (kg CO_2 eq/ (kW h))	4.23×10^{-1}	2.33	1.96×10^{-5}	2.76
	AP/ (kg SO_2 eq/ (kW h))	7.25×10^{-4}	7.17×10^{-3}	9.54×10^{-8}	7.90×10^{-2}
	EP/ (kg NO_3 eq/ (kW h))	3.45×10^{-7}	6.58×10^{-6}	0	6.92×10^{-6}
	HTP/ (kg / (kW h))	8.53×10^{-4}	8.47×10^{-3}	1.14×10^{-7}	9.32×10^{-2}
	SWP/ (kg / (kW h))	2.31×10^{-3}	9.87×10^{-2}	0	1.01×10^{-1}
	SAP/ (kg / (kW h))	4.64×10^{-4}	1.08×10^{-2}	0	1.13×10^{-2}
USC-CCS	GWP/ (kg CO_2 eq/ (kW h))	1.12×10^{-1}	1.30	3.69×10^{-5}	1.41
	AP/ (kg SO_2 eq/ (kW h))	7.67×10^{-4}	8.50×10^{-3}	5.87×10^{-8}	9.27×10^{-3}
	EP/ (kg NO_3 eq/ (kW h))	3.91×10^{-5}	7.80×10^{-6}	0	4.69×10^{-5}
	HTP/ (kg / (kW h))	9.04×10^{-4}	1.00×10^{-2}	6.92×10^{-8}	1.09×10^{-2}
	SWP/ (kg / (kW h))	2.70×10^{-3}	1.17×10^{-1}	0	1.20×10^{-1}
	SAP/ (kg / (kW h))	7.40×10^{-4}	1.28×10^{-2}	0	1.35×10^{-2}
IGCC	GWP/ (kg CO_2 eq/ (kW h))	6.05×10^{-1}	2.06	3.91×10^{-5}	2.66
	AP/ (kg SO_2 eq/ (kW h))	1.03×10^{-3}	6.54×10^{-3}	5.80×10^{-8}	7.57×10^{-3}
	EP/ (kg NO_3 eq/ (kW h))	4.90×10^{-7}	6.81×10^{-6}	0	7.30×10^{-6}
	HTP/ (kg / (kW h))	1.22×10^{-3}	7.72×10^{-3}	6.84×10^{-8}	8.94×10^{-3}
	SWP/ (kg / (kW h))	3.29×10^{-3}	8.98×10^{-2}	0	9.31×10^{-2}
	SAP/ (kg / (kW h))	6.44×10^{-4}	1.08×10^{-2}	0	1.15×10^{-2}

Power plants	Environmental impact potential	Construction	Operation	Decommissioning	Total
IGCC-CCS	GWP/ (kg CO_2 eq/ (kW h))	6.10×10^{-1}	1.19	3.96×10^{-5}	1.80
	AP/ (kg SO_2 eq/ (kW h))	1.04×10^{-3}	8.50×10^{-3}	5.85×10^{-8}	8.79×10^{-3}
	EP/ (kg NO_3 eq/ (kW h))	4.94×10^{-7}	7.80×10^{-6}	0	8.56×10^{-6}
	HTP/ (kg / (kW h))	1.23×10^{-3}	1.00×10^{-2}	6.92×10^{-8}	1.04×10^{-2}
	SWP/ (kg / (kW h))	3.32×10^{-3}	1.17×10^{-1}	0	1.10×10^{-1}
	SAP/ (kg / (kW h))	6.69×10^{-4}	1.28×10^{-2}	0	1.35×10^{-2}
Oxy-CCS	GWP/ (kg CO_2 eq/ (kW h))	4.8×10^{-1}	9.83×10^{-1}	3.12×10^{-5}	1.46
	AP/ (kg SO_2 eq/ (kW h))	1.11×10^{-3}	8.62×10^{-3}	6.23×10^{-8}	9.73×10^{-3}
	EP/ (kg NO_3 eq/ (kW h))	5.26×10^{-7}	8.45×10^{-6}	0	8.98×10^{-6}
	HTP/ (kg / (kW h))	1.28×10^{-3}	9.99×10^{-3}	7.21×10^{-8}	1.13×10^{-2}
	SWP/ (kg / (kW h))	3.07×10^{-3}	1.03×10^{-1}	0	1.06×10^{-1}
	SAP/ (kg / (kW h))	6.20×10^{-4}	1.18×10^{-2}	0	1.25×10^{-2}

After different environmental impact potentials were standardized and weighted, the severity of different environmental impacts was compared. The results show that the potential impacts on the environment are GWP, HTP, SWP, AP, SAP, and EP in descending order. The percentages of the potential value of each environmental impact in the total environmental impact were 28.02%, 27.64%, 21.12%, 16.37%, 6.85%, and 0.01%, respectively. EP had the least environmental impact at 0.00003 milli-human equivalents, while GWP had the most environmental impact at 0.1337 milli-human equivalents.

3.1.3 Power plant life cycle cost evaluation and sustainability assessment

Based on the life cycle cost composition (described in detail in 3.2.3), the internal cost is equal to LCOE. The internal cost of the coal-based CLC power plant is 0.122 $/kWh, accounting for 88.77% of the total life cycle cost. According to the calculation of environmental impact cost presented in Table 2, the external cost was 0.016 $/kWh. The reason why the external cost accounted for a relatively low share was that the full life cycle environmental impact of coal chemical looping combustion power generation system was relatively small and the environmental governance cost was reduced. Among them, the environmental governance cost caused by GWP accounts for 84.16%, and the proportion of SWP, HTP, AP, SAP, and EP is 5.30%, 4.15%, 3.44%, 2.95%, and 0.002% respectively.

The higher the SIPP, the better the sustainability of the power plant. SIPP values are related to the life cycle return on energy, resource consumption, life cycle environmental impact potential, and life cycle cost. According to Eqn. 15, the sustainable SIPP value of the coal chemical looping combustion power generation system is 1.51.

3.1.4 Life cycle energy consumption assessment

The energy rate of return is used as the evaluation index to evaluate the energy consumption in the life cycle of a power plant. As coal-based CLC power generation technology has higher power generation efficiency and energy-saving advantages, its energy return rate is 3.22. The detailed analysis and comparison are presented in section 3.2.1.

3.1.5 Sensitivity analysis

Due to data from varied sources, sensitivity analysis is used to estimate the accuracy of the data results. Input parameters are changed to see how much influence it has on the life cycle assessment results (energy payback ratio, resource consumption, and environmental impact potential, sustainability, life cycle cost) by using a sensitivity analysis method. Sensitivity analysis can identify parameters that have a significant impact on the life cycle assessment. Parameters including material transport distance, price of oxygen carrier and oxygen carrier lifetime, coal price, resource consumption and environmental emissions in power plant construction phase, and operation capacity of the power plant are studied. Sensitivity analysis results are presented in Fig. 7.

Fig. 7(a) shows the variations in the energy payback ratio of the different parameters. The energy payback ratio decreases with the increase of input of the power plant construction stage, and the variation range is [+0.39%, -0.39%]. The energy payback ratio increases with the increase of power plant operation capacity, and the change range is [-0.11%, +0.07%]. Other parameters such as material transport distance, oxygen carrier price, oxygen carrier lifetime, and coal price do not affect the energy rate of return. In conclusion, the above key parameters have no significant impact on the energy payback ratio.

It can be seen from Fig. 7(b) that the input in the power plant construction stage has the greatest effect on resource consumption. Resource consumption increases with the increase in input in the power plant construction stage, with the change varying between [-13.60%, +13.60%]. The resource consumption decreases with the increase in the operational capacity of the power plant and the lifetime of the oxygen carrier, and the change range is [+3.64%, -2.55%], [+1.22%, -0.13%], respectively. Other parameters such as material transport distance, oxygen carrier price, and coal price do not affect resource consumption. In conclusion, among these key parameters, the input in the power plant construction stage has the most significant impact on the resource consumption, followed by the operation capacity of the power plant and the lifetime of the oxygen carrier. Therefore, resource consumption can be reduced by reducing the input of the power plant construction stage and increasing the lifetime of the oxygen carrier.

Fig. 7 (c) shows the effect of different parameters on the environmental impact potential value. With the increase in the lifetime of the oxygen carrier, the value of environmental impact potential decreases, with a change range [+17.12%, -1.90%]. When the lifetime of the oxygen carrier is less than 850 h, the environmental impact potential value is sensitive to its variation. The reason is that the short lifetime of the oxygen carriers increases the number of oxygen carriers required in the power plant life cycle, which corresponds to the increase in pollutant emissions caused by oxygen carrier mining, transportation, and waste disposal, and thus leads to the increase in environmental impact potential value. Therefore, oxygen carriers with a lifetime of over 850 h need to be developed. The operation capacity of the power plant increases, and the environmental impact potential value decreases. The variation range is [+12.68%, -

8.50%]. The environmental impact potential value increases with the increase in power plant input in the construction stage, and the variation range is [-12.56%, +12.56%]. With the increase in transportation distance, the corresponding environmental impact potential value increases with the change interval of [-1.00%, +1.00%], while the oxygen carrier price and coal price have no influence on the environmental impact potential value. From the above analysis, it can be concluded that the parameters that have a significant impact on the environmental impact potential include the lifetime of the oxygen carrier, operation capacity of the power plant, and the input in the power plant construction stage, while the other parameters have no significant impact on the environmental impact potential. Therefore, the impact of power plants on the environment can be reduced by reducing the power plant construction stage input, increasing the operational capacity of the power plant, and increasing the lifetime of the oxygen carriers.

Fig. 7 (d) shows the influence of the changes of different parameters on life cycle cost. Life cycle cost increases with the increase in coal price, power plant input in the construction stage, oxygen carrier price and transportation distance, with the variation ranges of [-20.43%, +20.86%], [-3.35%, +3.35%], [-2.84%, +3.27%] and [-0.35%, +0.35%], respectively. Life cycle cost decreases with the increase in the operational capacity of the power plant and the lifetime of the oxygen carrier, and the variation range is [+12.67%, -8.50%] and [+16.69%, -1.61%], respectively. To sum up, the effects of coal price, operation capacity of the power plant, lifetime of the oxygen carrier, power plant input in the construction, oxygen carrier price, and transportation distance on the life cycle cost of the power plant are reduced sequentially. Therefore, reducing the price of coal and the power plant input in the construction, and increasing the operational capacity of the power plant, and the lifetime of the oxygen carrier are effective ways to reduce the life cycle cost.

Fig. 7(e) shows the impact of different parameter variations on plant sustainability. The sustainability of power plant decreases with the increase in coal price, power plant input in construction stage, oxygen carrier price and transportation distance, and the change range is [+25.66%, -17.25%], [+3.88%, -3.63%], [+2.92%, -3.17%] and [+0.36%, -0.35%], respectively. With the increase of operation capacity of the power plant and the lifetime of the oxygen carrier, the change range of the power plant's sustainability was [-11.34%, +9.37%] and [-14.31%, +1.64%], respectively. Through the sensitivity analysis of key parameters, it can be seen that coal price, operation capacity of the power plant, and oxygen carrier lifetime have significant impacts on the power plant sustainability, while power plant input in the construction stage, oxygen carrier price, and transportation distance has a less significant influence on the sustainability. Therefore, an effective way to increase the sustainability of the power plant is by reducing the input in the construction stage, increasing the operational capacity of the power plant, and increasing the lifetime of the oxygen carrier.

3.2 Comparison of life cycle comprehensive performance

On the principle of the same life-cycle boundary and calculation method, with 1 kWh energy output as the functional unit, the life-cycle impact assessment of coal-based CLC power plant was compared with the life-cycle impact assessment results of the five coal-based power plants: USC, USC-CCS, IGCC, IGCC-CCS and Oxy-CCS.

3.2.1 Comparison of resource consumption

Results comparing resource consumption are shown in Fig 8(a). In terms of absolute resource consumption, USC-CCS power plants had a maximum resource consumption of 648.69 g/kWh over the whole life cycle, and Oxy-CCS power plants had a minimum resource consumption of 461.37 g/kWh in those power plants with CCS, which is close to the resource consumption of CLC (461.87 g/kWh). The amount of coal has the greatest influence on resource consumption, accounting for 83.6% ~ 95.2%. Power generation technologies with high coal consumption should not be built far away from coal mines, such as USC-CCS, IGCC-CCS, USC, and IGCC power plants. Limestone is second only to coal in the proportion of resource consumption, and limestone is mainly used for desulfurization in power plants. The crude gas purification system of the IGCC power plant uses methyl diethanolamine for desulfurization. The consumption data of methyl diethanolamine during desulfurization can be replaced by a 20% ammonia solution. IGCC ammonia consumption is higher than that of other power plants.

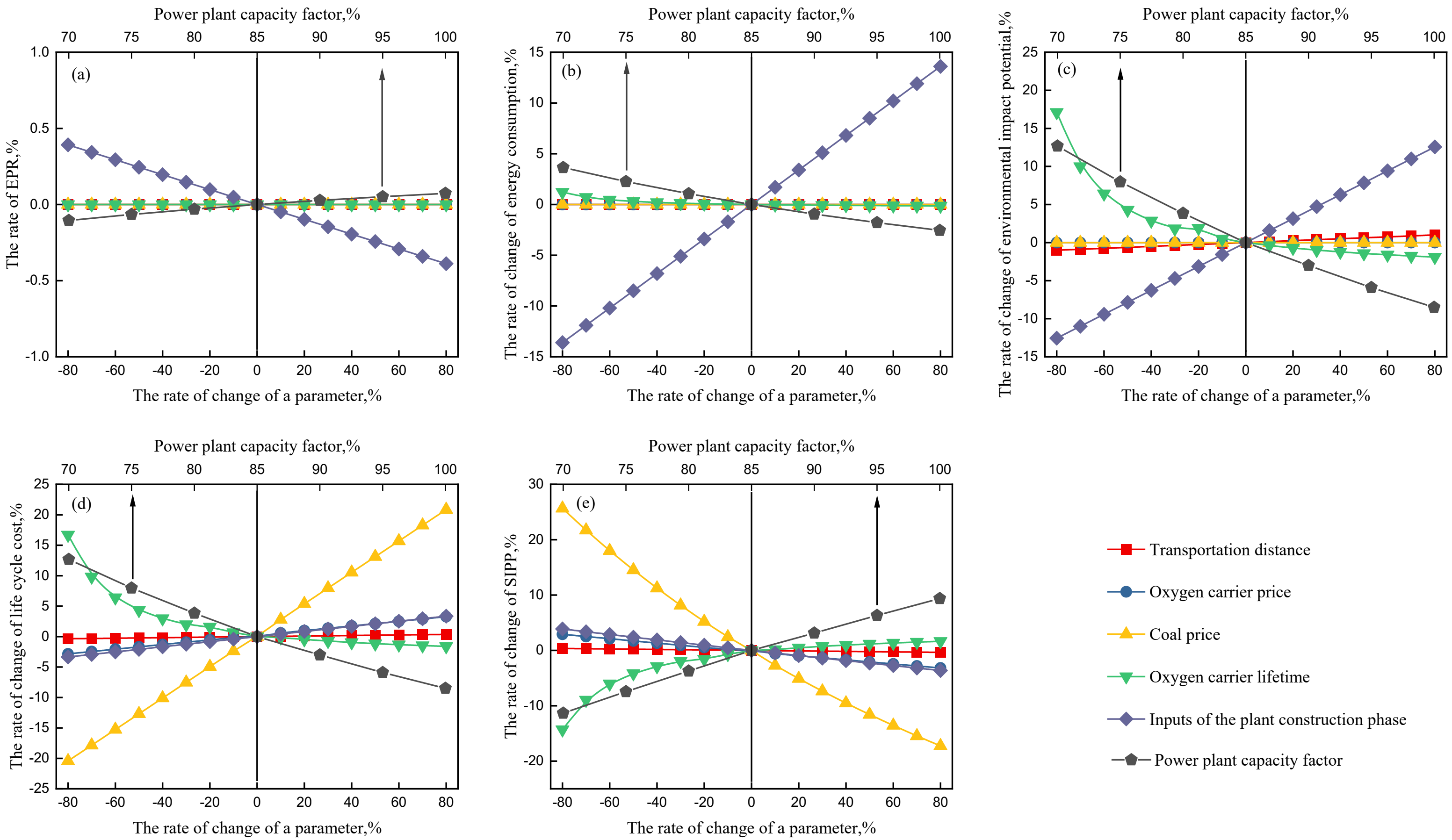


Fig. 7 Sensitivity analysis of life cycle assessment

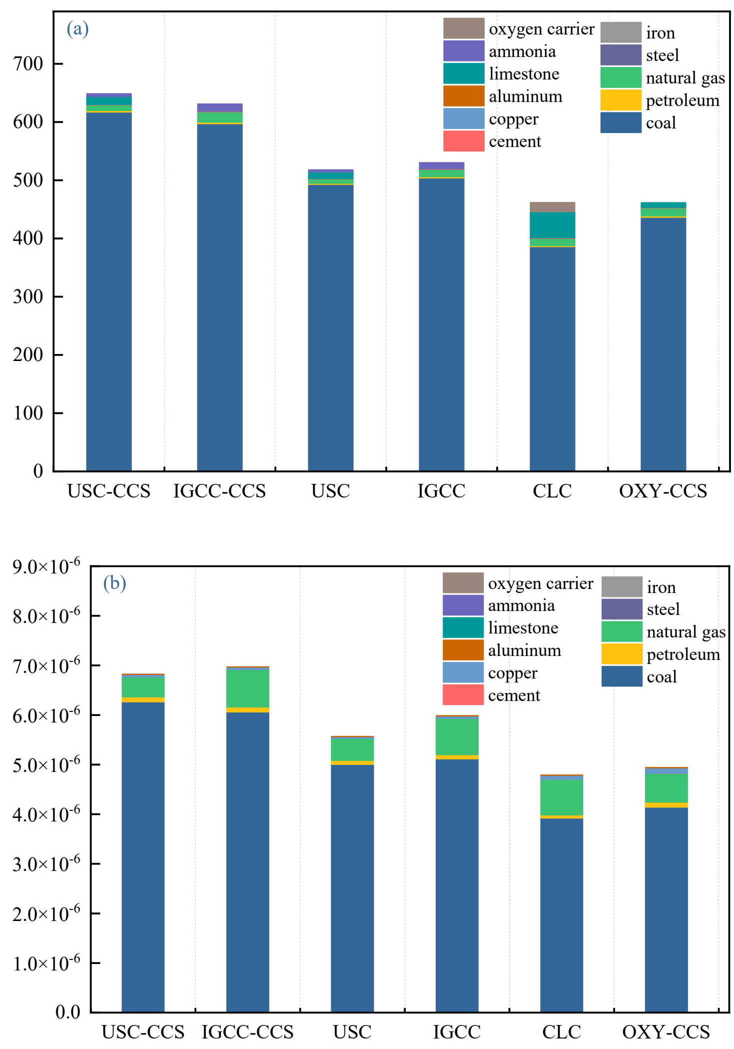


Fig. 8 Resource's consumption (a) (g/kWh) and resource depletion indicators (b) in the life cycle of six clean coal-fired power plants

To explore the influence of different resource consumption on the resource depletion indicators, the proportions of different resource consumption are obtained by standardizing and weighting different resource consumption, as shown in Fig.8(b). After standardization and weighting, coal consumption takes up the main part. Among the six types of coal clean power plants, the proportion of coal consumption of the coal-based CLC power plant is the lowest (81.88%), and that of the USC-CCS power plant is the highest (91.89%). The resource depletion indicators reflect the pressure of different power generation technologies on resource consumption. In which CLC has the lowest resource depletion indicators, while the resource depletion indicator of Oxy-CCS, USC, IGCC, USC-CCS, and IGCC-CCS power plants is 3.13%, 16.31%, 25.00%, 42.46%, and 45.61% higher than that of CLC, respectively. The consumption of natural gas and oil in the extraction, processing, and transportation of coal also accounts for a large proportion, with USC-CCS power plants having the lowest combined oil and gas consumption (7.39%), while CLC power plant having the highest combined oil and gas consumption (16.34%). And metallic minerals consumption of six power plants is the lowest section. Therefore, the consumption of energy resources accounts for a large proportion of the total resource consumption, and the reduction of the total resource consumption should start from looking at the energy resources.

3.2.2 Comparison of life cycle environmental impact assessment

The environmental impact potential values of different environmental impacts were standardized according to the standard human equivalent, and then multiplied by the corresponding weight factor for weight processing. To obtain the environmental impact potential values that could be used to reflect the severity of different environmental impacts. The results are shown in Fig.9, in which the potential environmental impacts of CLC power generation technology are SAP, SWP, HTP, GWP, AP, and EP in descending order. The environmental impact potentials of Oxy-CCS, USC-CCS and IGCC-CCS are SAP, HTP, SWP, AP, GWP, and EP in descending order. SAP, HTP, GWP, SWP, AP, and EP are the other two power (USC and IGCC) generation technologies' potential impacts on the environment in descending order. Order of potential environmental impacts of CLC, Oxy-CCS, USC-CCS, and IGCC-CCS power plants are different compared with the other two traditional clean coal power generation technologies mainly due to the CO_2 captured in those four power plants, which caused GWP reduction.

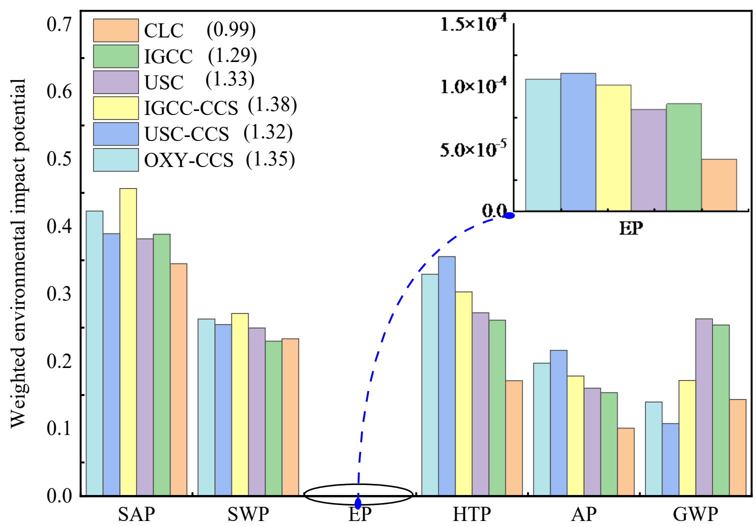


Fig. 9 Weigh of environment effect potential of six clean coal-fired power plants

3.2.3 Comparison of life cycle costs

Fig.10 presents the life cycle cost results of the six coal clean power plants. IGCC-CCS has the largest total life cycle cost, which is 0.193 $/kWh, followed by Oxy-CCS (0.180 $/kWh), USC-CCS (0.168 $/kWh), CLC (0.138 $/kWh), USC (0.123 $/kWh), and IGCC (0.122 $/kWh). The life cycle cost is mainly affected by the cost and amount of coal. USC-CCS, Oxy-CCS, IGCC-CCS, and CLC have a high life-cycle cost due to the energy-intensive CO_2 capture process which reduces the overall generation efficiency, which in turn leads to higher fuel consumption at the plant, resulting in higher life-cycle costs. The internal cost of the power plants with the CO_2 capture process accounts for as much as 77.77% to 91.83%, while the higher environmental impact potential power plants without CO_2 capture account for 1/4 of the total investment cost of the whole life cycle as external costs. Power plants with CCS (USC-CCS, CLC, IGCC-CCS and Oxy-CCS) have the advantage in external cost, however, its internal cost is higher than these power plants without CCS (USC and IGCC). In the external cost part, GWP accounts for 71.60% to 84.46%, which is the main cost for environmental protection.

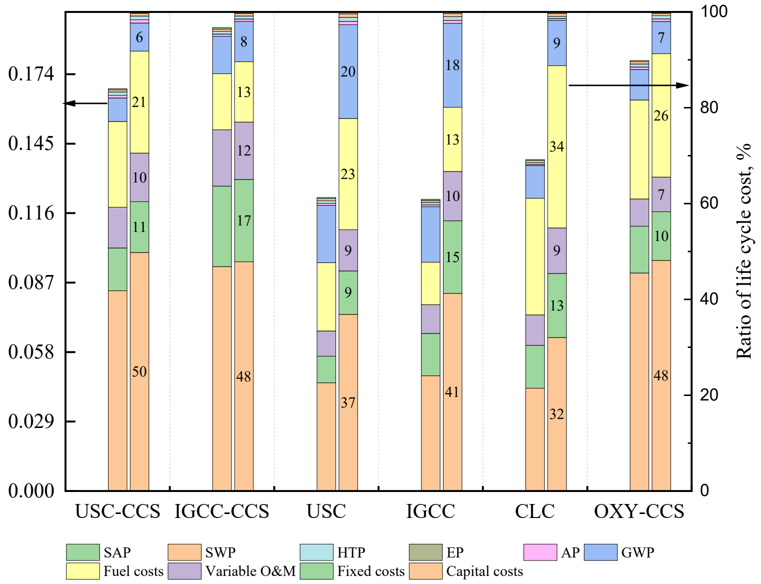


Fig. 10 Life cycle cost ($/kWh) of six clean coal-fired power plants

3.2.4 Comparison of energy consumption and plant sustainability

The energy rate of return is used to evaluate the energy consumption of different power generation technologies. The energy rate of return reflects the energy-saving effect of power plants. Results are shown in Fig.11(a). The energy returns values for USC, CLC, Oxy-CCS, IGCC, USC-CCS, and IGCC-CCS in descending order are 3.59, 3.22, 3.04, 2.81, 2.69, and 2.37, respectively. The results show that the CLC power plant has advantages in energy saving compared with other coal clean power generation technologies.

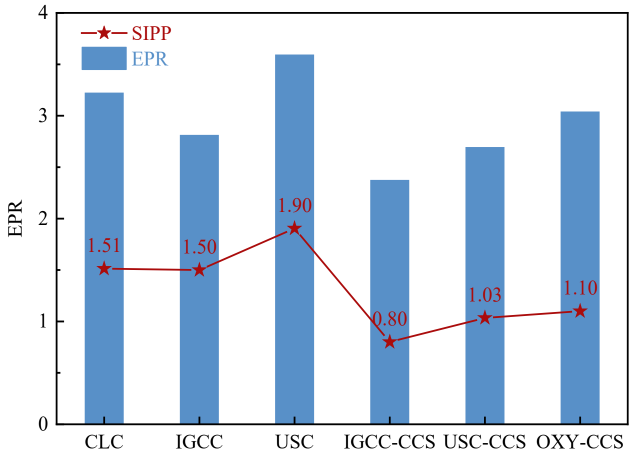


Fig. 11 Energy payback ratio (EPR)and sustainable index (SIPP) values of six clean coal-fired power plants

The sustainability index values of the six clean coal power plants are shown in Fig.11. The sustainability values of six clean coal-based power plants USC, CLC, IGCC, Oxy-CCS, USC-CCS, and IGCC-CCS from high to low are 1.90, 1.51, 1.50, 1.10, 1.03, and 0.80, respectively. USC has the highest sustainability, indicating that USC power plants have lower comprehensive impacts on the environment, resource consumption but higher costs, followed by IGCC power plants. The sustainability of the CLC plant is in the middle state, due to their higher energy returns and lower environmental impact potential. The main reason for the lower sustainability of USC-CCS and IGCC-CCS is that the increased CO_2 capture process reduces the power plant's energy efficiency.

With the range extension of assessment, many energy savings and reductions potential are identified, which are not available in traditional assessments. Compared to conventional techno-economic analysis of coal-based power plants, the life cycle assessment can help us realize the nodes that can reduce CO_2 and improve efficiency. In Table 4, in traditional assessment, resource consumption of the CLC power plant (381.00 g/kWh) is superior compared with other power plants. However, when the range extension to the life cycle, the Oxy-CCS power plant (461.37 g/kWh) becomes the optimal choice. And the gap of six power plants in resource consumption is narrowing after the assessment range is extended. For environmental impact assessment and CO_2 emission, compared with the traditional method, life cycle assessment reveals that the order of environmental impact is changed, especially in the power plants with CCS. In terms of economic analysis (LCOE), the CLC power plant is not the most attractive option. Yet, when considering total life cycle costs, the difference is become narrowing. In brief, the LCA results of this study can further reveal the difference in resource consumption, economic analysis, environmental impact and CO_2 emission, as described above.

Table 4 Results of life cycle assessment compared to conventional techno-economic analysis of coal-based power plants [38, 41-43]

Power plants	resource consumption (g/kWh)		environmental impact assessment (human equivalent)		economic analysis ($/kWh)		CO_2 emission (g/kWh)	
	conventional †	life cycle*	conventional †	life cycle*	conventional †	life cycle*	conventional †	life cycle*
CLC	381.00	461.87	0.86	0.99	0.122	0.138	86.97	383.7
IGCC	308.60	530.23	1.14	1.29	0.096	0.122	1150	1238.4
IGCC-CCS	408.41	631.06	1.23	1.38	0.173	0.193	115	204.1
USC	343.37	518.00	1.23	1.33	0.095	0.123	1350	1411.6
USC-CCS	435.76	648.69	1.31	1.32	0.154	0.168	107.58	140.89
Oxy-CCS	440.64	461.37	1.29	1.35	0.163	0.180	121	209.9

† only including operation stage of power plants

* Including construction stage, operation stage and decommissioning stage of power plant

3.3 Future technological development

A thorough comparison of energy and resource consumption, environmental impact, cost input, and plant sustainability among coal-based power plants was discussed and analyzed in the previous section. It discloses that from a resource consumption perspective, the CLC power plant had a minimum resource consumption due to the step-by-step chemical energy utilized in CLC. From the perspective of energy consumption, the energy rate of return is used to evaluate the energy consumption of power plants, which can reflect the energy-saving effect of power plants. Results indicating that the CLC power plant has advantages in energy-saving. Taking life cycle environmental assessment into consideration, the coal-based CLC power plant can be a primary technology to be considered in the future. By the comprehensive performance comparison, a coal-based CLC power plant reveals itself to be a probable alternative, because of its lower resource depletion indicator, higher energy-saving effect, good environmental benefits (nearly zero-carbon emission), and better sustainability. However, there are some shortcomings in terms of technology readiness levels (OC, AR and FR reactors, heat exchange network, etc.) related to the CLC power plant, which is needed to be broken through to reduce the life cycle cost, energy consumption, and environmental pollution, and to improve power plant sustainability.

Looking at the life cycle assessment of resource consumption, environmental impact, cost input, and energy consumption in different stages (construction, operation and decommissioning), coal and OC consume the major resource. Hence, the future developments in the CLC power plant should be focused on developing lower coal consumption CLC technology and higher lifetime OCs to reduce the high resource consumption in the CLC power plant. Further, through resource depletion indicators analysis, reducing resource consumption should start from coal, petroleum, and natural gas, etc. Moreover, in the aspect of environmental impact, the operation stage of CLC power plant accounts for a major proportion of GWP (53.48%), AP (77.9%), EP (85.2%), HTP (77.9%), SWP (96.4%) and SAP (93.0%). Therefore, researching into reducing the environmental impact in operation stages (coal/OC/mineral mining, raw material transportation, waste transportation, etc.) within the CLC power plant is vital to further improve the overall environmental impact of the CLC technology. In terms of the economic assessment, capital cost and fuel cost account for the majority of life cycle costs. It is expected for CLC technology to cut down capital cost and fuel consumption in the near future as it is still commercializing. Among the external cost, the environmental governance cost caused by GWP accounts for 84.16%, hence it is vital to reduce the GWP cost for external costs in further research. In conclusion, the CLC power plant offers a promising alternative for CO_2 reduction in the power sector. Further research into CLC power plant technology could be very an effective pathway to reach global peaking of greenhouse gas emissions for the power industry from the perfective of resource consumption, economy, and environment.

4. Conclusions

This study established the life cycle assessment model of the power plants including resource consumption, energy consumption, environmental and economic impact, followed by comparing them within different coal-based power plants w/o CO_2 capture. The main conclusions are as follows: Energy resource consumption accounts for the largest proportion in resource consumption, among which coal accounts for 81.88% to 91.89% of the total resource consumption. The key point to reduce resource consumption in the whole life cycle of power plants lies in reducing coal consumption; USC power plant has the highest energy payback ratio, followed by CLC, IGCC, Oxy-CCS, USC-CCS, and IGCC-CCS, with values equal to 3.59, 3.22, 3.04, 2.81, 2.69, and 2.37, respectively. The lower energy payback ratio for IGCC-CCS and USC-CCS is due to the high energy consumption during the construction and operation stages of the power plant. Therefore, the best way to improve the energy payback ratio is to improve the efficiency of power generation and reduce energy consumption during the construction and operation of power plants; Among the environmental impact potentials, SAP has the highest value while EP resulted in the lowest. For the power plants (CLC, Oxy-CCS, USC-CCS, IGCC-CCS) with CO_2 capture, their life cycle GWP is relatively low. The weighted environmental impact potential of a CLC power plant was at least 0.99 milli-human equivalent, while that of IGCC, USC-CCS, USC, Oxy-CCS, and IGCC-CCS were 29.49%, 33.15%, 33.49%, 36.36, and 38.92% higher than that of CLC. Therefore, the environmental impact of the six power plants is IGCC-CCS, Oxy-CCS, USC, USC-CCS, IGCC, and CLC in descending order. CLC power plants have great environmental advantages; The total life cycle costs of IGCC-CCS, Oxy-CCS, USC-CCS, CLC, USC, and IGCC in descending order is 0.193 $/kWh, 0.180 $/kWh, 0.168 $/kWh, 0.138 $/kWh, 0.123 $/kWh, and 0.122 $/kWh, respectively. The power plants were ranked from highest to lowest according to their sustainability as the following: USC, IGCC, CLC, Oxy-CCS, USC-CCS, and IGCC-CCS.

CO_2 emissions are the most important cause of global warming. More severe heat waves, floods, and droughts in a warmer climate are witnessed and getting worse in nowadays. Coal-based power plants make up the vast majority of CO_2 emissions from the sector. To solve this problem, the CLC power plant can be one of the most attractive options for carbon reduction in coal-based power systems in the future, due to its excellent CO_2 reduction performance and high energy efficiency in comparison with the others such as USC, IGCC, or oxy-combustion power plant with CO_2 capture. The results further demonstrated that the coal-based CLC power plant, a low carbon, economical and efficient power generation technology in the life cycle, can solve the issues involving CO_2 emission reduction and energy utilization simultaneously in the coal power generation process.

Acknowledgments

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (U1810125, 51776133), the National Key R&D Program of China (2018YFB0605404), and the Key R&D Program of Shanxi Province (201903D121031).

Nomenclature

Abbreviations

AP	Acidification Potentials
CCS	Carbon Capture and Storage
CLC	Chemical Looping Combustion
CML	Centre for Environment Studies
COE	Cost of Electricity
EP	Eutrophication Potential
EPR	Energy Payback Ratio
FGD	Flue Gas Desulphurization
GCLC-CC	CLC-based Natural Gas Combined Cycles
GHGs	Greenhouse Gases
GW	Global Warming
GWI	Global Warming Impact
GWP	Global Warming Potential
HP	High-pressure
HRSG	Heat Recovery Steam Generators
HTP	Human Toxicity Potential
IGCC	Integrated Coal Gasification Combined Cycle
IP	Intermediate-pressure
LCA	Life Cycle Assessment
LP	Low-pressure
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Electricity
OC	Oxygen Carrier
O&M	Operation and Maintenance
PC	Pulverized Coal
SIPP	Power Plant Sustainability Assessment
SWP	Solid Waste Potential
SAP	Smoke and Dust Potential
TLCC	Total Life Cycle Costs
T&S	Transport and Storage
USC	Ultra-supercritical
VOCs	Volatile Organic Compounds

w/o	with and without

Reference:

[1] Fahad S, Sonmez O, Saud S, Wang D, Wu C, Adnan M, Turan V. Plant growth regulators for climate-smart agriculture: CRC Press; 2021.

[2] Hasanuzzaman M, Fujita M, Oku H, Islam MT. Plant tolerance to environmental stress: Role of phytoprotectants: CRC Press; 2019.

[3] EIA. EIA forecasts renewables will be fastest growing source of electricity generation. 2020; https://www.eia.gov/todayinenergy/detail.php?id=38053. [accessed June, 6 2020].

[4] Lin X, Li Q, Wang L, Guo Y, Liu Y. Thermo-economic analysis of typical thermal systems and corresponding novel system for a 1000 MW single reheat ultra-supercritical thermal power plant. Energy. 2020;201.

[5] Yang M, Zhou Y-l, Wang D, Han J, Yan Y. Thermodynamic cycle analysis and optimization to improve efficiency in a 700 °C ultra-supercritical double reheat system. J Therm Anal Calorim. 2019;141:83-94.

[6] Dzikuć M, Kuryło P, Dudziak R, Szufa S, Dzikuć M, Godzisz K. Selected aspects of combustion optimization of coal in power plants. Energies. 2020;13.

[7] Zhang Z, Zhou R, Ge X, Zhang J, Wu X. Perspectives for 700 °C ultra-supercritical power generation: Thermal safety of high-temperature heating surfaces. Energy. 2020;190.

[8] Vu TT, Lim Y-I, Song D, Mun T-Y, Moon J-H, Sun D, Hwang Y-T, Lee J-G, Park YC. Techno-economic analysis of ultra-supercritical power plants using air- and oxy-combustion circulating fluidized bed with and without CO_2 capture. Energy. 2020;194.

[9] Hoya R, Fushimi C. Thermal efficiency of advanced integrated coal gasification combined cycle power generation systems with low-temperature gasifier, gas cleaning and CO_2 capturing units. Fuel Process Technol. 2017;164:80-91.

[10] Falcke TJ, Hoadley AFA, Brennan DJ, Sinclair SE. The sustainability of clean coal technology: IGCC with/without CCS. Process Saf Environ Prot. 2011;89:41-52.

[11] Qing M, Jin B, Ma J, Zou X, Wang X, Zheng C, Zhao H. Thermodynamic and economic performance of oxy-combustion power plants integrating chemical looping air separation. Energy. 2020;206.

[12] Wu XD, Yang Q, Chen GQ, Hayat T, Alsaedi A. Progress and prospect of CCS in China: Using learning curve to assess the cost-viability of a 2×600 MW retrofitted oxyfuel power plant as a case study. Renewable Sustainable Energy Rev. 2016;60:1274-1285.

[13] Nikam KC, Kumar R, Jilte R. Economic and exergoeconomic investigation of 660 MW coal-fired power plant. J Therm Anal Calorim. 2020:1-15.

[14] Zhai H, Rubin ES. Systems analysis of physical absorption of CO_2 in ionic liquids for pre-combustion carbon capture. Environ Sci Technol. 2018;52:4996-5004.

[15] Xia C, Ye B, Jiang J, Shu Y. Prospect of near-zero-emission IGCC power plants to decarbonize coal-fired power generation in China: Implications from the GreenGen project. J Cleaner Prod. 2020;271.

[16] Wang Y, Zhao Y, Zhang J, Zheng C. Technical-economic evaluation of O_2/CO_2 recycle combustion power plant based on life-cycle. Sci China: Technol Sci. 2010;53:3284-3293.

[17] Tang Y, You F. Life cycle environmental and economic analysis of pulverized coal oxy-fuel combustion combining with calcium looping process or chemical looping air separation. J Cleaner Prod. 2018;181:271-292.

[18] Sikarwar SS, Surywanshi GD, Patnaikuni VS, Kakunuri M, Vooradi R. Chemical looping combustion integrated organic rankine cycled biomass-fired power plant–energy and exergy analyses. Renewable Energy. 2020.

[19] Surywanshi GD, Pillai BBK, Patnaikuni VS, Vooradi R, Anne SB. Energy and exergy analyses of chemical looping combustion-based 660 MWe supercritical coal-fired power plant. Int J Exergy. 2020;31:14-33.

[20] Fan J, Zhu L, Hong H, Jiang Q, Jin H. A thermodynamic and environmental performance of in-situ gasification of chemical looping combustion for power generation using ilmenite with different coals and comparison with other coal-driven power technologies for CO2 capture. Energy. 2017;119:1171-1180.

[21] Thorne RJ, Bouman EA, Sundseth K, Aranda A, Czakiert T, Pacyna JM, Pacyna EG, Krauz M, Celińska A. Environmental impacts of a chemical looping combustion power plant. Int J Greenhouse Gas Control. 2019;86:101-111.

[22] Zhu L, He Y, Li L, Wu P. Tech-economic assessment of second-generation CCS: Chemical looping combustion. Energy. 2018;144:915-927.

[23] Surywanshi GD, Patnaikuni VS, Vooradi R, Anne SB. 4-E and life cycle analyses of a supercritical coal direct chemical looping combustion power plant with hydrogen and power co-generation. Energy. 2021;217.

[24] Surywanshi GD, Pillai BBK, Patnaikuni VS, Vooradi R, Anne SB. 4-E analyses of chemical looping combustion based subcritical, supercritical and ultra-supercritical coal-fired power plants. Energy Convers Manage. 2019;200:112050.

[25] Rajabi M, Mehrpooya M, Haibo Z, Huang Z. Chemical looping technology in CHP (combined heat and power) and CCHP (combined cooling heating and power) systems: A critical review. Applied Energy. 2019;253.

[26] Mendiara T, García-Labiano F, Abad A, Gayán P, de Diego LF, Izquierdo MT, Adánez J. Negative CO2 emissions through the use of biofuels in chemical looping technology: A review. Applied Energy. 2018;232:657-684.

[27] Adnan MA, Pradiptya I, Haque TI, Hossain MM. Integrated diesel fueled chemical looping combustion for power generation and CO_2 capture – Performance evaluation based on exergy analysis. Energy Convers Manage. 2020;206.

[28] Sikarwar SS, Surywanshi GD, Patnaikuni VS, Kakunuri M, Vooradi R. Chemical looping combustion integrated Organic Rankine Cycled biomass-fired power plant – Energy and exergy analyses. Renewable Energy. 2020;155:931-949.

[29] Fan C, Cui Z, Wang J, Liu Z, Tian W. Exergy analysis and dynamic control of chemical looping combustion for power generation system. Energy Convers Manage. 2021;228:113728.

[30] Shijaz H, Attada Y, Patnaikuni VS, Vooradi R, Anne SB. Analysis of integrated gasification combined cycle power plant incorporating chemical looping combustion for environment-friendly utilization of Indian coal. Energy Convers Manage. 2017;151:414-425.

[31] He Y, Zhu L, Li L, Sun L. Zero-energy penalty carbon capture and utilization for liquid fuel and power cogeneration with chemical looping combustion. J Cleaner Prod. 2019;235:34-43.

[32] Navajas A, Mendiara T, Goñi V, Jiménez A, Gandía LM, Abad A, García-Labiano F, de Diego LF. Life cycle assessment of natural gas fuelled power plants based on chemical looping combustion technology. Energy Convers Manage. 2019;198:111856.

[33] Fan J, Hong H, Jin H. Power generation based on chemical looping combustion: Will it qualify to reduce greenhouse gas emissions from life-cycle assessment? ACS Sustainable Chem Eng. 2018;6:6730-6737.

[34] Baumann CT. Cost-to-Capacity Method: Applications and Considerations. The M&Ts Journal. 2014.

[35] Peltola P, Saari J, Tynjälä T, Hyppänen T. Process integration of chemical looping combustion with oxygen uncoupling in a biomass-fired combined heat and power plant. Energy. 2020;210:118550.

[36] Lyngfelt A. Chemical looping combustion: Status and development challenges. Energy Fuels. 2020;34:9077-9093.

[37] Hong H, Jiang Q, Liu X, Zhang H, Jin H. Development of chemical looping combustion power systems at the chinese academy of sciences. Energy Fuels. 2020;34:11791-11812.

[38] Zoelle A, Keairns D, Pinkerton LL, Turner MJ, Woods M, Kuehn N, Shah V, Chou V. Cost

and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3. ; National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV (United States); 2015. p. Medium: ED.

[39] Cau G, Tola V, Bassano C. Performance evaluation of high-sulphur coal-fired USC plant integrated with SNO_X and CO_2 capture sections. Appl Therm Eng. 2015;74:136-145.

[40] Fichera A, Volpe R. Investigating the competitiveness of Carbon Capture and Storage in Italian power plants under different investment scenarios. Int J Greenhouse Gas Control. 2020;93:102859.

[41] James III PhD RE, Kearins D, Turner M, Woods M, Kuehn N, Zoelle A. Cost and performance baseline for fossil energy plants volume 1: bituminous coal and natural gas to electricity. NETL; 2019.

[42] Skone TJ, Jamieson M, Schivley G, Marriott J, Cooney G, Littlefield J, Mutchek M, Krynock M, Shih CY. Life Cycle Analysis: Oxy-combustion Supercritical Pulverized Coal (OxyPC) Power Plants. ; National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States); 2018. p. Medium: ED; Size: 132 p.

[43] Iyengar A, Kuehn N, Shah V, Turner MJ, Woods M, Keairns D. Advanced Oxy-combustion Technology for Pulverized Bituminous Coal Power Plants. ; National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV (United States); 2017. p. Medium: ED.

[44] Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. The international journal of life cycle assessment. 2006;11:80-85.

[45] Jianxin Y. Method and application of product life cycle assessment. Beijing: Published by China Meteorological Press; 2002.

[46] Lianglinag Z. Assessment of whole life cycle of clean coal-fired power generation technology. Chongqing: Chongqing University; 2011.

[47] The calculation method of actual pollutant discharge of 17 industries including thermal power and so on included in the management of pollutant discharge permit. Beijing, China: Ministry of Ecological Environment of the People's Republic of China; 2017.

[48] Di XH, Nie Z, Yuan BR, Zuo TY. Life cycle inventory for electricity generation in China. Int J Life Cycle Assess. 2007;12:217-224.

[49] Lee SH, Lee TH, Jeong SM, Lee JM. Economic analysis of a 600 MWe ultra supercritical circulating fluidized bed power plant based on coal tax and biomass co-combustion plans. Renewable Energy. 2019;138:121-127.

[50] Studies CfE. CML 2 Baseline Method (2000). University of Leiden Leiden; 2001.

[51] Zhou D, An Y, Zha D, Wu F, Wang Q. Would an increasing block carbon tax be better? A comparative study within the stackelberg game framework. J Environ Manage. 2019;235:328-341.

[52] Zhang Y-S, Lu C, Hu Y-X, Zhang B-M, Li J, Tian C-Y, Zhang D-T, Kong L-B, Liu M-C. Assemble from 0D to 3D: anchored 0D molybdenum carbide on 3D octahedral amorphous carbon with excellent capacitive properties. Journal of Materials Science. 2020;55:15562-15573.

[53] Gan Y, Griffin WM. Analysis of life-cycle GHG emissions for iron ore mining and processing in China—Uncertainty and trends. Resour Policy. 2018;58:90-96.

[54] Guimarães da Silva M, Costa Muniz AR, Hoffmann R, Luz Lisbôa AC. Impact of greenhouse gases on surface coal mining in Brazil. J Cleaner Prod. 2018;193:206-216.