

Article

Life-Cycle Exergy Evaluation of Power Generation from Underground Coal Gasification with CCS

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Abstract

Under the carbon neutrality context, underground coal gasification combined cycle (UGCC) power generation with carbon capture and storage (CCS) technology can effectively mitigate climate change and reduce pollutant emissions. However, due to the complexity of the UGC process and significant fluctuations in syngas composition, the overall power generation efficiency of the plant may be affected to some extent. Existing studies have predominantly focused on single-link energy efficiency analysis, with a lack of full life-cycle resource–environment synergistic evaluation based on the extended exergy analysis framework, and comparative sustainability research between UGCC and integrated gasification combined cycle (IGCC) systems remains inadequate. Accordingly, this study establishes an exergy Life-Cycle Assessment model for UGCC power plants based on Aspen Plus, systematically evaluates the resource utilization rate and environmental sustainability index, identifies key influencing factors, and conducts a comparative analysis with IGCC power plants. The results indicate that the comprehensive sustainability performance of UGCC power plants is significantly enhanced after CCS retrofitting, with exergy efficiency reaching 37.56% at an oxygen-to-coal ratio of 0.6 and a water-to-coal ratio of 0.1; compared with IGCC, UGCC demonstrates a superior resource utilization rate but relatively weaker environmental sustainability; and the underground gasification unit is the critical link affecting exergy efficiency. This study offers a new perspective for sustainability assessment of energy systems and provides theoretical support and technical reference for the construction of a low-carbon reliable supply system in the power industry, thereby facilitating the implementation and refinement of a novel sustainable energy system.

Keywords: underground gasification combined cycle; carbon capture and storage; life cycle; exergy efficiency; exergy loss



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1. Introduction

Energy processing and utilization are the primary causes of substantial greenhouse gas (GHG) emissions [1]. Currently, global energy-related carbon emissions account for approximately 80% of total GHG emissions, with one-third originating from the power sector. This proportion is projected to reach approximately 40% by 2040 [2]. The low-carbon transformation of the power sector is therefore of great significance for achieving carbon peaking and carbon neutrality goals. Renewable energy sources such as wind and solar power have become the main sources of incremental electricity supply; however, their supply capacity is subject to considerable uncertainty due to uncontrollable natural

conditions such as climate and solar irradiance [3], resulting in limited energy supply and regulation capabilities. In the process of continuously optimizing the power structure, the power sector should consider China's coal-dominated energy resource endowment and utilize coal as a foundational energy source to provide a reliable safeguard for economic and social development. Seeking efficient clean coal power generation technologies is particularly important for the low-carbon transformation of the power sector.

Underground gasification combined cycle (UGCC) integrates underground coal gasification (UCG) with integrated gasification combined cycle (IGCC), which can not only improve coal resource recovery rates and reduce environmental pollution but can also effectively shorten the traditional coal power industry chain and enhance thermoelectric conversion efficiency [4]. Furthermore, carbon capture and storage (CCS) is regarded as a critical pathway for near-zero emissions from fossil energy [5,6], and the utilization of UCG cavities for CO₂ storage has been validated [7]. The coupling of UGCC with CCS aligns with the low-carbon development requirements of the power industry and holds profound strategic significance for energy security. However, the UCG process, which is located upstream in the UGCC system, is relatively complex and difficult to control, resulting in significant fluctuations in syngas composition and quality [8]. When utilized for power generation, this may introduce considerable uncertainty into the overall energy conversion efficiency of the plant, potentially leading to excessive resource and energy consumption or severe environmental emissions.

Currently, scholars have employed traditional exergy efficiency methods to evaluate the efficiency of UCG and its syngas application energy systems. Eftekhari et al. [9] first predicted the syngas composition, temperature, and coal conversion rate for unmineable deep, thin coal seams under alternating air/steam injection conditions based on existing mathematical models and conducted energy and exergy analyses for UCG-CCS. Verma et al. [10] assessed the hydrogen production efficiency from UCG syngas and the power generation efficiency in combined cycle power plants based on a constructed model. The results indicated that the energy efficiency of hydrogen production from UCG syngas was 58.1%. Without CCS, approximately 4.7% of the energy was converted into electricity fed into the grid in addition to hydrogen production. Shan Peijin et al. [11] established an exergy evaluation model for the UCG system based on the first and second laws of thermodynamics in conjunction with coal underground gasification model tests and analyzed the exergy efficiency and irreversible exergy destruction of the UCG system under different oxygen concentration conditions. The aforementioned studies primarily focused on the exergy efficiency of specific equipment or systems in UCG and syngas application systems, without considering the entire production chain of products from a life-cycle perspective. Consequently, the corresponding analytical results can only provide optimization methods for certain parts of the system, and these studies did not quantify resource consumption and pollutant emissions.

Existing research has primarily focused on technical improvements, yet it remains insufficient for making scientifically sound predictions regarding the overall energy utilization and energy-saving potential of the entire UGCC system. Furthermore, these studies have not assessed the comprehensive sustainability performance of the technology from the perspectives of resources and environment. Energy-saving retrofitting that considers only a single process or unit is inadequate for achieving system-wide optimization.

The mainstream methods for energy system sustainability assessment currently include exergy analysis [12], Life-Cycle Assessment (LCA) [13], and Multi-Criteria Decision Analysis (MCDA) [14,15]. Conventional exergy analysis is widely used to study the thermodynamic perfection of energy conversion systems. However, this method neither considers the total cumulative exergy consumption associated with various resources and utilities

during system construction and operation nor accounts for the environmental impacts caused by pollutant emissions over the entire life cycle. Up to now, among numerous evaluation methods of environmental impact, Life-Cycle Assessment (LCA) can assess the environmental sustainability of industrial processes from a life-cycle perspective and has been extensively applied. However, a major limitation of such evaluation indicators is that there is a general lack of an objective and unified benchmark scale when classifying, characterizing, and standardizing various environmental effects. Although MCDA can aggregate heterogeneous indicators from different dimensions to achieve comprehensive multi-scheme optimization, the weight assignment step is highly subjective, and it is difficult to explain the thermodynamic loss mechanisms underlying energy degradation.

The Exergetic Life-Cycle Assessment (ExLCA) theory was proposed by scholar Cornelissen in 1997 [16]. As a methodology integrating conventional exergy analysis and LCA, ExLCA accounts for the cumulative exergy consumption corresponding to all resources and utilities and conducts quantitative evaluation of the environmental impacts of pollutant emissions throughout the entire life cycle. It considers not only the quantity of energy but also evaluates the energy losses throughout the entire system, yielding more comprehensive results. Currently, ExLCA has been gradually applied to multiple fields, including thermal power generation, solar thermal power plants, optimal thickness design of building pipelines, and biodiesel production. Based on this theory, this paper conducts quantitative assessments of system resource utilization, pollutant emissions, and energy conversion, identifies unscientific energy utilization links, and aims to provide a scientific quantitative basis for optimizing the deep underground coal gasification power generation process.

The contributions of this study are reflected in several aspects. Firstly, the new life-cycle exergy analysis framework has been established for UGCC-CCS power plants. Two categories of evaluation indicators are innovatively configured: resource exergy sustainability and pollutant environmental sustainability, enabling the collaborative quantitative assessment of full life-cycle resource depletion and pollutant emissions. This forms a comprehensive evaluation system that simultaneously accounts for thermodynamic energy efficiency and environmental sustainability. Secondly, we have constructed a full life-cycle exergy assessment model for UGCC-CCS using Aspen Plus (AspenTech, Bedford, MA, USA), which concurrently accounts for resource, pollutant, and energy conversion indicators. This model precisely identifies low-efficiency energy utilization units and guides system optimization. The model possesses universal applicability and can be extended to other deep decarbonization industrial sectors. Finally, the research results provide a new perspective for evaluating and improving the comprehensive sustainability of energy systems and offer a scientific basis for technical personnel in relevant industries to identify critical links for efficiency improvement. Additionally, the findings contribute to the energy-saving and carbon reduction upgrading of low-carbon energy systems.

2. Methods and Data

Extended exergetic life-cycle analysis can be regarded as an exergy analysis of the entire life cycle of a system. Its framework follows the LCA framework in accordance with ISO standards [17,18] and is divided into four stages, as shown in Figure 1. The detailed description of each stage is as follows:

- (1) The first stage of extended ExLCA is identical to that of traditional LCA, encompassing the research objectives and system boundaries.
- (2) The inventory analysis is more detailed than that of traditional LCA. According to the defined system boundaries, energy and resource consumption as well as pollutant emissions throughout the entire life cycle of the system need to be obtained.

The physical parameter exergy is selected as a unified standard for measuring energy consumption and environmental impact.

- (3) The impact assessment differs considerably from LCA. This stage introduces cumulative exergy and exergy abatement indicators, based on which the resource utilization rate and environmental sustainability index are defined to evaluate the comprehensive sustainability of the power plant from the perspectives of resource utilization and GHG emissions. Finally, traditional exergy analysis is employed for further optimization and improvement.
- (4) The interpretation of results presents relevant conclusions and recommendations for decision makers.

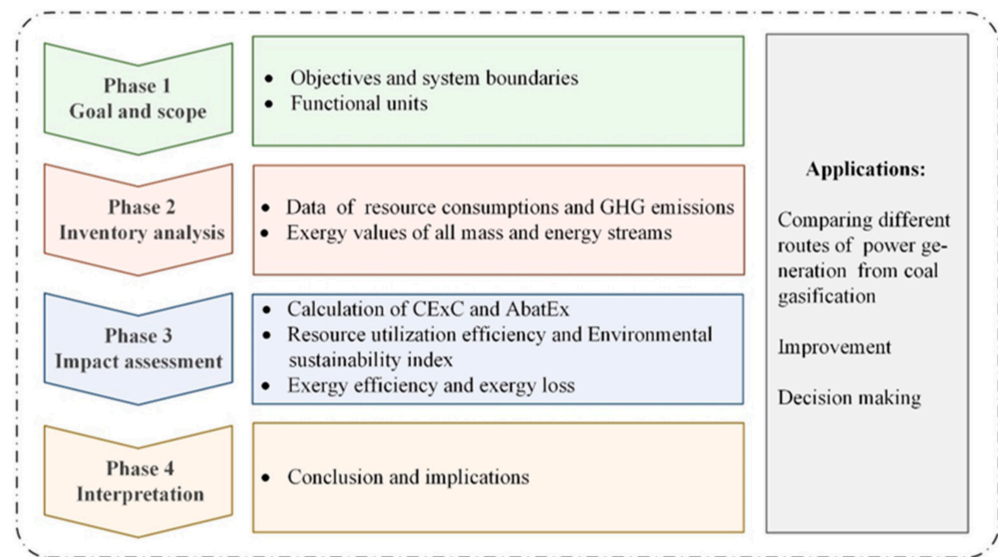


Figure 1. The extended ExLCA framework for all cases.

2.1. Goal and Scope

2.1.1. Research Objectives

This study primarily focuses on the exergy efficiency, resource utilization rate, and environmental sustainability of UGCC power plants. The results are compared with those of IGCC power plants to determine whether UGCC power plants possess advantages in energy efficiency. Meanwhile, to better understand the potential role of CCS in coal-fired power plants and its impact on plant energy efficiency, the scenario with CCS retrofitting is also considered. Accordingly, this study mainly includes four scenarios: UGCC, IGCC, UGCC-CCS, and IGCC-CCS power plants.

2.1.2. System Boundary and Functional Unit

The system boundary encompasses all units related to power generation [19]. The system boundary of the IGCC-CCS is divided into three stages: an upstream stage encompassing coal mining, washing, and transportation; a plant stage involving power generation and carbon capture; and a downstream stage comprising CO₂ transport and storage. The system boundary of UGCC-CCS is identical to that of IGCC-CCS in both the plant and downstream stages, with significant differences existing only in the upstream stage. The upstream stage of UGCC comprises gasification agent preparation, underground coal gasification, and syngas purification units. Owing to data unavailability, coupled with the negligible impact of infrastructure construction and personnel activities on the overall results, the system boundary of this study excludes various infrastructure constructions and human production activities.

Given the high similarity between the system boundaries of power plants with and without CCS retrofitting, only UGCC-CCS and IGCC-CCS are selected as representatives. As shown in Figures 2 and 3, the system boundary is divided into three stages: (i) First is the upstream stage (S1), which includes all processes for fuel acquisition. Since the fuels delivered to the plant differ between UGCC and IGCC—syngas and coal, respectively—the upstream stage processes also vary. For UGCC power plants, the upstream stage includes gasification agent preparation (S1-1) and underground gasifier construction (S1-2). For IGCC power plants, the upstream stage includes coal mining and washing (S1-1) and coal transportation (S1-2). (ii) The power production stage is next (S2), which includes power generation and CO₂ capture. (iii) The downstream stage is last (S3), which includes CO₂ transportation and storage. To ensure comparability of results across all stages of the power plants, the production of 1 MWh of electricity is adopted as the unified functional unit.

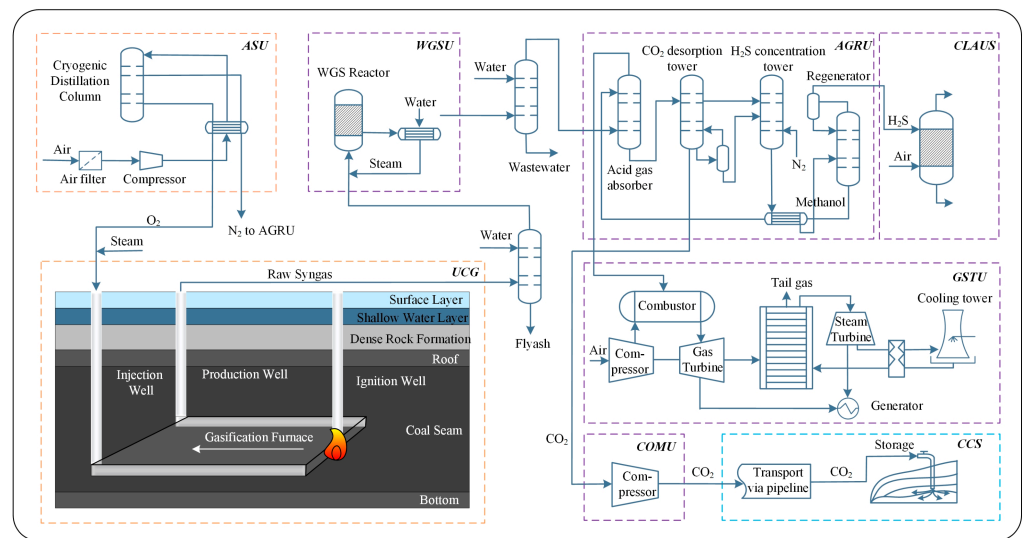


Figure 2. The system boundary for UGCC-CCS.

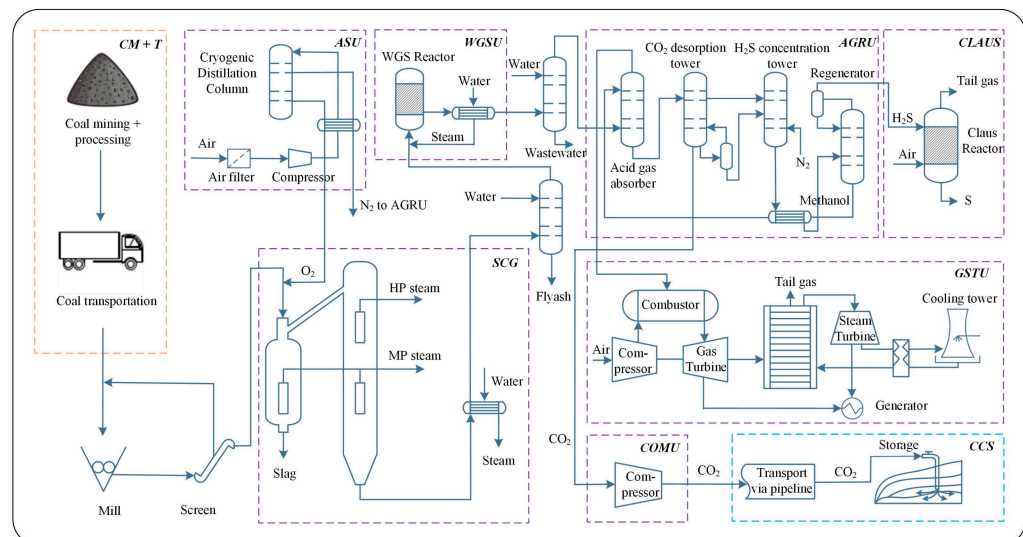


Figure 3. The system boundary for IGCC-CCS.

2.2. Process Flow and System Modeling

The key to assessing the exergy efficiency and comprehensive sustainability performance of UGCC and IGCC power plants lies in obtaining energy and resource input and output data for each stage of the plant, which is rather difficult. To compensate for this

deficiency, Aspen Plus models for UGCC and IGCC power plants with and without CCS retrofitting were established. Figures 2 and 3 illustrate the basic power generation processes for the two types of power plants.

In addition, the process units for power generation in both types of power plants are similar, including the air separation unit, coal gasification unit, water–gas shift unit, acid gas removal unit, CLAUS unit, gas and steam turbine units, CO₂ compression unit, and CO₂ transportation and storage unit. It should be noted that the energy consumption for CO₂ capture mainly includes the energy consumption for methanol recycling and CO₂ compression. Inner Mongolia bituminous coal was selected as the fuel, and the coal composition is listed in Table 1.

Table 1. Coal characteristics in the study [2].

Rank	Bituminous Coal
Proximate analysis (% wt. dry basis)	
Fixed carbon	33.00
Volatile matter	4.95
Ash	14.29
Moisture	14.29
Ultimate analysis (% wt. dry basis)	
Carbon	69.94
Hydrogen	4.69
Oxygen	19.38
Nitrogen	0.79
Sulfur	0.25
Ash	4.95
Lower heating value (MJ/kg)	28.18

The underground coal gasification power generation system uses oxygen with a purity of 95%, pressurized to 20 MPa, combined with liquid water as gasification agents injected into the coal seam. The underground gasification pressure is set at 12 MPa according to experimental conditions. After extraction from the well, the raw gas is progressively spray-cooled to 230 °C with condensed water, separated, and then subjected to CO water-gas shift and waste heat recovery to co-produce 1.2 MPa low-pressure steam. Subsequently, deep removal of H₂S and CO₂ is achieved through Rectisol. The purified clean syngas is supplied to the combined power generation cycle unit, where energy conversion is accomplished via a gas turbine–steam turbine combined cycle, realizing clean and efficient power generation from deep coal resources. The key parameters for process modeling are shown in Table 2.

In UGCC power plants, the Controlled Retracting Injection Point (CRIP) gasification process is adopted. This process first ignites the coal seam through an ignition system; after the ignited coal seam is consumed, the ignition system is retracted via coiled tubing above the ground surface to form a new gasification zone until the coal seam is completely gasified, enabling orderly control of the underground gasification combustion reaction. This is a widely adopted process at the present stage [21]. In contrast, the Shell gasifier commonly used in IGCC power plants is selected. Since the rational design and operation of the gasifier is the key to project success, the accuracy of gasification unit simulation will significantly affect the results. To verify the reliability of the model, the UCG and SCG simulation results were compared with field test data and literature data, respectively. As shown in Table 3, the deviations in syngas composition are relatively small, ranging from 0.1% to 5%, based on the assumed conditions and selected parameters and in accordance with the principles of energy conservation and mass conservation.

Table 2. Design parameters in Aspen Plus simulation for UGCC and IGCC systems [20].

Process Parameter	Value
Air separation unit	
Oxygen purity (vol.)	95%
Oxygen and nitrogen delivery pressure (MPa)	4
Power consumption (kWh/tO ₂)	402.78
Coal gasification unit	
Oxygen/coal ratio (kg/kg)	0.63
H ₂ O (steam)/coal ratio (kg/kg)	0.12
Gasification pressure (MPa)	4
Gasification temperature (°C)	1400
Water–gas shift unit	
Pressure in the reactor (MPa)	3.47
H ₂ O/CO mole ratio	2
Inlet temperature (°C)	280
Outlet temperature (°C)	386
Acid gas removal unit	
Absorber pressure (MPa)	3.2
H ₂ S removal yield (%)	>99.99
CO ₂ removal yield (%)	99.2
Temperature in CLAUS burner (°C)	1100
Pressure in CLAUS burner (MPa)	0.06
Gas turbine	
Net power output (MW)	370
Gas turbine pressure ratio	30
Turbine inlet temperature (°C)	1327
Turbine outlet temperature (°C)	690
Heat recovery steam generator	
Pump efficiency	0.92
Steam turbine	
Net power output (MW)	170
Three pressure levels for HP/MP/LP (MPa)	12/3.5/0.3
HP/IP/LP ST isentropic efficiency (%)	90/87/85
Inlet HP/IP steam temperature (°C)	564/322
Carbon capture	
Carbon capture rate (%)	80

Table 3. The validation of UCG and SCG modeling results.

Syngas Component	UGC (mol%)		SCG (mol%)	
	Simulation	Field Test	Simulation	Literature [2]
CO	9.93	8.83	55.83	54.85
H ₂	15.59	18.21	35.11	31.21
CO ₂	33.19	31.77	2.5	4.25
N ₂	0.79	0.27	0.59	0.73
H ₂ O	29.76	30	5.18	7.9

Lurgi fixed-bed pressurized gasification and underground coal in situ gasification share similar reaction mechanisms. This study adopts a staged reactor modeling approach for the surface pressurized gasifier. The RStoic reactor is employed to simulate coal drying and devolatilization, with the Calculator block embedded with a Fortran subroutine to calculate the drying ratio and pyrolysis product yields based on coal quality analysis data. The RGibbs reactor is used to solve the combustion reactions and homogeneous/heterogeneous gas-phase reactions. Two sets of HeatX heat exchangers are configured to simulate the medium-pressure steam generation from the water jacket and

the low-pressure steam production from waste heat boiler recovery, respectively. Finally, the Sep block is used to separate and discharge solid ash residues. According to the results of the Aspen model, the mass and energy balance data for the power generation stage under the four scenarios were obtained, as detailed in Tables 4 and 5.

Table 4. Mass and energy balances for UGCC with and without CCS.

Input	Units	Value		Output	Units	Value	
		UGCC	UGCC-CCS			UGCC	UGCC-CCS
Coal	t/h	237.70	254.80	Electricity product	MWh/h	540	540
Air	t/h	2002.31	2126.69	Captured CO ₂	t/h	0	409.61
Boiler feed water	t/h	351.03	367.99	Flue gases	t/h	1605.56	1429.89
Cooling water	t/h	0	346.19	Sulfur	t/h	0.44	0.26
Methanol	t/h	640.20	1114.41	Ash and loss	t/h	20.18	21.65
Steam	t/h	0	350.22	Condensate	t/h	41.50	200.91
				Waste gas	t/h	128.77	512.42
				Regenerated methanol	t/h	640.93	1105.11
				Waste nitrogen	t/h	25.23	10.67
				Exhaust steam	t/h	322.51	337.41
				Nitrogen	t/h	446.13	186.18
				Circulating cooling water	t/h	0	346.19

Table 5. Mass and energy balances for IGCC with and without CCS.

Input	Units	Value		Output	Units	Value	
		IGCC	IGCC-CCS			IGCC	IGCC-CCS
Coal	t/h	204.17	218.20	Electricity product	MWh/h	540	540
Air	t/h	1743.74	1851.16	Captured CO ₂	t/h	0	356.33
Boiler feed water	t/h	297.50	317.95	Flue gases	t/h	1593.85	1428.53
Cooling water	t/h	0.00	346.19	Sulfur	t/h	0.39	0.23
Methanol	t/h	542.15	1049.70	Ash and loss	t/h	10.62	11.35
Steam	t/h	0	354.43	Condensate	t/h	15.47	188.55
				Waste gas	t/h	73.73	448.89
				Regenerated methanol	t/h	542.85	1036.50
				Waste nitrogen	t/h	15.78	16.86
				Exhaust steam	t/h	273.00	291.76
				Nitrogen	t/h	261.89	12.43
				Circulating cooling water	t/h	0	346.19

2.3. Life-Cycle Inventory Analysis

Life-cycle inventory data collection is the most critical task in this study. The inventory includes a series of data on inputs (such as materials, energy, resources, etc.) and outputs (emissions to air, water, and soil) throughout the entire life cycle of the power plant. Its accuracy directly affects the final assessment results and should be handled with caution. The data sources for each stage are described below.

2.3.1. Coal Mining and Washing (IGCC-S1-1)

According to the China Energy Statistical Yearbook 2018 [22], producing 1 MJ of coal requires 0.0472 MJ of raw coal, 0.0007 MJ of natural gas, 0.0007 MJ of diesel, and 0.0029 MJ of electricity. Based on the above process energy consumption for producing 1 MJ of coal and the total coal production, the process energy consumption for this stage of the power plant can be obtained. It should be noted that coal loss during the coal mining and washing process accounts for 18% [23], and this portion of coal resources is also included in the calculation. The process energy consumption results for each stage of the two power plants are shown in Table 6. The GHG emissions for this stage are calculated based on the total

coal production and the indirect GHG emission coefficients for coal during the mining and washing process.

Table 6. Process energy consumption for each stage of UGCC and IGCC with and without CCS.

Power Plants	Process Energy Consumption in Each Stage (MJ/540 MWh)						
	Coal	NG	Diesel	Electricity	Furnace Oil	Steam	Gasoline
UGCC							
Underground gasifier construction	-	-	3308	-	-	-	-
Power generation	6,698,466			428,684		270,308	
UGCC-CCS							
Underground gasifier construction	-	-	3308	-	-	-	-
Power generation	7,179,728	-	-	587,859	-	1,317,844	-
CO ₂ transportation and storage	-	-	-	13,360	-	-	-
IGCC							
Coal mining and washing	271,507	4114	4114	16,455			
Coal transportation	-	-	17,596	10,171	8521	-	2430
Power generation	5,753,116	-	-	337,811	-	316,604	-
IGCC-CCS							
Coal mining and washing	290,179	4396	4396	17,584			
Coal transportation	-	-	18,806	10,869	9105		2597
Power generation	6,148,768	-	-	484,841	-	1,400,978	-
CO ₂ transportation and storage	-	-	-	11,356	-	-	-

2.3.2. Coal Transportation (IGCC-S1-2)

It is assumed that the UGCC power plant is built near the UCG site, and the produced syngas can be directly transported to the power plant, avoiding long-distance fuel transportation. Therefore, the transportation stage only considers coal transportation. Generally, coal transportation employs a combination of railway, waterway, and highway [24]. According to relevant reports, the average transportation distances are 659 km by railway, 1410 km by waterway, and 310 km by highway [25]. Table 7 provides energy consumption intensity, the proportion of each transportation mode, and process energy consumption data used in transportation, which can be used to calculate all energy consumption for the transportation stage. In addition, GHG emissions at this stage include both direct and indirect emissions. Direct emissions originate from process energy use during transportation, while indirect emissions are caused by the production of process energy. The total GHG emissions for this stage can be calculated based on the process energy consumption data for the transportation stage shown in Table 6.

Table 7. Related data of three coal transportation modes.

Transportation Mode	Average Distance (km)	Proportion (%)	Energy Consumption Intensity (kJ/(t·km))			
			Diesel	Gasoline	Electricity	Residual Oil
Railway	659	70	132	-	108	-
Waterway	1410	20		-	-	148
Road	310	10	816	384	-	-

2.3.3. Underground Gasifier Construction (UGCC-S1-2)

The prerequisite for obtaining UCG syngas is the completion of underground gasifier construction, which can be regarded as being composed of multiple UCG modules. Each UCG module consists of three parts: an injection well, a production well, and a gasification channel connecting the two [26]. It is assumed that the coal seam mining depth is 800 m and the coal seam pressure is 4 MPa. The plant operating life is 30 years with a capacity factor of 80%. According to the existing literature, the coal production capacity of a single UCG module is 230 t/d [27]. Combined with the total coal demand of the UGCC power plant, the number of UCG modules required is calculated to be 34. Diesel is used as the power source for drilling, and the total diesel consumption can be calculated based on the number of UCG modules using the calculation methods from the existing literature [28,29].

2.3.4. Power Generation (UGCC-S2 and IGCC-S2)

In the power generation stage, energy consumption originates from two parts: process energy consumption required for electricity production and energy consumption for the CO₂ capture process. All process energy consumption data for this stage are derived from Aspen Plus modeling results (see Table 6). To achieve the established target of producing 540 MWh of electricity, the coal demands for UGCC and IGCC power plants are 237.7 t/h and 204.2 t/h, respectively. After CCS retrofitting, the coal demands for the two power plants increase to 254.7 t/h and 218.2 t/h, respectively. GHG emissions at this stage are similar to those described above, including both direct and indirect emissions. Direct emissions mainly come from exhaust gas, which contains a large amount of CO₂ and almost no CH₄ and N₂O. In UGCC and IGCC power plants, the direct CO₂ emissions are 512.5 t/h and 442.6 t/h, respectively. After CCS retrofitting, the CO₂ emissions from the two power plants are reduced to 117.7 t/h and 107.1 t/h, respectively.

2.3.5. CO₂ Transportation and Storage (UGCC-S3 and IGCC-S3)

The energy consumption at this stage is primarily electricity consumption, originating from two aspects. On the one hand, the captured and compressed CO₂ is transported to the storage site via pipeline, with an assumed transportation distance of 200 km. Due to pressure drop during pipeline transportation of CO₂, two booster stations are established for safety considerations. The electricity consumption of compressors at the booster stations is 0.00864 MJ/kg CO₂ [30]. On the other hand, to achieve the required storage pressure, the CO₂ needs to be recompressed to 15 MPa before injection into the storage site. The electricity consumption for compressing 1 kg of CO₂ in this process is 0.0252 MJ [31]. The total electricity consumption results for this stage are shown in Table 6.

2.4. Extended Exergetic Life-Cycle Impact Assessment

Traditional exergy analysis only analyzes system efficiency and identifies improvement potential, without quantifying resource and energy consumption or GHG emissions. Therefore, an extension was made here based on traditional exergy analysis by adding cumulative exergy and exergy abatement indicators.

2.4.1. Comprehensive Sustainability Performance Assessment Indicators

Sustainable energy conversion systems require sufficient energy and resources while minimizing environmental impact. Referring to the research by Dewulf et al. [32], two assessment indicators are defined as tools for evaluating the comprehensive sustainability performance of UGCC and IGCC power plants: the resource utilization rate (γ) and the environmental sustainability index (ϵ).

(1) Resource utilization rate

Cumulative exergy refers to the exergy value of cumulative resource consumption throughout the entire process from raw material acquisition, transportation, and processing to the obtainment of products or energy, representing the resource and energy consumption of the system [33]. It can quantify not only renewable resources but also non-renewable resources. The calculation method for cumulative exergy is shown in Equation (1), and the cumulative exergy values of process energy are listed in Table 8.

$$CExC = \sum_{s=1}^3 \sum_{k=1}^7 EC_{s,k} \times CExC_k \quad (1)$$

where s represents each sub-stage of the coal gasification power plant life cycle, k represents the type of process energy consumed by the power plant throughout its life cycle, $EC_{s,k}$ refers to the total consumption of process energy k at stage s of the power plant, and $CExC_k$ represents the cumulative exergy consumption for production per unit of process energy k .

Table 8. The exergy and CExC values of process resources and energy sources.

Process Energy	Exergy	CExC
Coal (MJ/kg)	23.57	31.1
NG (MJ/MJ)	1.04	1.07
Diesel (MJ/kg)	44.4	53.2
Gasoline (MJ/kg)	46.08	57.07
Furnace oil (MJ/kg)	44.74	55.49
Electricity (MJ/kWh)	3.6	12.37
Steam (MJ/kg)	1.51	3.86

To evaluate the sustainability of system energy and resource utilization, the resource utilization rate (γ) is calculated based on cumulative exergy. It is defined as the ratio of the total product exergy output of the system to the cumulative exergy consumption of energy and resources consumed by the system, as shown in Equation (2). The resource utilization ratio γ is calculated based on the life-cycle cumulative exergy, essentially reflecting the actual conversion efficiency of raw coal for the entire system. It can quantify the incremental raw coal consumption caused by the energy penalty of CCS, thereby providing guidance for on-site process parameter optimization. A higher resource utilization rate (γ) indicates better conversion and utilization of system resources and superior resource sustainability.

$$\gamma = \frac{Ex_{p,sys}}{CExC} \quad (2)$$

(2) Environmental sustainability index

Exergy abatement refers to the exergy consumption required to treat pollutants emitted by a system to an environmentally friendly level under existing technological conditions, in other words, the cost incurred to reduce pollutant emissions [32]. The main objective of this study is to quantitatively compare the carbon reduction potential and climate benefits of UGCC-CCS and IGCC-CCS, and therefore only GHG emissions are considered as the environmental impact factor. Exergy abatement can be used to measure the environmental impact of GHG emissions. The calculation method is shown in Equation (3).

According to the Intergovernmental Panel on Climate Change (IPCC)'s sixth assessment report (AR6), GHGs mainly include CO₂, CH₄, and N₂O. These greenhouse gas emissions can be further classified into two categories: direct emissions and indirect emissions. Direct emissions primarily come from flue gases discharged during the power generation process, while indirect emissions originate from fuel acquisition, processing,

and transportation stages, as well as emissions from process energy production stages. The greenhouse gases include CO₂, CH₄, and N₂O, with exergy abatement values of 5.86 MJ/kg, 66.32 MJ/kg, and 268.06 MJ/kg, respectively [32,34].

$$AbatEx = \sum_{s=1}^3 \sum_{k=1}^7 \sum_{m=1}^3 EC_{s,k} \times (DF_{m,k} + IF_{m,k}) \times AbatEx_m \quad (3)$$

Here, m represents the type of GHG emitted by the power plant, including CO₂, CH₄, and N₂O; $DF_{m,k}$ and $IF_{m,k}$ refer to the direct and indirect emission coefficients of the m th type of GHG per unit of process energy k consumed, respectively; and $AbatEx_m$ represents the exergy abatement consumption per unit mass of GHG m . It should be noted that the direct and indirect emission coefficients per unit of process energy consumption are calculated based on the GREET model data and the Chinese Life Cycle Database, and the final results are listed in Table 9.

Table 9. Direct and indirect GHG emission factors for process energy.

Process Energy	DF _{CO2} (g/MJ)	DF _{CH4} (g/MJ)	DF _{N2O} (mg/MJ)	IF _{CO2} (g/MJ)	IF _{CH4} (g/MJ)	IF _{N2O} (mg/MJ)
Coal	81.642	0.001	0.001	0.84	0.04	0.018
NG	55.612	0.001	0.001	5.4	0.13	0.103
Diesel	72.585	0.004	0.028	8.38	0.36	0.167
Gasoline	67.914	0.08	0.002	10.73	0.38	0.194
Steam	0.000	0.000	0.000	95.7	0.1	1.22
Electricity	0.000	0.000	0.000	258.47	0.73	3.932
Furnace oil	75.819	0.002	0.000	6.75	0.32	0.141

Based on cumulative exergy and exergy abatement, the environmental sustainability index (ϵ) is obtained. It represents the environmental impact of all GHG emissions from the system. The environmental sustainability index ϵ introduces equivalent emission reduction exergy to unify the dimensions on the basis of actual GHG emissions. Its core function is to evaluate the cost effectiveness between carbon reduction benefits and the cost of additional energy input, avoiding one-sided assessments that focus solely on absolute emission quantities while neglecting the high energy consumption drawback of CCS. The greater the GHG emissions, the smaller the environmental sustainability index, and the greater the harm to the environment. The calculation method is shown in Equation (4).

$$\epsilon = \frac{CExC}{CExC + AbatEx} \quad (4)$$

2.4.2. Exergy Efficiency and Exergy Destruction Coefficient

There are two traditional exergy analysis indicators: exergy efficiency and exergy destruction coefficient. Exergy efficiency is the ratio of the product exergy output to the total input exergy of the system, representing the overall useful energy efficiency of the system. This study only considers valuable output products, including by-product steam, recovered sulfur, captured CO₂, and generated electricity, while heat losses and waste materials during the production process are excluded. It should be noted that the system boundary of this study includes CO₂ capture, transport, and storage. The stored CO₂ can achieve stable carbon reduction environmental benefits. Therefore, CO₂ is defined as a valuable output of the system. CO₂ that is only captured but not properly disposed of is not counted as effective exergy output. Exergy efficiency can be classified into two types: general exergy efficiency and functional exergy efficiency. General exergy efficiency is the ratio of the total output energy to the input energy of the system, as shown in Equation (5):

$$\eta_{gen} = \frac{Ex_{out}}{Ex_{in}} \quad (5)$$

In fact, there is always a portion of energy that remains unutilized and therefore should not be regarded as a valuable product. Examples include exhaust gases, solid wastes, and heat discharged into the surrounding environment. The system exergy efficiency that excludes these products is termed functional exergy efficiency, as shown in Equation (6).

$$\eta_{obj} = \frac{Ex_{out} - Ex_{waste}}{Ex_{in}} \quad (6)$$

To more accurately evaluate the thermodynamic performance of UGCC and IGCC systems, the following assumptions are proposed:

- (1) All processes are assumed to be in steady state, with the reference environment state at 298.15 K and 101.325 kPa.
- (2) Changes in system kinetic and potential energy are neglected, and all gases are treated as ideal gases.
- (3) Changes in the environmental state are neglected.

It should be noted that the steady-state assumption neglects the dynamic cavity expansion and the real characteristics of non-uniform spatial distributions of temperature and composition, yielding only average operating condition results, but it does not alter the relative conclusions of the comparison between the two technologies; neglecting the potential and kinetic energy losses of underground logistics slightly overestimates the system exergy output, yet the energy proportion of this part is extremely low, resulting in a very small quantitative deviation; the ideal gas approximation under high-pressure conditions involves slight errors, which have been corrected in this study by employing the Peng–Robinson equation of state, with the calculation deviation controlled within a reasonable range.

The calculation of exergy efficiency requires the exergy values of each stream. Based on the stream exergy values and the exergy balance equation, the exergy efficiency and exergy losses can be obtained. Equation (7) presents the system exergy balance equation:

$$\sum Ex_{in} - \sum Ex_{out} = \Delta Ex_{loss} \text{ or } \sum \left(1 - \frac{T_0}{T}\right) Q - W + \sum m_{in} \psi_{in} - \sum m_{out} \psi_{out} = \Delta Ex_{loss} \quad (7)$$

where Ex_{in} and Ex_{out} represent the input and output exergy flows of the system, respectively; ΔEx_{loss} denotes the energy that remains unutilized in all energy sources and resources; Q represents the heat transfer at temperature T ; W represents power; and m and ψ refer to the mass flow rate and specific exergy, respectively.

In each energy system, exergy can be classified into four types: physical exergy, chemical exergy, kinetic exergy, and potential exergy [35]. Considering that the contributions of kinetic exergy and potential exergy to the system are quite small, they can be neglected. Therefore, the specific exergy ψ in Equation (7) can be composed of two parts: physical exergy and chemical exergy. Physical exergy can be calculated using Equation (8):

$$Ex_{ph}^{steam} = (H - H_0) - T_0(S - S_0) \quad (8)$$

where Ex_{ph}^{steam} represents the physical exergy of each stream; H and S denote the enthalpy and entropy of the system at a given temperature and pressure, respectively; and H_0 and S_0 represent the enthalpy and entropy of the system at the reference environmental state. It is noteworthy that since the contribution of coal to the entire system is quite small, the physical exergy of coal is neglected. The chemical exergy expression is shown in Equation (9):

$$Ex_{ch}^{steam} = \sum y_i Ex_{ch,i} + RT_0 \sum y_i \ln y_i \quad (9)$$

where Ex_{ch}^{steam} represents the chemical exergy of each stream; $Ex_{ch,i}$ is the chemical exergy of the i th input stream; y_i is the mole fraction of the i th stream; and R is the gas constant (8.314 kJ/kmol/K).

Although the exergy efficiency indicator can effectively evaluate the thermodynamic perfection of energy systems and quantitatively illustrate the effectiveness and rationality of energy utilization, it cannot objectively reflect the influence of each sub-unit on the overall process perfection. According to the second law of thermodynamics, during the energy conversion process in energy systems, energy quality losses occur in order to achieve a state of complete equilibrium with the surrounding environment; this loss can be termed exergy destruction. To reveal the degree of influence of exergy destruction in different sub-units of the two types of power plants on the system, another indicator of exergy analysis, namely the exergy destruction coefficient δ , is introduced. Based on the principles of mass and energy conservation, the exergy destruction of the system and sub-units is calculated as the difference between the exergy flow entering and leaving the system or sub-unit. The expression for the exergy destruction coefficient is shown in Equation (10).

$$\delta = \frac{Ex_{in,n} - Ex_{out,n}}{Ex_{in,sys} - Ex_{out,sys}} \quad (10)$$

Here, n represents the sub-units in the life-cycle process of the power plant; $Ex_{in,n}$ and $Ex_{out,n}$ denote the input and output exergy flows of sub-unit n , respectively. Similarly, $Ex_{in,sys}$ and $Ex_{out,sys}$ represent the input and output exergy flows of the entire energy conversion system.

3. Life-Cycle Comprehensive Sustainability Assessment

Extended exergy analysis can calculate the cumulative exergy consumption of all process energy and resources for the power plant and quantitatively evaluate the environmental issues caused by GHG emissions throughout the entire life cycle of the power plant.

3.1. Resource Utilization Rate Analysis

The installed capacity of the power plant in this study is 540 MW. The cumulative exergy and resource utilization rates for the four scenarios were obtained from Equations (1) and (2), and the results are shown in Figure 4.

The resource utilization rate is the ratio of the power plant product exergy output to the total cumulative exergy. The resource utilization rates of UGCC and IGCC power plants are 19.39% and 18.29%, respectively. Without CCS retrofitting, since the power generation of the two plants is the same, the product exergy output is identical, both being the exergy of the generated electricity. Therefore, the higher resource utilization rate of the UGCC power plant stems from its lower cumulative exergy, which also implies lower energy and resource consumption. According to the bar chart, the cumulative exergy consumption of both power plants is mainly concentrated in the power generation stage (S2), where the cumulative exergy consumption accounts for more than 80% of the total cumulative exergy consumption. At this stage, the process energy consumed by the two power plants is the same, both being electricity and steam. The difference lies in the fact that for the IGCC power plant, a large amount of steam is required as a gasification agent, with steam being the main process energy, while the UGCC power plant consumes more electricity, with the total amount differing slightly. However, the calorific value of syngas in the UGCC power plant is lower than that in the IGCC power plant, resulting in higher coal consumption for the UGCC power plant to produce the same amount of electricity and ultimately higher cumulative exergy in the power generation stage.

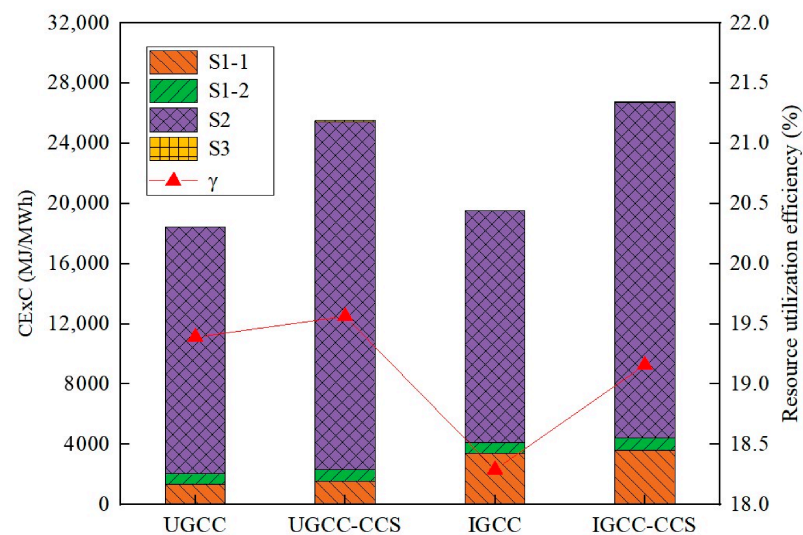


Figure 4. The CExC of different sub-stages and resource utilization rate for four cases.

In the upstream stage (S1), the processes involved in the two power plants differ. The UGCC power plant includes gasification agent preparation (S1-1) and underground gasifier construction (S1-2), while the IGCC power plant includes coal mining and washing (S1-1) and coal transportation (S1-2). The cumulative exergy values for the UGCC and IGCC power plants at this stage are 2055.51 MJ/MWh and 4127.37 MJ/MWh, respectively. The lower cumulative exergy of the UGCC power plant is attributable to two factors. On the one hand, the coal recovery rate of the UCG process is relatively high, with coal loss of only 5%, allowing coal resources to be fully utilized; in contrast, the coal losses during coal mining and washing and coal transportation for the IGCC power plant are 18% and 4.89%, respectively. On the other hand, this is due to the different fuel acquisition methods of the two power plants. The syngas required by the UGCC power plant is obtained through the underground gasifier, thereby replacing the traditional coal mining, washing, and transportation processes. This process mainly consumes diesel, with a process energy cumulative exergy of 728.17 MJ/MWh, accounting for only 3.95% of the total cumulative exergy. In contrast, the coal mining, washing, and transportation stages of the IGCC power plant involve substantial resource and energy consumption, with their cumulative exergy consumption accounting for 21.13%. This result fully demonstrates the energy-saving advantage of in situ gasification. By avoiding the massive irreversible dissipation of mechanical work in solid coal mining and transportation processes, in situ gasification reduces the exergy degradation losses throughout the entire chain from the source of resources.

It should be noted that the electricity consumption for the CO₂ transportation and storage stage accounts for a very small proportion of the total resource consumption, less than 1%, and its impact on the power plant can be neglected. After CCS retrofitting, although the energy penalty increases the cumulative exergy of the UGCC and IGCC power plants by 38.49% and 37.03%, respectively, the resource utilization rates (γ) of both power plants still increase slightly. This is because after CCS retrofitting, the product exergy output of the power plant increases, including not only electricity exergy but also by-product steam and captured CO₂. It can be seen that the additional product benefits generated by the system after CCS retrofitting promote an improvement in the resource utilization rate. In general, the UGCC power plant exhibits better resource utilization sustainability than the IGCC power plant.

3.2. Environmental Sustainability Indices Analysis

The environmental sustainability indices (ϵ) for the four scenarios and the GHG exergy abatement for each sub-stage of the power plant life cycle are shown in Figure 5. Based on the cumulative exergy and exergy abatement results, the environmental sustainability index (ϵ) of the power plant can be obtained from Equations (3) and (4). It can be seen from the figure that the environmental sustainability index (ϵ) of the UGCC power plant is 72.21%, which is lower than that of the IGCC power plant at 75.84%. The reason for the relatively poor environmental sustainability of the UGCC power plant lies in its slightly higher exergy abatement. The exergy abatement values for the UGCC and IGCC power plants are 7090.52 MJ/kg and 6222.9 MJ/kg, respectively, with the UGCC exergy abatement being 1.14 times that of the IGCC power plant. From a physical perspective, the emission reduction exergy reflects the equivalent exergy consumption per unit mass of GHG emissions. A higher value indicates a greater “energy cost” per unit of carbon emission, meaning that the system needs to invest more high-quality energy to eliminate per unit of environmental impact.

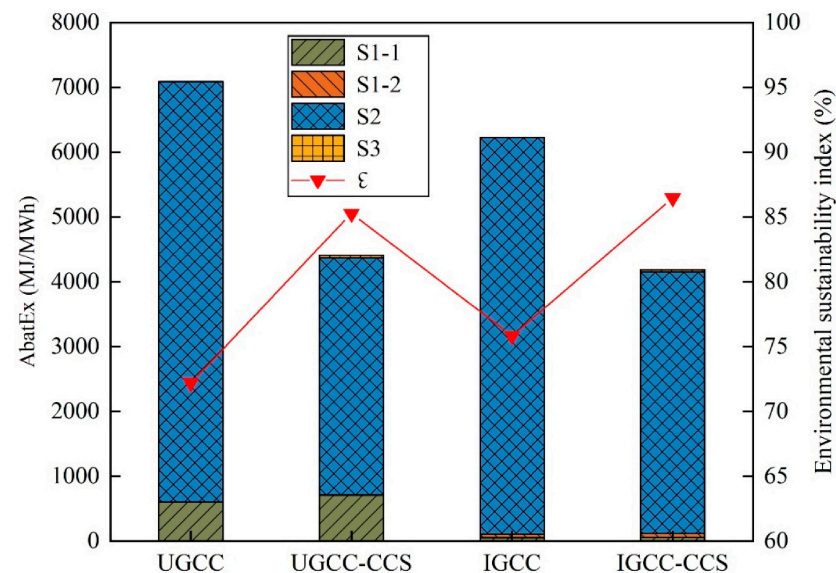


Figure 5. The AbatEx of different sub-stages and environmental sustainability index for four cases.

As can be clearly seen from the figure, the exergy abatement for both the upstream stage and the power generation stage of the UGCC power plant is higher than that of the IGCC power plant. In the upstream stage, although the GHG emissions from underground gasifier construction (S1-2) are much lower than those from coal mining and washing (S1-1) and transportation (S1-2), gasification agent preparation (S1-1) consumes a large amount of electricity, generating substantial CO₂, which ultimately results in higher GHG emissions for the upstream stage. In the power generation stage, the UGCC power plant has higher GHG emissions due to the lower calorific value of its syngas compared to that of the IGCC power plant. The syngas compositions for UCG and SCG are detailed in Table 10.

The electricity consumption for the CO₂ transportation and storage stage accounts for less than 1% of the total resource consumption, so its impact on the power plant can be neglected. After CCS retrofitting, due to the significant reduction in CO₂ emissions, the exergy abatement of the UGCC and IGCC power plants decreased by 12.24% and 5.1%, respectively, while the environmental sustainability indices increased by 85.27% and 86.47%, respectively. Overall, compared with the IGCC power plant, the UGCC power plant performs relatively poorly in terms of environmental sustainability and needs further improvement. CCS substantially reduces the total carbon emissions, directly decreasing

the emission reduction input that needs to be paid for by energy consumption exergy. As a result, the environmental sustainability indices of both units show a significant leap, which also confirms the strong constraining effect of carbon capture in the life-cycle environmental exergy balance.

Table 10. The mole fractions of syngas created by UCG and SCG.

Component	Mole Fraction (%)	
	UCG	SCG
H ₂	27.41	35.11
CO	51.47	55.83
CO ₂	7.64	2.50
CH ₄	0.01	0.05
N ₂	0.71	0.59
H ₂ O	11.78	5.18

3.3. Sensitivity Analysis

The baseline scenario in this study assumes that the power plant is situated adjacent to the UCG site, without considering the effect of syngas transportation distance on the results. However, differences in syngas and CO₂ transportation distances can reflect the diverse site layout for UGCC-CCS power plants. To systematically assess the impact of different siting options for UGCC-CCS power plants, this study conducts a sensitivity analysis using syngas and CO₂ transportation distances as variables to determine the effects of transportation distance on the resource utilization rate and environmental sustainability index, thereby providing a quantitative decision-making basis for UGCC-CCS power plant siting.

In this study, syngas is transported via pipeline. Owing to frictional resistance and other factors during pipeline transportation, syngas undergoes pressure drop, necessitating the installation of booster stations along the route. Consequently, the energy consumption of syngas transportation is attributed to the electricity consumption of compressors at pipeline booster stations. The UGCC-CCS power plant employs pre-combustion carbon capture technology, and therefore, following underground coal gasification, the raw syngas is subjected to water–gas shift and CO₂ removal, yielding high-purity hydrogen as the medium transported through the pipeline. Given that the compression characteristics of syngas are broadly comparable to those of pure hydrogen, the operating parameters of the booster stations are set in accordance with standards for high-pressure hydrogen long-distance pipelines, with one intermediate booster station installed every 100 km. The energy consumption of a single booster station compressor adopts a literature-based benchmark value of 0.36 MJ/kg [36].

The effects of syngas and CO₂ transportation distances on the resource utilization rate and environmental sustainability index of UGCC-CCS are presented in Figure 6. In the figure, the horizontal axis represents the transportation distance, while the vertical axes, respectively, indicate the impacts of syngas (solid line) and CO₂ (dashed line) transportation distances on the resource utilization rate and environmental sustainability index, with δ denoting the change rate of each indicator as the distance increases. Sensitivity results indicate that the impact of syngas transportation distance on the sustainable performance of UGCC-CCS is significantly greater than that of CO₂ transportation distance. When the distance increases from 0 km to 1000 km, the syngas distance leads to a 2.55% decrease in the resource utilization rate and a 0.61% decrease in the environmental sustainability index, whereas the CO₂ distance only causes a 0.42% decrease in the resource utilization rate and a 0.10% decrease in the environmental sustainability index, with the magnitude of

the former being approximately six times that of the latter. Particularly, when the syngas transportation distance reaches 800 km, the resource utilization rate of the UGCC-CCS decreases to 19.16%, which is consistent with the level of existing IGCC-CCS power plants. This indicates that 800 km can be regarded as the critical distance for the UGCC-CCS to maintain its resource utilization advantage; once the syngas transportation distance exceeds this threshold, the comparative advantage of UGCC-CCS in the resource utilization rate will be significantly narrowed or even reversed. Therefore, syngas transportation distance should be treated as the primary constraint in site selection.

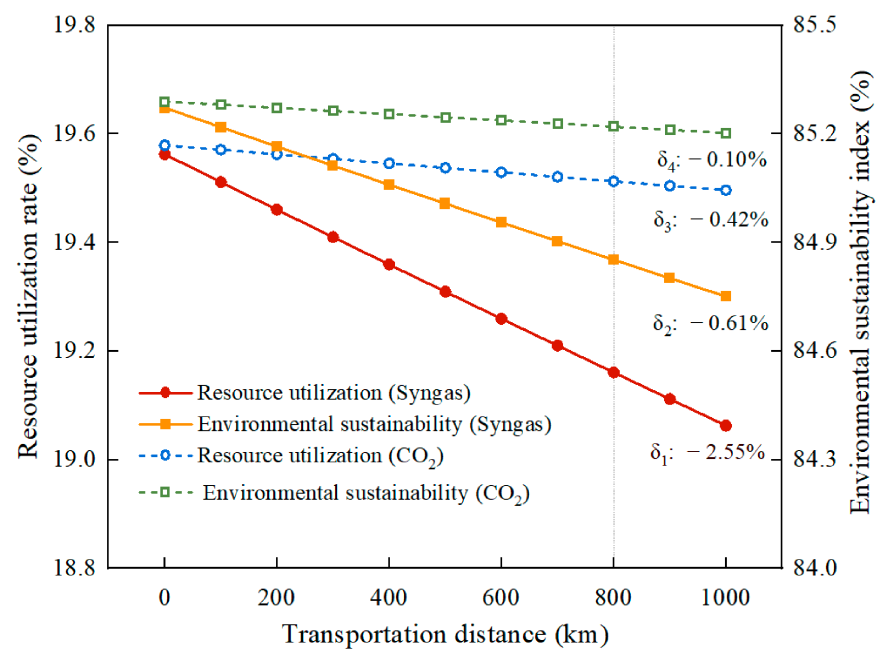


Figure 6. Sensitivity analysis of transportation distance on UGCC-CCS sustainability indicators.

In addition, based on the principle of consistency in technical comparison, this study uniformly sets the CO₂ transportation distance for both UGCC-CCS and IGCC-CCS power plants at 200 km. However, this is a conservative estimate for UGCC-CCS. Existing studies have shown that UCG cavities possess an inherent advantage for in situ CO₂ storage [37,38]. If this advantage is fully considered, the CO₂ transportation distance for the UGCC-CCS could be significantly lower than 200 km or even approach 0 km, and its environmental sustainability index and resource utilization rate would be further improved. Based on the above analysis, it is recommended that practical engineering projects prioritize an integrated or proximal layout of the power plant and the UCG site. Meanwhile, the potential for in situ CO₂ storage in UCG cavities should be comprehensively considered during the site selection evaluation stage, with priority given to sites that possess conditions for in situ storage, to maximize the resource-environment synergistic benefits for UGCC-CCS.

4. Life-Cycle Exergy Efficiency and Exergy Loss Analysis

4.1. Life-Cycle Exergy Efficiency Analysis

To further improve the environmental sustainability of the UGCC power plant, it is necessary to analyze the plant's exergy efficiency and identify units that can be improved. The unit processes of power plants equipped with CCS are more comprehensive; therefore, UGCC and IGCC power plants with CCS are selected for exergy efficiency analysis. Figure 7 shows the exergy efficiency of each unit and the exergy values flowing into and out of each sub-unit throughout the entire life cycle of the two types of power plants. Based on the coal consumption for producing 1 MWh of electricity by UGCC-CCS and IGCC-CCS

(471.8 kg/h vs. 404.1 kg/h), the coal exergy values of the power plants are 11,700 MJ and 9520 MJ, respectively. The output electricity exergy values of the two types of power plants are the same, at 3610 MJ. Here, only valuable output products are considered, including by-product steam, recovered sulfur, captured CO₂, and generated electricity, while heat losses and waste materials during the production process are excluded. According to Equation (6), the exergy efficiencies of the UGCC-CCS and IGCC-CCS power plants are calculated to be 34.27% and 33.15%, respectively.

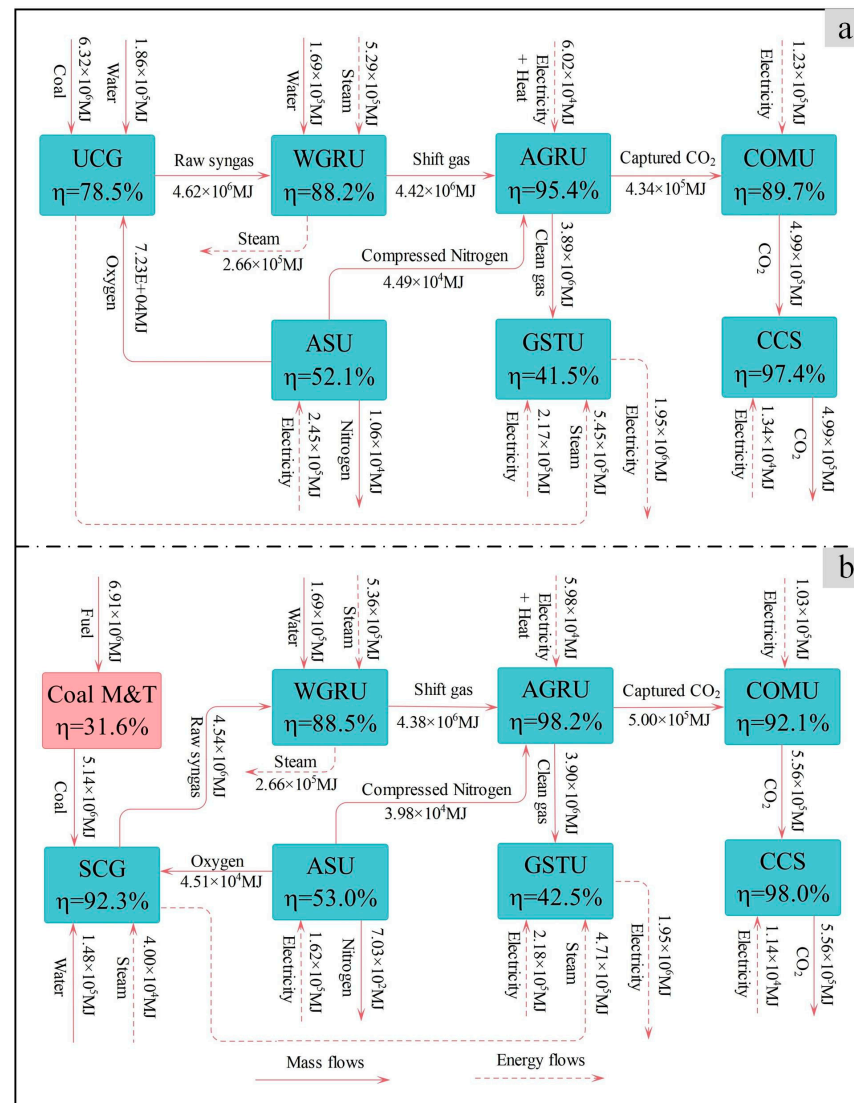


Figure 7. Exergy flowchart: (a) the UGCC-CCS power plant; (b) the IGCC-CCS power plant.

The difference in exergy efficiency mainly stems from the gasification unit: the exergy efficiency of underground gasification is 78.5%, lower than that of surface gasification at 92.3%. The underlying physical mechanisms are as follows: the gas–solid reaction interface in the underground gasification cavity is constrained by geological heterogeneity, and the unstable contact area leads to significant chemical reaction irreversibility; meanwhile, large heat losses through surrounding rock and non-uniform temperature field distribution cause high-temperature raw gas to undergo unplanned heat exchange with the surrounding rock during upward transport, dissipating large amounts of high-quality thermal energy in low-grade form; furthermore, the raw gas contains high dust content with large composition

fluctuations, requiring more compression and cooling work for subsequent purification and separation, which further intensifies the unit exergy loss.

Although the underground gasification unit of the UGCC-CCS power plant has relatively low exergy efficiency, the coal resource recovery rate during the gasification process is high, with the exergy value of lost coal resources accounting for only 4.02% of the total input exergy of the power plant. For the IGCC-CCS power plant, however, coal losses during the upstream coal mining and transportation stages are substantial. Combined with the additional fuel consumption in this process, the energy and resource consumption exergy value of the coal mining and transportation unit accounts for 21.11% of the total input exergy value of the power plant, ultimately resulting in lower exergy efficiency for the IGCC-CCS power plant. If the fuel consumption and coal losses in the upstream stage are not considered, the overall exergy efficiency of the IGCC-CCS power plant could be increased to 42.03%. It is evident that in situ gasification technology, with its energy-saving advantages, has a significant effect on improving system exergy efficiency.

4.2. Life-Cycle Exergy Loss Analysis

All irreversible processes in practice are accompanied by exergy loss. The magnitude of exergy loss reflects the perfection degree of energy conversion and utilization in the system; the smaller the exergy loss, the higher the system exergy efficiency. Although the exergy efficiency of each sub-unit was analyzed in the previous section, it cannot be determined whether a particular unit definitely has optimization potential. Only when a sub-unit has both low exergy efficiency and a large exergy loss coefficient can it be considered to have improvement potential. Therefore, further analysis of the exergy loss coefficient of each sub-unit is necessary. Through analysis of this indicator, we can gain an in-depth understanding of the units with large exergy loss in the power plant and the causes of exergy destruction, thereby identifying which units have further improvement potential. The exergy destruction coefficient can be calculated from the exergy flow values of each unit in the Aspen model using Equation (10). Figures 8 and 9 show the proportion of total exergy loss in each sub-unit of the power plant.

As can be seen from Figure 7, the unit with the largest exergy loss in the UGCC-CCS power plant is the gas turbine unit, accounting for 52.74% of the total losses, followed by the underground gasification unit and the water–gas shift unit, accounting for 27.37% and 12.21% of the total losses, respectively. The three units with relatively large exergy loss in the IGCC-CCS power plant are the gas turbine unit, the coal mining and transportation unit, and the water–gas shift unit, accounting for 47.25%, 31.59%, and 10.8% of the total losses, respectively. The units with large exergy loss in both types of power plants include the gas turbine unit and the water–gas shift unit. In the gas turbine unit, in addition to the irreversible chemical reactions occurring during syngas combustion, the limitation of the gas turbine inlet temperature also causes heat losses during syngas cooling. Although these two units have relatively large exergy loss, their potential for further improvement is limited due to technical constraints.

The core exergy loss difference between the two systems is manifested in the front-end feedstock and gasification stages (see Figure 8). The high exergy loss of IGCC-CCS is concentrated in the coal mining and transportation phase, where the losses arise from sustained mechanical work dissipation and resource spillage during solid coal excavation and transfer, representing inherent irreversible losses in the industrial chain that are extremely difficult to mitigate through engineering optimization. In contrast, the prominent weakness of UGCC-CCS lies in the underground gasification unit, with its exergy loss accounting for as high as 27.37%. From the perspective of physical mechanisms, underground gasification is affected by heterogeneous geological conditions of coal seams, non-steady-state seepage

combustion, and non-uniform distribution of temperature and concentration fields in the cavity, resulting in poor gasification reaction stability. This readily leads to incomplete combustion and uncontrolled energy dissipation, causing fluctuations in syngas composition and low calorific value, thereby generating significant process exergy degradation.

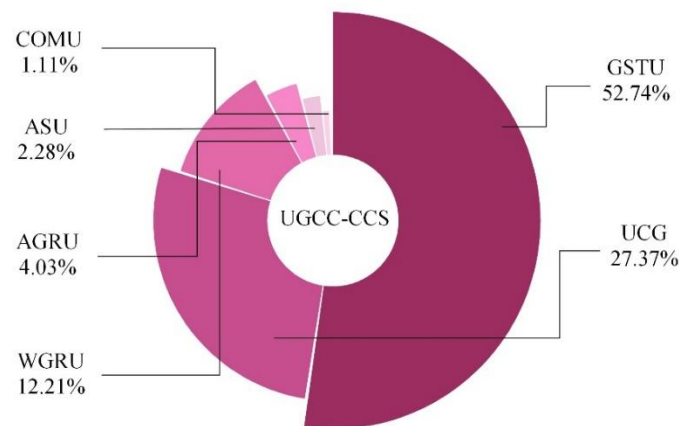


Figure 8. Exergy loss distribution of different sub-units in the UGCC-CCS plant.



Figure 9. Exergy loss distribution of different sub-units in the IGCC-CCS plant.

In summary, the high exergy losses in IGCC-CCS are predominantly rigid losses in the upstream industrial chain that are difficult to circumvent, with minimal room for optimization, whereas the underground gasification losses in UGCC-CCS stem from insufficient controllability of the reaction process rather than inherent technological shortcomings. If the controllability of the gasification cavity can be enhanced through optimizing gasification agent ratios (water-to-coal ratio and oxygen-to-coal ratio) and injection strategies to improve syngas calorific value and stability, the exergy loss of this unit can be effectively reduced, thereby enhancing system exergy efficiency. Additionally, the CCS unit accounts for less than 1% of total system exergy loss, with a negligible impact on overall energy efficiency, and is therefore not listed in the figure.

4.3. Efficiency Improvement Analysis

Although the UGCC power plant exhibits a relatively high resource utilization rate and exergy efficiency, its environmental sustainability index is comparatively low. It is therefore necessary to optimize the exergy efficiency of the UGCC power plant, reduce energy and resource consumption and GHG emissions, and improve the plant's resource utilization rate and environmental sustainability index. Through exergy efficiency and exergy loss analysis, it is evident that the underground gasification unit is the most promising unit for optimization in the UGCC power plant. During the underground gasification process, the

water and oxygen contents in the gasification agent are critical conditions for controlling the underground gasification reaction process and influencing syngas composition. Excessive oxygen will consume combustible gases and reduce the syngas calorific value, while excessive water will lower the gasification temperature and cause the gasification reaction to terminate. The effects of the water-to-coal ratio and oxygen-to-coal ratio on the exergy efficiency of the UGCC power plant can be investigated through analysis. Since the modeling process adjusts the oxygen-to-coal ratio by changing the gasification temperature, the gasification temperature in this study represents the variation of the oxygen-to-coal ratio. The effects of gasification temperature and water-to-coal ratio on the exergy efficiency of the UGCC-CCS power plant are shown in Figure 10.

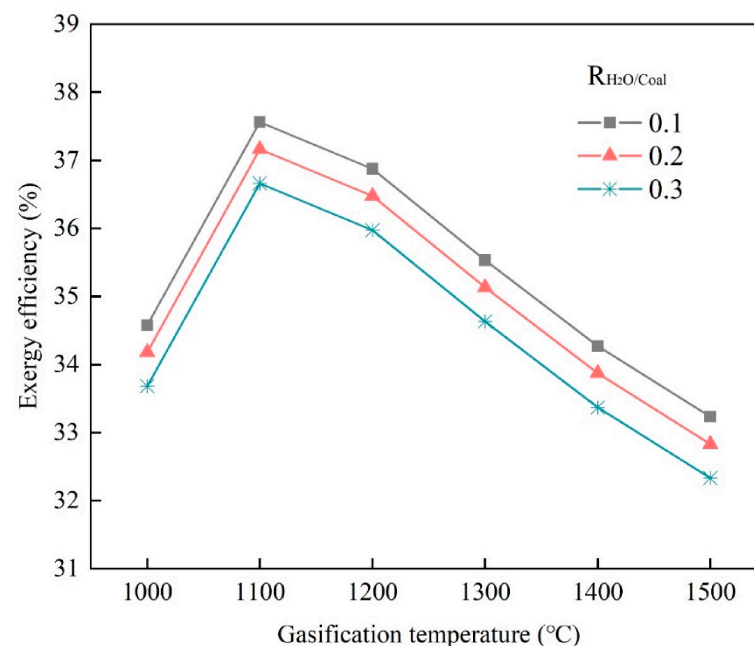


Figure 10. The effect of gasification temperature and H₂O-to-coal ratio on exergy efficiency in UGCC-CCS plant.

For the different water-to-coal ratios, the exergy efficiency of the UGCC-CCS power plant exhibits a consistent trend of initial increase followed by decrease with rising gasification temperature. At lower temperatures, increasing temperature accelerates the water–gas reaction, enhancing the effective syngas components and thus improving exergy efficiency; at excessively high temperatures, hydrogen combustion dominates, shifting the water–gas shift equilibrium leftward and reducing the effective components, thereby decreasing exergy efficiency. There exists an optimal oxygen-to-coal ratio that maximizes exergy efficiency, with the critical value being 0.6 at 1100 °C.

An increase in the water-to-coal ratio leads to a monotonic decline in exergy efficiency; for instance, when the ratio increases from 0.2 to 0.3, the exergy efficiency drops from 37.16% to 36.66%. The underlying mechanism is that excess steam drives the water–gas reaction equilibrium in the reverse direction, reducing the overall effective components (CO and H₂) and lowering the chemical exergy density; simultaneously, the additional heat required to raise the temperature of excess steam increases the energy consumption for gasification agent preparation. The oxygen-to-coal ratio exerts a significantly stronger influence on exergy efficiency than the water-to-coal ratio, as it directly determines the heat release in the combustion zone and the temperature level in the gasification zone, thereby governing the overall reaction pathway. In summary, the UGCC-CCS power plant

achieves its maximum exergy efficiency of 37.56% at an oxygen-to-coal ratio of 0.6 and a water-to-coal ratio of 0.1.

The comprehensive comparison results between the optimized UGCC-CCS power plant and the original IGCC-CCS power plant are shown in Figure 11. As can be seen from the figure, the exergy efficiency of the optimized UGCC-CCS power plant increases to 37.56%, which is 13.30% higher than that of the IGCC-CCS power plant. Correspondingly, the cumulative exergy and exergy abatement of this power plant decrease by 9.59% and 7.46%, respectively, indicating that both resource consumption and GHG emissions decline to a certain extent after the efficiency improvement. Meanwhile, due to the reduction in resource consumption and GHG emissions, the resource utilization rate (γ) and environmental sustainability index (ε) of the UGCC-CCS power plant increase by 10.53% and 1.34%, respectively. Overall, by adjusting the water-to-coal ratio and oxygen-to-coal ratio of the underground gasification unit, the comprehensive sustainability performance of the UGCC-CCS power plant in terms of resource utilization and GHG environmental impact has been significantly improved.

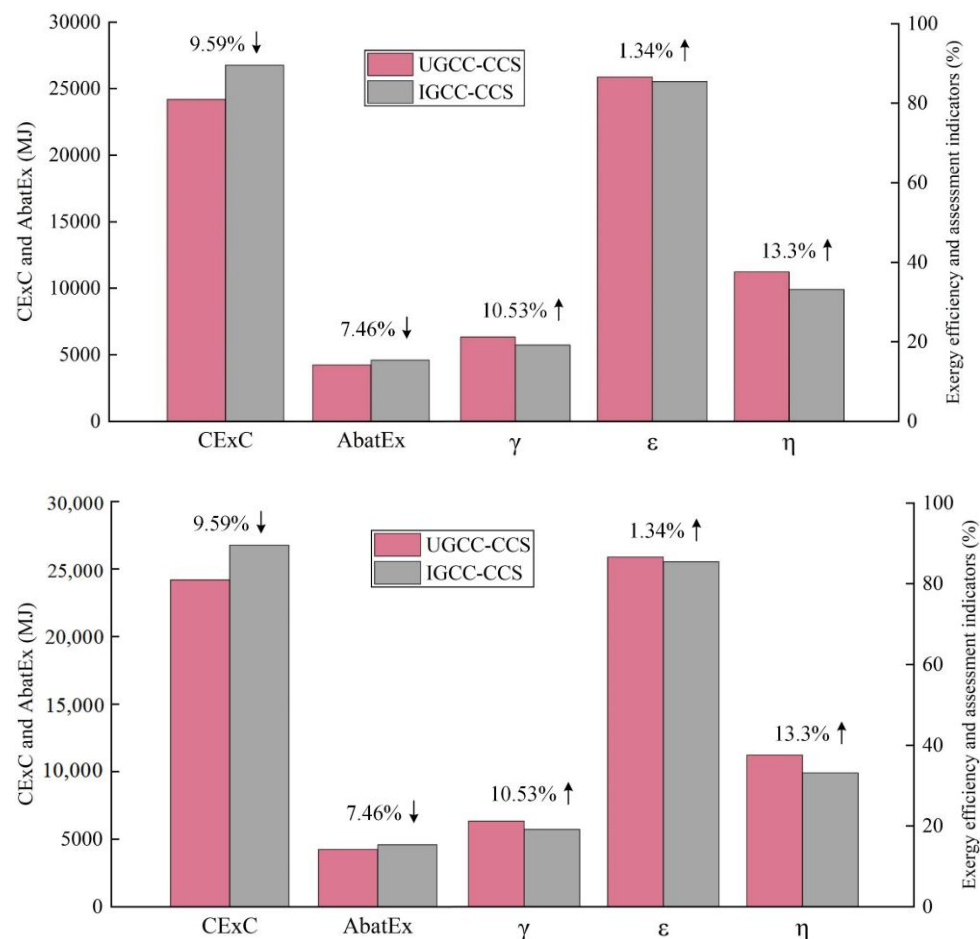


Figure 11. The comparison of results between the improved UGCC-CCS and existing IGCC-CCS.

5. Conclusions

Based on Aspen Plus, this study established exergy efficiency assessment models for UGCC and IGCC power plants. While quantifying the resource and energy consumption as well as pollutant emissions of the power plants, detailed energy efficiency evaluation and optimization were conducted, key units affecting efficiency were identified, and energy consumption and GHG emissions were further reduced to promote sustainable development. According to the obtained results, the following conclusions can be drawn:

- (1) The resource utilization rates of the UGCC and IGCC power plants are 19.39% and 18.29%, respectively, and the environmental sustainability indices are 72.21% and 75.84%, respectively. This indicates that the UGCC power plant exhibits better sustainability in resource utilization but performs poorly in environmental performance regarding GHG emissions. After CCS retrofitting, both the resource utilization rate and environmental sustainability index increase. Sensitivity analysis indicates that syngas transportation distance is the primary constraint for UGCC-CCS power plant siting. In practical engineering, priority should be given to an integrated layout of the power plant and UCG site while fully utilizing the potential for in situ CO₂ storage in UCG cavities.
- (2) The exergy efficiencies of the UGCC-CCS and IGCC-CCS power plants are 34.27% and 33.15%, respectively. Compared with the IGCC-CCS power plant, the underground gasification unit of the UGCC-CCS power plant has a lower exergy efficiency of 78.5%, but its exergy loss proportion reaches 27.37%, indicating considerable optimization potential.
- (3) When the oxygen-to-coal ratio is 0.6 and the water-to-coal ratio is 0.1, the exergy efficiency of the UGCC-CCS power plant reaches its maximum value of 37.56%. Compared with the IGCC-CCS power plant, the exergy efficiency increases by 13.30%. The resource utilization rate and environmental sustainability index also increase by 10.53% and 1.30%, respectively. Through efficiency optimization, the comprehensive sustainability performance of the power plant in terms of both resource utilization and GHG environmental impact is improved.

6. Limitations and Future Research Directions

Due to the constraints of existing research conditions and the evaluation framework, this study still has certain limitations. The study introduced several deterministic assumptions and has not yet conducted a systematic uncertainty and sensitivity analysis in the existing model for UGCC-CCS. In practical engineering, fluctuations in coal quality conditions, variable-load operation of the unit, and parameter disturbances of CCS can all affect the system's resource utilization rate and environmental sustainability index, and the idealized fixed-parameter conditions cannot adequately reflect the real operational state in the field. Furthermore, the environmental sustainability indicator in this study only incorporates greenhouse gas emissions and has not yet covered conventional atmospheric pollutants such as sulfur dioxide, nitrogen oxides, particulate matter, and so on.

In future work, we will introduce uncertainty and sensitivity analysis to quantify the impact of fluctuations in various input parameters on the results and calibrate the theoretical model based on pilot demonstration data to further compare the discrepancies between measured results and simulated results. Meanwhile, we will incorporate multiple environmental impact indicators such as SO₂, NO_x, particulate matter, etc., and add an economic dimension assessment to establish a comprehensive life-cycle evaluation system covering resources, environment, and economy.

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