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Impacts of Carbon Capture and Storage (CCS) Technology on the Sustainability of Coal-Based Power Generation Pathways

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Abstract

Carbon capture and storage (CCS) technology mitigates greenhouse gas (GHG) emissions. However, comprehensive studies assessing the sustainability of coal-based power generation (CBPG) with CCS remain limited. This study focuses on developing comparative sustainability indicators across the entire life cycle of CBPG integrated with CCS technology. Sixty-six pathways were analyzed after establishing five sustainability indicators for each. These indicators were standardized per megawatt-hour (MWh) of energy, encompassing quantitative impacts on water, land, air quality, and the levelized cost of electricity (LCOE). Among the pathways examined, the highest sustainability indicators were recorded for LCOE (118.05 USD/MWh), GHG emissions (374 kg of CO_2 eq./MWh), and land use (0.513 m^2/MWh). These were associated with a life cycle involving underground coal mining, subcritical power generation technology with dry cooling, and pre-combustion CCS technology. Conversely, the lowest LCOE (65.17 USD/MWh) and land use (0.337 m^2/MWh) indicators were observed in a life cycle scenario involving surface coal mining, ultra-supercritical technology with a cooling tower, and oxyfuel CCS technology. This study presents sustainable scenarios encompassing the most cost-effective approaches, minimal use of natural resources, and the most minor GHG emissions. These scenarios cover an electricity demand range from 250 MW to 5000 MW.

Keywords
Carbon capture and storage; sustainable power generation; sustainability assessment; electricity optimization; clean coal technologies

1. Introduction

The implementation of carbon capture and storage (CCS) technology has proven to be a significant means of mitigating greenhouse gas (GHG) emissions originating from coal-based power generation (CBPG) [1-4]. Retrofitting coal power plants (CPPs) with CCS technology has demonstrated its potential to compete with renewable energy power generation pathways in GHG mitigation [5]. However, integrating CCS technology into CBPG presents varied impacts on natural resource utilization and the cost of power generation. Consequently, a comprehensive sustainability assessment approach becomes imperative to encompass the diverse factors influencing the effectiveness of CCS technology retrofitted to CBPG throughout its complete life cycle (CLC). Solving one or two factors would lead to misleading decision-making. For instance, while CCS may positively impact GHG emissions, its effects on water, land usage, and generation costs may present challenges that must be considered holistically.

Life cycle assessment (LCA), sustainability indicators, and categorizing CBPG with CCS into distinct pathways are valuable tools for facilitating decision-making and analyzing sustainability-related concerns. LCA allows for the examination of each unit operation's impact throughout the entire process, employing a cradle-to-grave approach to identify the most efficient path toward more sustainable power generation [6-8]. Sustainability indicators track the trajectory of these pathways, quantifying various aspects and aiding in the comparative assessment of different options by establishing a standardized functional unit [9, 10]. Given the diverse impacts on natural resources, GHG emissions, and the cost of generation, structuring the unit operations involved in CBPG with CCS into pathways that cover the entire life cycle becomes crucial. These pathways underscore critical stages in the process, emphasizing the necessity of considering all relevant factors [11].

The unit operations involved in CBPG with CCS exhibit diverse quantitative environmental, economic, and social impacts. Coal extraction methods encompass surface mining (SM) and underground mining (UM). CCS technology manifests through post-combustion (POC), pre-combustion (PRC), and oxyfuel (OXF) combustion configurations. Moreover, coal power generation employs various pathways, ranging from conventional subcritical (SUB) pulverized coal technology to advanced coal technologies with enhanced efficiencies such as supercritical (SUPER), ultra-supercritical (ULTSUPER), and integrated gasification combined cycle (IGCC). The choice of the cooling system significantly determines water usage. Both power generation and CCS technologies can influence the operational performance of the coal-based power plant (CBPP), and their impacts are quantified in terms of water volume, land area, or GHG emissions per unit of energy generated (MWh). The conversion efficiency of the power plant directly impacts the levelized cost of electricity (LCOE) by affecting operational costs per energy unit. A higher conversion efficiency results in greater power generation from the same input fuel compared to a plant with lower efficiency. Retrofitting a coal power plant with CCS reduces average efficiency by around 10% [12]. On the other hand, advanced ULTSUPER technology without CCS can improve the efficiency of a conventional SUB power plant by approximately 8%. However, incorporating POC CCS into a ULTSUPER plant may reduce efficiency by 10.8% [13]. Key determinants affecting the competitiveness of CCS technologies in the LCOE with other clean power generation pathways include coal price and transportation distance [14]. Notably, transportation distance emerges as a critical factor, with a recommended maximum of 300 km for deep saline aquifers in China [15].

There remains a scarcity of comprehensive studies evaluating the sustainability of CBPG with CCS from multifaceted perspectives. Previous studies focused on GHG mitigation through CCS while neglecting the broader impacts on crucial natural resources like water and land [16-19]. Moreover, certain studies independently emphasized the implications of CCS technology on singular aspects such as water, land, or the cost of generation [20-25], without concurrently integrating all these impactful dimensions.

The novelty and contribution of the current study to the scientific knowledge lies in its comprehensive sustainability assessment, bridging the gap by integrating the impacts of CBPG with CCS on air quality, water usage, land utilization, and the LCOE. By examining these factors simultaneously, this study be motivated by providing a holistic view of the sustainability implications associated with CBPG integrated with CCS technology. The current paper is intended to be in line with a previously developed sixty pathways of alternative energy power generation [26] and to form a comparative sustainability assessment platform.

The objectives and focus of the present study are as follows:

1. Alignment and development of sustainable indicators specifically tailored for CBPG with CCS technology.
2. Comprehensive integration of the multifaceted effects stemming from CBPG with CCS, encompassing water demand, land use, GHG emissions, and cost-effectiveness.
3. Comparative analysis and evaluation of the sustainability levels among different CBPG pathways integrated with CCS technology.
4. Identification of the specific electricity generation mix derived from each pathway concerning the total specific electricity demand. This evaluation occurs while conducting sustainable scenarios that are confined by minimal constraints.
5. Estimation of the minimal natural resource requirements, the lowest achievable GHG emissions, and the most efficient LCOE following the execution of sustainable scenarios at a designated level of power generation.

2. Methods

Figure 1 illustrates the system boundary and the unit operations incorporated within the CLC of this study. The sixty-six pathways are structured based on a combination of three coal mining types, four power generation technologies, three CCS technologies, and four distinct cooling systems. Coal mining operations are categorized as surface mining (SM) with or without V, and UM involves various unit operations. Activities such as coal preparation, transportation, and other relevant operations are encompassed within the coal processes unit operations. The CBPP technologies cover SUB, SUPER, ULTSUPER, and IGCC. Each power plant technology can be equipped with either POC or OXF, except for IGCC, which exclusively utilizes PRC. The choice of cooling system significantly impacts water demand indicators, and this study considers four distinct technologies: OTC, CT, CP, and DC. The pathways in the current study are based on a previously developed 36 pathways for coal-based power plants without CCS [27]. The first original 30 pathways are doubled to 60 pathways by introducing POC and OXF technologies for each pathway. The PRC is added to the rest six IGCC pathways. Reviewed and aligned with existing literature, sustainability indicators have been harmonized to evaluate each pathway of CBPG with CCS, all standardized per output unit of energy (MWh).

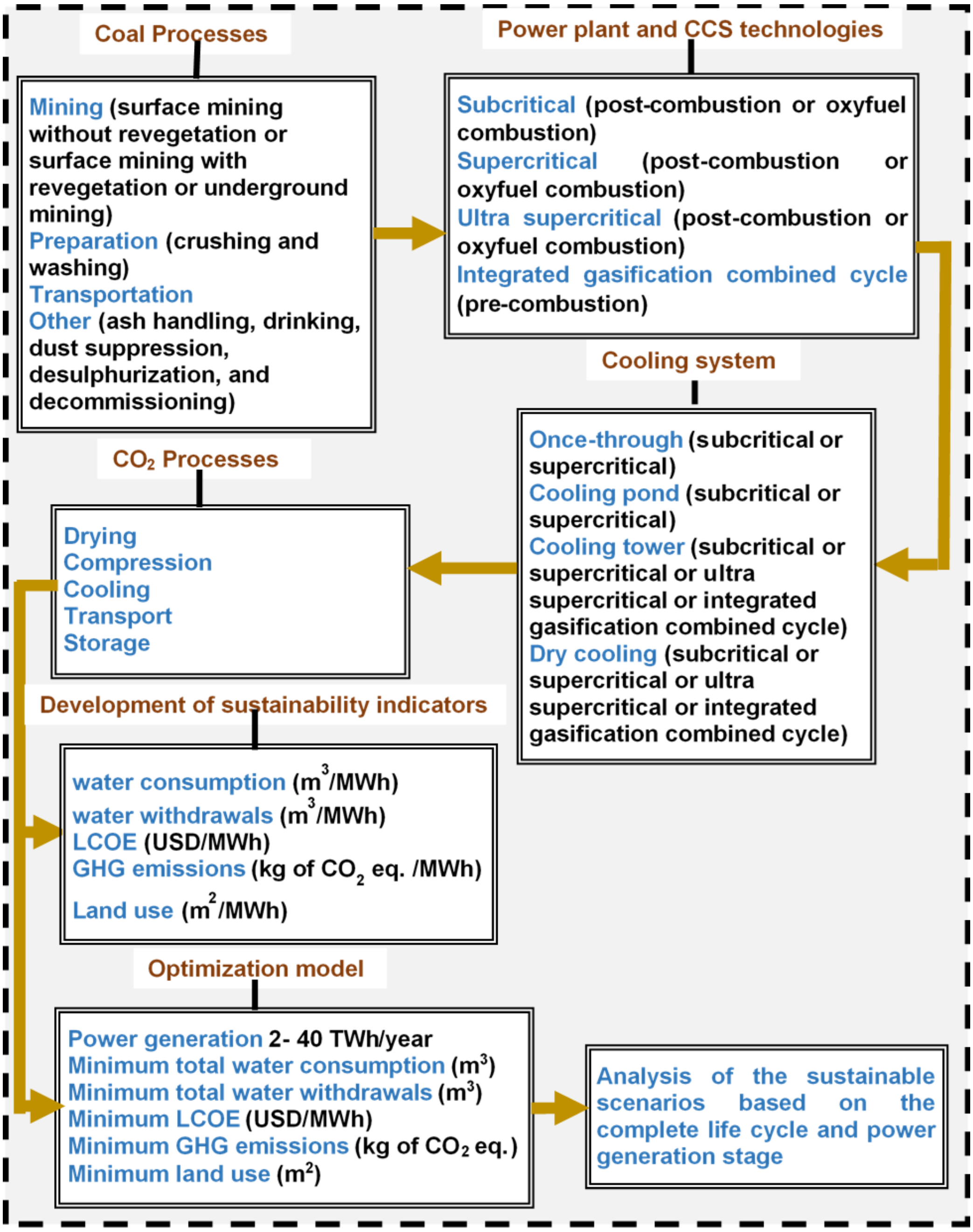

Figure 1 Flow diagram of the study.

The established indicators for each pathway encompass quantitative assessments concerning water demand (in m^3/MWh), land use (in m^2/MWh), GHG (in kg of CO_2 eq./MWh), and the LCOE measured in USD/MWh. These indicators provide insights into the economic dimension of sustainability alongside environmental considerations. The structure of the pathways, water demand indicators, and LCOE are based on a previous study integrating the cost and water demand of CCS technologies [28], as well as another study focusing on the development of sustainability indicators for CBPG without CCS [11]. Additional sustainability indicators, including GHG emissions and land use, have been reviewed from existing literature and further developed as integral components of the current study's sustainability assessment. These sustainability indicators are applied to an electricity demand scenario with a maximum capacity range of 250-5000 MW and a capacity factor of 90% (equivalent to 7884 hours per year), effectively covering an annual energy range of 2-40 TWh [26]. This broad range enables a comprehensive evaluation of sustainability across varying scales of power generation.

The specified electricity demand range facilitated the implementation of sustainable scenarios designed to minimize natural resource utilization (specifically water and land), reduce air impact (GHG emissions), and optimize cost-effectiveness (LCOE) within the CBPG with CCS pathways. Two distinct sustainable scenarios were established to evaluate different operational boundaries. The first scenario comprehensively covers the CLC of CBPG with CCS, encompassing both the upstream stages involving coal extraction and subsequent power generation stages (PGS) integrated with CCS processes. This scenario caters to geographical locations where coal is locally mined and utilized for power generation. In contrast, the second scenario focuses solely on the PGS without incorporating the upstream stages. This scenario suits sites that import fuel, where only the power generation stage occurs without involvement in the upstream processes. For a detailed understanding of the sustainable scenario methodologies employed, additional information can be referenced in the literature [11, 29]. The comparative assessment in the current study evaluates the sustainable scenarios within the CBPG with CCS context against CBPG without CCS, considering factors such as water demand, land use, GHG emissions, and generation costs.

3. Input Data and Assumptions

To ensure consistency and alignment in assessing the impact on air indicators, harmonization has been established by referencing the newly established data concerning the retrofitted pulverized CPPs CCS by [30]. This source provided crucial insights to refine and standardize the gathered data on GHG emissions, which have been disaggregated for each unit operation within CBPG integrated with CCS, as outlined in Table 1. Moreover, a study conducted in Brazil by [31] outlined a range of GHG emissions (100-180 kg of CO_2 eq./MWh) for various CCS pathways based on the electricity generation boundary. The indicators developed in the current study for the combustion unit operations, derived from the data presented in Table 1, fall within a range of 85-121 kg of CO_2 eq./MWh.

Table 1 Impact of CCS on air in kg of CO_2 eq./MWh[a].

Technology	Combustion	Fuel production	Methane leakage	Pollution control	N_2O exhaust	CCS components	Construction and decommissioning	Operation and maintenance	Total for the CLC
SM-SUB	121	51	37	59	20	53	7	10	358
SM-SUPER	111	47	34	55	19	49	6	9	330
SM-ULTSUPER	94	40	29	45	16	41	5	8	278
SM-IGCC	85	36	26	33	9	27	3	8	227
UM-SUB	121	56	41	59	20	53	7	10	367
UM-SUPER	111	52	37	55	19	49	6	9	338
UM-ULTSUPER	94	44	32	45	16	41	5	8	285
UM-IGCC	85	40	28	33	9	27	3	8	233

[a] Indicators are assumed with carbon capture 90% for all CCS pathways [30, 32, 33], and the variation in GHG emissions due to the different CCS technologies was neglected.

Retrofitting CBPPs with dry cooling (DC) technology has been observed to impact power plant performance, as indicated in studies by Zhai and Rubin [34], Stillwell et al. [35], and the World Nuclear Association [36]. In the current study, to account for pathways retrofitted with this technology, a moderate increase of 2% in GHG emissions is assumed, acknowledging its influence on plant performance. Additionally, within the upstream operations associated with fuel production, specifically pertaining to methane leakage related to UM compared to SM, assumptions are made based on insights from prior research [11]. These assumptions propose a 10% increase in GHG emissions for UM operations compared to their SM counterparts. Land use indicators employed in this study are sourced from pertinent literature, drawing from the work of Fthenakis and Kim [37] for gathering initial data and subsequent harmonization for the complete life cycle of CBPG with CCS as per insights from Singh et al. [38]. Fthenakis and Kim [37] provided a comprehensive review study evaluating LCA across various power generation pathways, forming the basis for land use indicators associated with CBPG without CCS. Meanwhile, Singh et al. [38] contributed to determining land use indicators specific to incorporating CCS technology within CPPs, focusing on investigating materials utilized in CPPs integrated with CCS. Detailed input data regarding land use indicators for CBPG with CCS are outlined in Table 2, offering a comprehensive overview derived from these sources.

Table 2 Impact of CCS on land use in m^2/MWh[a].

Technology	Coal upstream stage		PGS		Total for the CLC
	Direct[b]	Indirect	Direct[d]	Indirect[e]	
SM-SUB	0.400	0.005[c]	0.028	0.000	0.433
SM-SUPER	0.368	0.005[c]	0.026	0.000	0.399
SM-ULTSUPER	0.311	0.004[c]	0.022	0.000	0.337
SM-IGCC	0.311	0.004[c]	0.022	0.000	0.337
UM-SUB	0.200	0.275	0.028	0.000	0.503
UM-SUPER	0.184	0.254	0.026	0.000	0.464
UM-ULTSUPER	0.156	0.214	0.022	0.000	0.392
UM-IGCC	0.156	0.214	0.022	0.000	0.392

[a] The variation in land use due to the different CCS technologies was neglected.

[a] An increase of 2% in land use indicator is assumed for pathways using a DC system [11].

[b] Derived from [37], as the U.S. average.

[c] Derived from [37] for the SM of other materials/fuel in the Eastern U.S.

[d] Derived from [37], as average land transformation during power plant operation in the U.S., an extra 37% was added for CCS technology [38].

[e] Negligible values smaller than 0.00062 m^2/MWh.

4. Results and Discussion

4.1 Sustainability Indicators of the CLC

A comprehensive set of sixty-six power generation pathways utilizing coal with CCS technology have been developed, and their sustainability indicators are detailed in Table 3. Notably, advanced coal technologies such as ULTSUPER and IGCC exhibit more favorable sustainability indicators compared to less efficient technologies like SUB. Among the pathways assessed across their CLC, Pathway no. 23, involving UM with SUB-DC power generation and POC, demonstrates notably high sustainability indicators. However, this pathway presents severe negative impacts on certain indicators, with values of 118.05 USD/MWh for the LCOE, 374 kg of CO_2 eq./MWh for GHG emissions, and 0.513 m^2/MWh for land use. The substitution of CT involved in Pathway no. 19 by DC in Pathway no. 23 results in a significant decrease in water demand indicators. Specifically, there is a reduction by 68% in water consumption (from 4.85 m^3/MWh to 1.57 m^3/MWh) and a decrease by 71% in water withdrawals (from 5.71 m^3/MWh to 1.65 m^3/MWh). However, despite reducing water demand indicators, the adoption of DC in this scenario (Pathway no. 23) adversely impacts other sustainability indicators due to its effect on lowering the power plant's conversion efficiency. Retrofitting Pathway no. 23 with POC technology has notably reduced GHG emissions by 67% across the CLC while concurrently increasing the LCOE by 61% and marginally elevating the land use indicator by 1.4% compared to its corresponding CBPG without CCS reference [11]. Pathway no. 54, employing SM, OXF, ULTSUPER technology, and conventional CT, stands out with the lowest LCOE of 65.17 USD/MWh and the smallest land use indicator of 0.337 m^2/MWh among all pathways examined. If the same Pathway no. 54 adopts DC technology (Pathway no. 56), it achieves the lowest water demand indicators across the CLC, with 1.01 m^3/MWh for consumption and 1.04 m^3/MWh for withdrawals. Similarly, Pathways no. 61 and no. 63, utilizing SM (with V or without V) and IGCC with CT-PRC, respectively, also achieve the lowest land use indicators of 0.337 m^2/MWh and the lowest GHG emissions indicator of 227 kg of CO_2 eq./MWh. These pathways demonstrate the minimal impact on land use and GHG emissions, highlighting the effectiveness of efficient advanced coal power generation technologies in minimizing sustainability indicators.

Table 3 Sustainability indicators of CBPG pathways with CCS.

		CLC					PGS				
NO.	Pathway	Water Consumption (m^3/MWh)	Water Withdrawals (m^3/MWh)	LCOE (USD/MWh)	GHG emissions (kg of CO_2 eq./MWh)	Land use (m^2/MWh)	Water Consumption (m^3/MWh)	Water Withdrawals (m^3/MWh)	LCOE (USD/MWh)	GHG emissions (kg of CO_2 eq./MWh)	Land use (m^2/MWh)
1	SM with REV-SUB-OTC-POC	2.90	200.25	115.48	358	0.433	1.77	199.11	124.13	270	0.028
2	SM with REV-SUB-OTC-OXF	2.41	133.59	88.30	358	0.433	1.27	132.45	96.95	270	0.028
3	SM with REV-SUB-CT-POC	4.79	5.65	115.48	358	0.433	3.65	4.51	124.13	270	0.028
4	SM with REV-SUB-CT-OXF	3.58	3.88	88.30	358	0.433	2.44	2.74	96.95	270	0.028
5	SM with REV-SUB-CP-POC	4.73	5.67	115.48	358	0.433	3.59	4.53	124.13	270	0.028
6	SM with REV-SUB-CP-OXF	3.52	3.90	88.30	358	0.433	2.38	2.76	96.95	270	0.028
7	SM with REV-SUB-DC-POC	1.50	1.59	118.05	365	0.442	0.36	0.45	127.22	275	0.029

8	SM with REV-SUB-DC-OXF	1.38	1.41	90.87	365	0.442	0.24	0.27	100.04	275	0.029
9	SM without REV-SUB-OTC-POC	2.87	200.21	115.48	358	0.433	1.77	199.11	124.13	270	0.028
10	SM without REV-SUB-OTC-OXF	2.37	133.55	88.30	358	0.433	1.27	132.45	96.95	270	0.028
11	SM without REV-SUB-CT-POC	4.75	5.61	115.48	358	0.433	3.65	4.51	124.13	270	0.028
12	SM without REV-SUB-CT-OXF	3.54	3.84	88.30	358	0.433	2.44	2.74	96.95	270	0.028
13	SM without REV-SUB-CP-POC	4.69	5.63	115.48	358	0.433	3.59	4.53	124.13	270	0.028
14	SM without REV-SUB-CP-OXF	3.48	3.86	88.30	358	0.433	2.38	2.76	96.95	270	0.028
15	SM without REV-SUB-DC-POC	1.47	1.55	118.05	365	0.442	0.36	0.45	127.22	275	0.029
16	SM without REV-SUB-DC-OXF	1.35	1.38	90.87	365	0.442	0.24	0.27	100.04	275	0.029

17	UM-SUB-OTC-POC	2.97	200.31	115.48	367	0.503	1.77	199.11	124.13	270	0.028
18	UM-SUB-OTC-OXF	2.47	133.65	88.30	367	0.503	1.27	132.45	96.95	270	0.028
19	UM-SUB-CT-POC	4.85	5.71	115.48	367	0.503	3.65	4.51	124.13	270	0.028
20	UM-SUB-CT-OXF	3.64	3.94	88.30	367	0.503	2.44	2.74	96.95	270	0.028
21	UM-SUB-CP-POC	4.79	5.73	115.48	367	0.503	3.59	4.53	124.13	270	0.028
22	UM-SUB-CP-OXF	3.58	3.96	88.30	367	0.503	2.38	2.76	96.95	270	0.028
23	UM-SUB-DC-POC	1.57	1.65	118.05	374	0.513	0.36	0.45	127.22	275	0.029
24	UM-SUB-DC-OXF	1.44	1.47	90.87	374	0.513	0.24	0.27	100.04	275	0.029
25	SM with REV-SUPER-OTC-POC	1.90	162.54	112.55	330	0.399	0.85	161.49	120.51	249	0.026
26	SM with REV-SUPER-OTC-OXF	1.46	103.98	82.72	330	0.399	0.42	102.93	90.68	249	0.026
27	SM with REV-SUPER-CT-POC	4.11	5.19	112.55	330	0.399	3.06	4.14	120.51	249	0.026
28	SM with REV-SUPER-CT-OXF	3.03	3.61	82.72	330	0.399	1.99	2.57	90.68	249	0.026

29	SM with REV-SUPER-CP-POC	3.38	4.60	112.55	330	0.399	2.33	3.55	120.51	249	0.026
30	SM with REV-SUPER-CP-OXF	2.30	3.03	82.72	330	0.399	1.26	1.98	90.68	249	0.026
31	SM with REV-SUPER-DC-POC	1.35	1.46	115.17	336	0.407	0.31	0.41	123.60	254	0.027
32	SM with REV-SUPER-DC-OXF	1.24	1.30	85.34	336	0.407	0.2	0.26	93.77	254	0.027
33	SM without REV-SUPER-OTC-POC	1.87	162.51	112.55	330	0.399	0.85	161.49	120.51	249	0.026
34	SM without REV-SUPER-OTC-OXF	1.43	103.94	82.72	330	0.399	0.42	102.93	90.68	249	0.026
35	SM without REV-SUPER-CT-POC	4.07	5.15	112.55	330	0.399	3.06	4.14	120.51	249	0.026
36	SM without REV-SUPER-CT-OXF	3.00	3.58	82.72	330	0.399	1.99	2.57	90.68	249	0.026
37	SM without REV-SUPER-CP-POC	3.35	4.57	112.55	330	0.399	2.33	3.55	120.51	249	0.026

38	SM without REV-SUPER-CP-OXF	2.27	2.99	82.72	330	0.399	1.26	1.98	90.68	249	0.026
39	SM without REV-SUPER-DC-POC	1.32	1.43	115.17	336	0.407	0.31	0.41	123.60	254	0.027
40	SM without REV-SUPER-DC-OXF	1.21	1.27	85.34	336	0.407	0.2	0.26	93.77	254	0.027
41	UM-SUPER-OTC-POC	1.96	162.60	112.55	338	0.464	0.85	161.49	120.51	249	0.026
42	UM-SUPER-OTC-OXF	1.52	104.04	82.72	338	0.464	0.42	102.93	90.68	249	0.026
43	UM-SUPER-CT-POC	4.17	5.25	112.55	338	0.464	3.06	4.14	120.51	249	0.026
44	UM-SUPER-CT-OXF	3.09	3.67	82.72	338	0.464	1.99	2.57	90.68	249	0.026
45	UM-SUPER-CP-POC	3.44	4.66	112.55	338	0.464	2.33	3.55	120.51	249	0.026
46	UM-SUPER-CP-OXF	2.36	3.09	82.72	338	0.464	1.26	1.98	90.68	249	0.026
47	UM-SUPER-DC-POC	1.41	1.52	115.17	344	0.473	0.31	0.41	123.60	254	0.027
48	UM-SUPER-DC-OXF	1.30	1.36	85.34	344	0.473	0.2	0.26	93.77	254	0.027
49	SM with REV-	3.42	4.33	106.53	278	0.337	2.53	3.44	113.25	210	0.022

	ULTSUPER-CT-POC										
50	SM with REV-ULTSUPER-CT-OXF	2.43	2.75	65.17	278	0.337	1.54	1.86	71.89	210	0.022
51	SM with REV-ULTSUPER-DC-POC	1.14	1.23	108.97	284	0.344	0.25	0.34	116.10	214	0.022
52	SM with REV-ULTSUPER-DC-OXF	1.04	1.07	67.61	284	0.344	0.15	0.19	74.74	214	0.022
53	SM without REV-ULTSUPER-CT-POC	3.39	4.30	106.53	278	0.337	2.53	3.44	113.25	210	0.022
54	SM without REV-ULTSUPER-CT-OXF	2.40	2.72	65.17	278	0.337	1.54	1.86	71.89	210	0.022
55	SM without REV-ULTSUPER-DC-POC	1.11	1.20	108.97	284	0.344	0.25	0.34	116.10	214	0.022
56	SM without REV-	1.01	1.04	67.61	284	0.344	0.15	0.19	74.74	214	0.022

	ULTSUPER-DC-OXF										
57	UM-ULTSUPER-CT-POC	3.47	4.38	106.53	285	0.392	2.53	3.44	113.25	210	0.022
58	UM-ULTSUPER-CT-OXF	2.48	2.80	65.17	285	0.392	1.54	1.86	71.89	210	0.022
59	UM-ULTSUPER-DC-POC	1.19	1.28	108.97	291	0.399	0.25	0.34	116.10	214	0.022
60	UM-ULTSUPER-DC-OXF	1.09	1.12	67.61	291	0.399	0.15	0.19	74.74	214	0.022
61	SM with REV-IGCC-CT-PRC	2.83	3.28	104.20	227	0.337	1.95	2.40	110.92	165	0.022
62	SM with REV-IGCC-DC-PRC	1.08	1.12	107.14	232	0.344	0.20	0.24	114.27	168	0.022
63	SM without REV-IGCC-CT-PRC	2.81	3.26	104.20	227	0.337	1.95	2.40	110.92	165	0.022
64	SM without REV-IGCC-DC-PRC	1.05	1.10	107.14	232	0.344	0.20	0.24	114.27	168	0.022
65	UM-IGCC-CT-PRC	2.88	3.33	104.20	233	0.392	1.95	2.40	110.92	165	0.022

66	UM-IGCC-DC-PRC	1.13	1.17	107.14	238	0.399	0.20	0.24	114.27	168	0.022

The water consumption and withdrawals indicators are derived from [27] for electricity generation, and the CCS increments are added from [28].

The LCOE indicators are derived from [28].

The GHG emissions indicators are taken and rearranged from Table 1.

The land use indicators are taken and rearranged from Table 2.

4.2 Sustainability Indicators of the PGS

When limiting the CLC boundary to encompass solely the PGS, the upstream unit operations' influence on sustainability indicators is eliminated, emphasizing the importance of power plant performance in determining these indicators. Pathways utilizing SUB technology with DC and POC (Pathways no. 7, 15, and 22 in Table 3) exhibit the highest cost, GHG emissions, and land use indicators, with values of 127.22 USD/MWh, 275 kg of CO_2 eq./MWh, and 0.029 m^2/MWh, respectively. In contrast, pathways integrating advanced coal technology, particularly ULTSUPER with oxyfuel CCS and CT (Pathways no. 50, 54, and 58), demonstrate the lowest LCOE at 71.89 USD/MWh. Despite a remarkable 74% reduction in GHG emissions indicators due to CCS technology, these pathways also reveal an increase in water consumption by 18%, water withdrawals by 15%, LCOE by 34%, and land use by 27% [11]. Notably, all pathways featuring advanced ULTSUPER coal technologies and IGCC with CCS showcase the lowest land use indicator at 0.022 m^2/MWh. Furthermore, the ULTSUPER technology combined with DC and OXF pathways (Pathways no. 52, 56, and 60) demonstrates the minimum water consumption indicator of 0.15 m^3/MWh and the lowest water withdrawals indicator of 0.19 m^3/MWh, alongside the lowest land use indicator.

On average, 75% of the full life cycle GHG emissions indicator occurs during the PGS. Specifically, the combustion unit operation accounts for approximately 34% of this total GHG emissions during the PGS. Contrarily, the land use indicator allocation during power generation amounts to an average of 6%. Remarkably, the majority, approximately 94%, of the land use indicator is allocated to upstream unit operations.

4.3 Sustainable Scenario of the CLC

The outcomes of the sustainable scenarios were derived using an optimization model previously devised and implemented by [29]. This model aimed to ascertain the proportional contribution of each pathway toward meeting the total electricity demand within an optimized sustainability zone. The specified electricity demand range for analysis encompassed 2-40 TWh/year, accommodating a maximum power capacity between 250-5000 MW and operating at a capacity factor of 90% (equivalent to 7884 hours per year) as outlined in [11]. Utilizing the sustainability indicators developed and detailed in Table 3, alongside additional minimum constraints, the model was employed to estimate the generation mix required to fulfill the specified electricity demand under sustainable conditions.

On average, Pathway no. 64, characterized by SM without V IGCC and DC with PRC, can generate 71% of the total electricity demand within the optimum sustainability zone. This pathway demonstrates a significant range of feasibility, from 47% to 90%. The potential requirement for a revegetation process could marginally increase the water consumption indicator by 3% and water withdrawals by 2%. The utilization of the highly efficient IGCC technology, coupled with the low water impact of DC, solidifies Pathway no. 64's selection within the model's optimum sustainability zone for power generation. The remaining electricity demand is met by Pathway no. 56, employing SM without V, ULTSUPER power generation technology, DC, and OXF. Pathway no. 56 boasts the lowest water consumption and withdrawals indicators alongside the second-best LCOE among all studied pathways. However, despite sharing the same land use indicator, it exhibits a 22% higher indicator for GHG emissions compared to Pathway no. 64. On average, around 1% of the electricity demand falls within the optimum sustainability zone, attributed to a pathway akin to Pathway no. 56 in unit operations, except for the use of conventional CT instead of DC (Pathway no. 54). While Pathway no. 54 boasts the best LCOE and minimal land use impact among all sixty-six pathways, the employment of CT leads to higher water demand indicators compared to competitive pathways utilizing DC, such as Pathway no. 56 and Pathway no. 64. The sustainable scenario yields an average LCOE of 95.71 USD/MWh across the CLC, with a range spanning from 86.18 to 103.34 USD/MWh. Pathway no. 64 plays a dominant role in shaping this level of LCOE due to its significant contribution. Figure 2 presents the results of the optimization model, showcasing the most sustainable pathways considering the full life cycle based on the specified electricity demand and the resulting average LCOE.

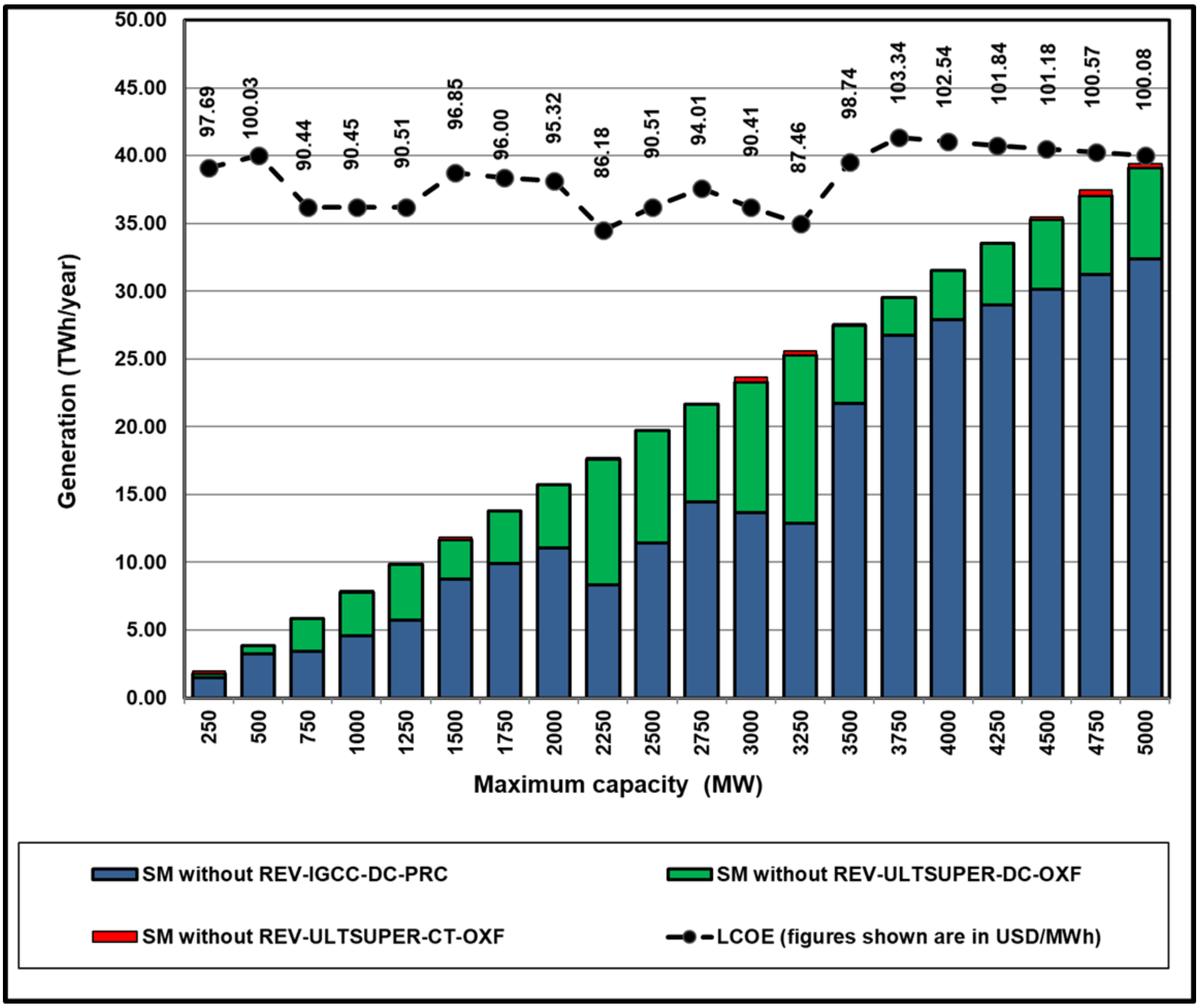

Figure 2 CLC sustainable scenario.

4.4 Sustainable Scenario of the PGS

On average, 69% (ranging from 38% to 100%) of the total electricity demand can be met by pathways utilizing ULTSUPER configuration with DC and OXF-CCS technology (Pathways no. 52, 56, and 60) after narrowing the boundary to include solely the PGS. During the PGS, these pathways exhibit the most negligible impact on natural resources, specifically water, and land, and rank with the second lowest LCOE among the sixty-six developed pathways. Covering the remaining demand, pathways integrating IGCC, DC, and PRC unit operations (Pathways no. 62, 64, and 66) account for an average of 31% (ranging from 0% to 61%). ULTSUPER pathways equipped with conventional CT and OXF-CCS technology (Pathways no. 50, 54, and 58) cover approximately 1% of the demand. When considering only the PGS, the sustainable scenario yields an average LCOE of 86.84 USD/MWh, from 74.73 to 98.86 USD/MWh. Notably, this average is lower than the LCOE calculated for the CLC boundary due to variations in the dominant pathway's LCOE in each boundary (107.14 USD/MWh for CLC and 74.74 USD/MWh for PGS). Figure 3 showcases the results generated by the optimization model, outlining the best sustainable pathways based on the PGS, addressing the determined demand, and presenting the resulting average LCOE.

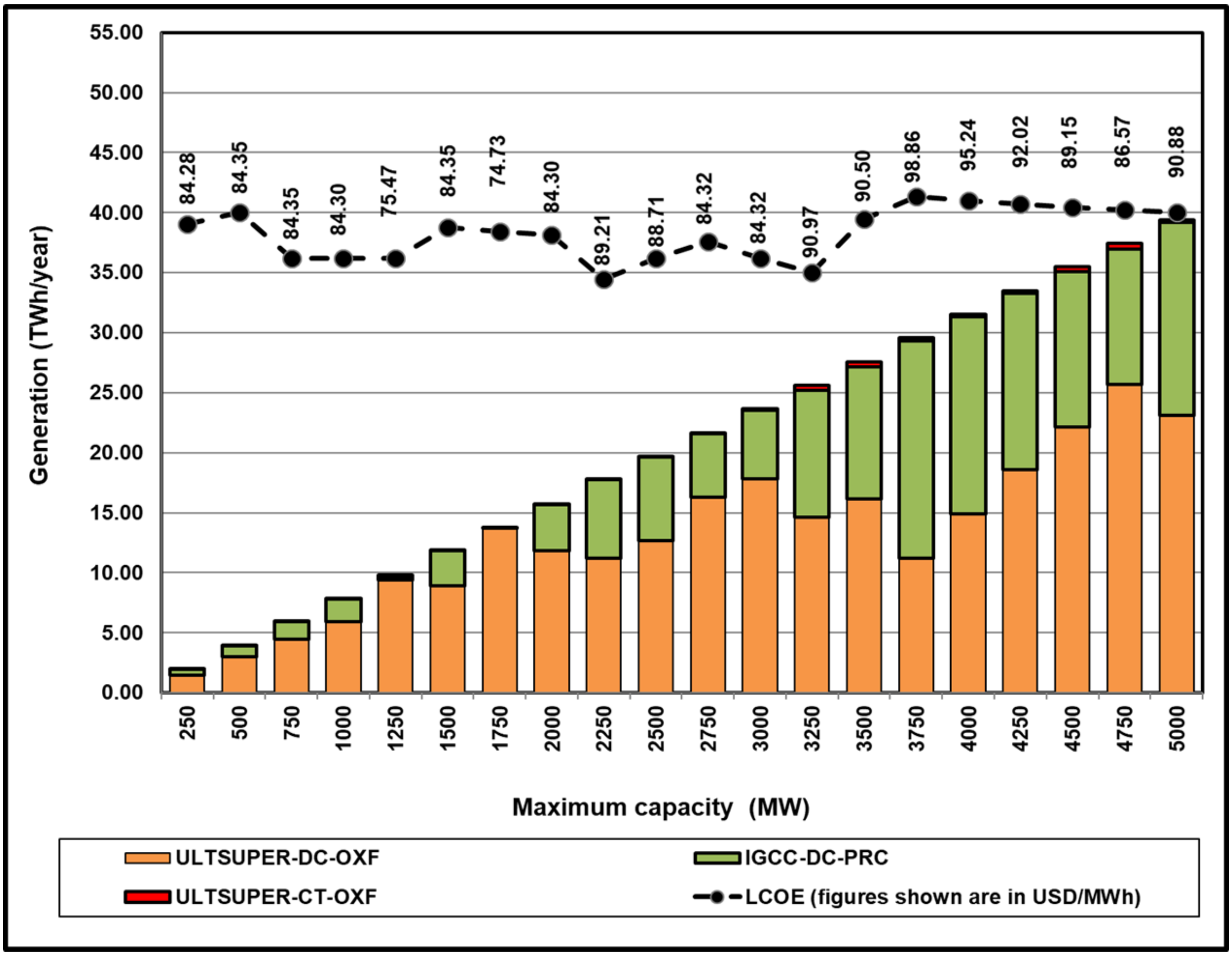

Figure 3 PGS sustainable scenario pathways.

4.5 GHG Emissions, Resources Used, and LCOE of the Sustainable Scenarios

Figure 4 illustrates the GHG emissions profile for sustainable scenarios of CBPG with CCS within the specified electricity demand range of 250-5000 MW, considering both the CLC and the PGS boundaries. For comparative analysis, the GHG emissions profile for sustainable scenarios of CBPG without CCS, as detailed in [11], has been included in Figure 4. The annual GHG emissions profile with CCS, based on the CLC, falls within the range of 0.48-9.5 Mt of CO_2 eq., while within the PGS boundary, it ranges from 0.4-7.7 Mt of CO_2 eq. Retrofitting CCS technology onto the CBPPs operating under the same electricity demand range leads to an annual mitigation of GHG emissions in the 1.2-

23.5 Mt of CO_2 eq range across the CLC boundary, while based on the PGS, the mitigation ranges from 1.1-22.9 Mt of CO_2 eq.

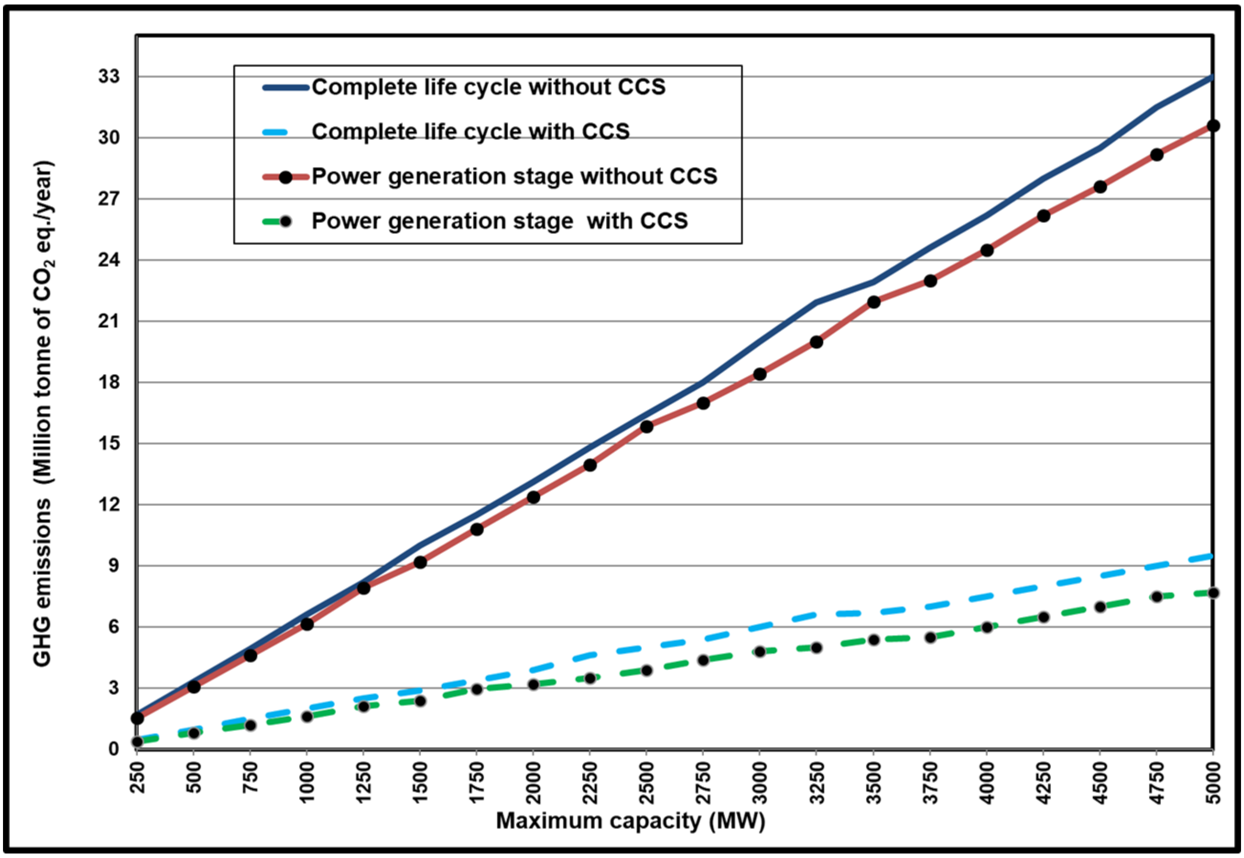

Figure 4 Effect of CCS technology on the GHG emissions of sustainable scenarios for CBPG.

In the context of GHG emissions mitigation, implementing CCS technology in CBPG required additional water and land resources, as depicted in Figure 5 and Figure 6, respectively. Based on the CLC boundary of CBPG with CCS, the annual surplus water consumption ranged from 0.25 to 2.30 Mm^3, with an average of 1.20 Mm^3. Correspondingly, the yearly incremental water withdrawals ranged between 0.30 and 2.70 Mm^3, averaging 1.40 Mm^3. Additionally, the impact of CCS technology on land use in coal power generation, based on the CLC, exhibited a range of 11,413 m^2/year for a demand point of 250 MW to 250,231 m^2/year for a demand point of 5000 MW. This additional land area was primarily required during the PGS. Consequently, considering the LCOE for the CLC of CBPG with CCS (as shown in Figure 2), the increment over power generation without CCS (as detailed in [11]), averaged 45.55 USD/MWh, covering a range from 35.18 to 53.62 USD/MWh. Figure 7 offers a comprehensive breakdown illustrating the variance in LCOE resulting from the retrofitting of CCS technology onto CBPPs.

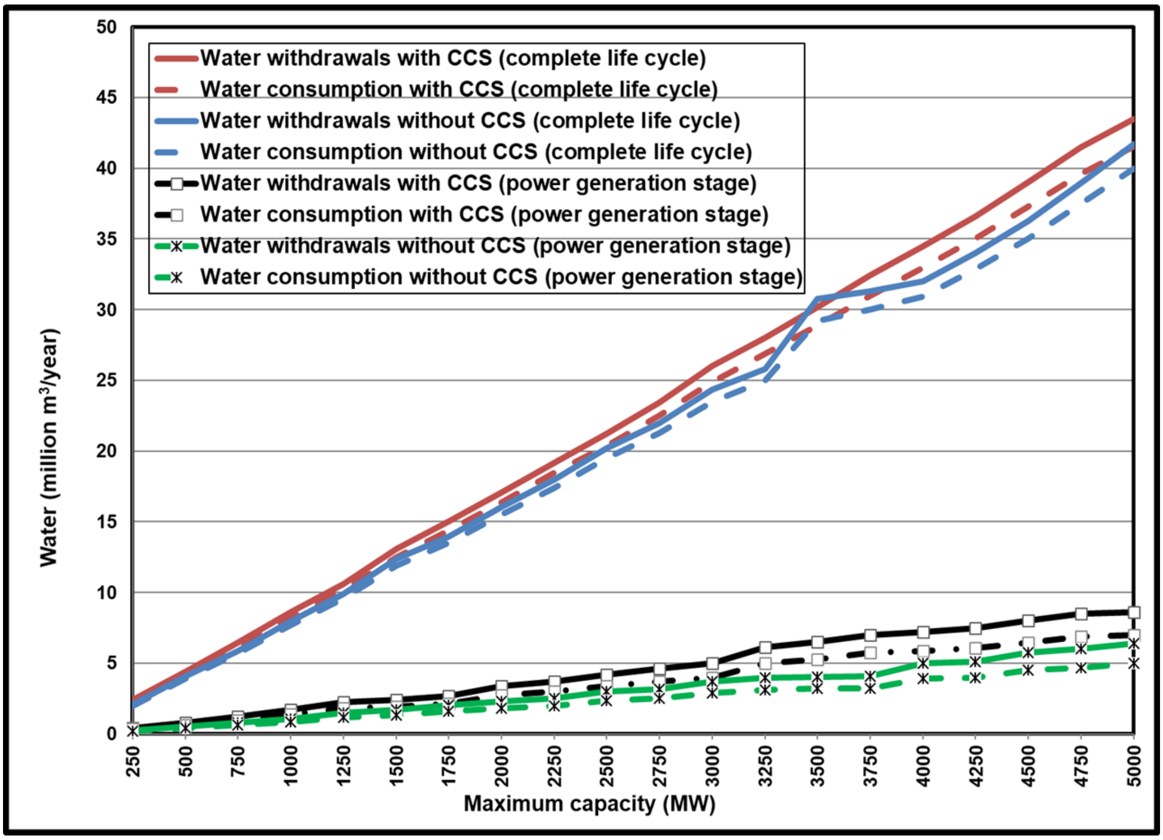

Figure 5 Effect of CCS technology on the water demand of sustainable scenarios for CBPG.

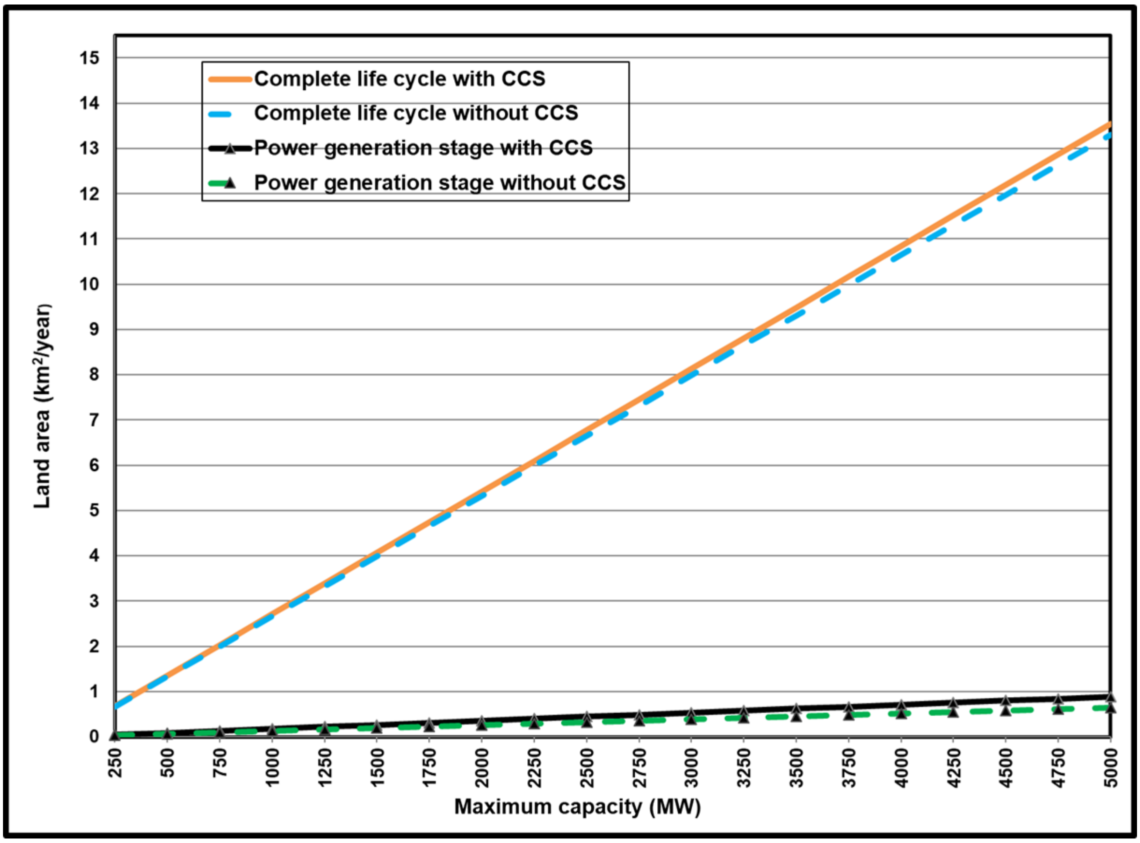

Figure 6 Effect of CCS technology on the land use of sustainable scenarios for CBPG.

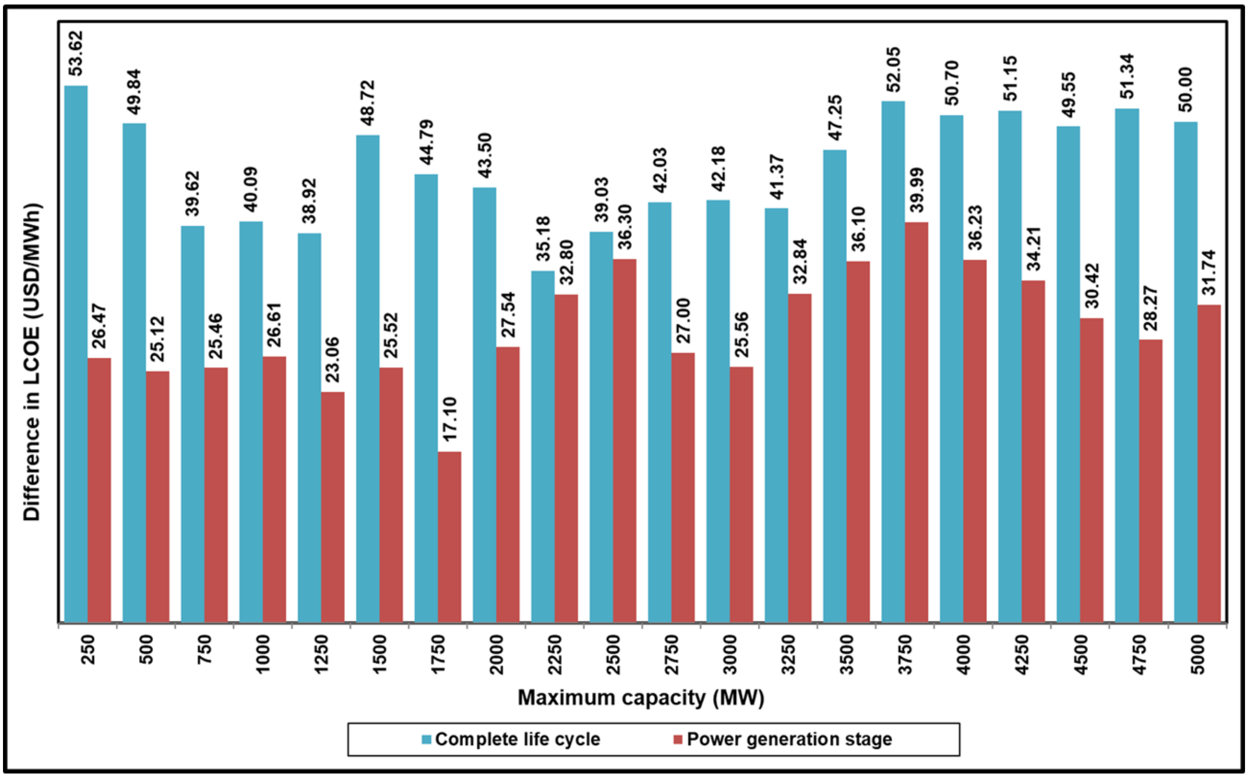

Figure 7 Incremental increase in LCOE due to the retrofitting CCS technology on CBPG.

5. Conclusions

This study undertakes a comprehensive sustainability evaluation of CBPG integrated with CCS technology through LCA. The assessment aims to amalgamate the quantitative impacts of power generation on vital natural resources like water and land, in addition to GHG emissions and the cost of generation. Notably, more efficient technologies in CBPG exhibit greater sustainability due to their reduced utilization of natural resources, minimized air impact, and enhanced cost-effectiveness. Pathways involving SM in coal operations, IGCC technology paired with conventional CT, and PRC configuration demonstrate the lowest quantitative impacts on air and land use. These pathways showcase sustainability indicators of 227 kg of CO_2 eq. per MWh for GHG emissions and 0.337 m^2 per MWh for land use. Conversely, the highest GHG emissions and land use indicators—374 kg of CO_2 eq. per MWh and 0.513 m^2 per MWh, respectively—are observed in the full life cycle of CBPG with CCS through UM of coal and SUB technology with DC. The most sustainable approach to cover the electricity demand range of 250-5000 MW emerges from the full life cycle of a pathway that employs SM of coal without revegetation, utilizing IGCC power generation technology, DC, and PRC. Furthermore, pathways incorporating ULTSUPER technology with DC and OXF are identified within the optimum sustainability zone by the model based on the reduced boundary of the PGS.

The comparative assessment of CBPG with and without CCS reveals that retrofitting CCS technology onto the power plant has significantly mitigated GHG emissions. However, this mitigation has resulted in negative quantitative impacts on water, land, and the LCOE. Annually, the GHG mitigation attributed to implementing CCS technology for an electricity demand ranging from 250 to 5000 MW, based on the CLC, falls within the range of 1.2 to 23.5 Mt of CO_2 eq. Correspondingly, the mitigation range based on the PGS spans from 1.1 to 22.9 Mt of CO_2 eq.

The methodology used in the current study is limited by covering only quantitative analysis; air quality is represented only by GHG emissions without considering SO_x and NO_x emissions, and the social pillar of sustainability is not covered.

Nomenclatures

CBPG	coal-based power generation
CBPP	Coal-based power plant
CCS	carbon capture and storage
CLC	complete life cycle
CP	cooling pond
CPPS	coal power plants
CT	cooling tower
DC	dry cooling
GHG	greenhouse gas
GWh	gigawatt-hour, equal one thousand MWh
IGCC	integrated gasification combined cycle
kg of CO_2 eq.	kilogram of carbon dioxide equivalent
LCA	life cycle assessment
LCOE	levelized cost of electricity
Mt of CO_2 eq.	megatonne of carbon dioxide equivalent
m^3/MWh	cubic meters of water per megawatt-hour
m^2/MWh	square meters of land area per megawatt-hour
OTC	once-through cooling
OXF	oxyfuel combustion CCS technology
PGS	power generation stage
POC	post-combustion CCS technology
PRC	pre-combustion CCS technology
SM	surface mining
SM without V	surface mining without revegetation
SM with V	surface mining with revegetation
SUB	subcritical pulverized coal
SUPER	supercritical pulverized coal
ULTSUPER	ultra-supercritical pulverized coal
UM	underground mining
USD/MWh	the United States Dollars per megawatt-hour

Author Contributions

Babkir Ali: Methodology, analysis, and writing the original draft. **Ahmed Gamil:** Writing review, editing, investigation, and validation.

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Competing Interests

The authors have declared that no competing interests exist.

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