

LIFE CYCLE ASSESSMENT AND INTEGRATED SUSTAINABILITY EVALUATION OF COAL-SLUDGE CO-FIRING POWER GENERATION

Hongting Jiang, Shuai Che *, Junhong Liu and Pengfei Yu

School of Mechanical and Power Engineering, Shenyang University of Chemical Technology, Shenyang, 110142, Liaoning, China

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ABSTRACT

The co-firing of municipal sewage sludge in coal-fired power plants is considered a viable waste-to-energy pathway for sludge disposal and low-carbon transition, yet comprehensive sustainability evaluations under China's dual-carbon goals remain limited. This study fills this gap by quantifying the environmental, economic, and integrated performance of a typical 2×330 MW co-firing plant in northern China using a cradle-to-gate life cycle assessment (LCA), life cycle costing (LCC), and the analytic hierarchy process (AHP). The results show that global warming potential dominates the total environmental impact (82.3%). Co-firing reduces internal costs by 1.1% while slightly increasing external costs by 0.8%. The integrated sustainability score of the co-firing scenario (0.5021) is statistically indistinguishable from that of conventional coal power (0.4979; bootstrap 95% CI of the difference [-0.008, +0.016]), indicating that co-firing does not compromise overall sustainability while providing the additional function of sludge disposal. Dynamic life cycle assessment further reveals that while centennial-scale GWP is nearly equivalent, co-firing exhibits an ~80% higher short-term (20-year) climate impact under time-resolved biogenic carbon accounting, underscoring the need to distinguish long-term carbon neutrality from near-term climate penalties in policy formulation. The evidence indicates that coal-sludge co-firing represents a viable transitional co-processing solution that should be supported through waste-disposal subsidies rather than carbon credits, without a significant net increase in centennial-scale climate burdens.

1. INTRODUCTION

Global climate change has intensified, with the past decade being the warmest on record (IPCC, 2021). China, as the world's largest energy producer and consumer, has committed to peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 (State Council, 2021). Thermal power, which constitutes roughly 63% of China's total electricity generation (China Electricity Council, 2024), persists as the principal source of carbon emissions and air pollution. Therefore, promoting the low-carbon transformation of the thermal power industry is critical for achieving the dual carbon goals.

Meanwhile, China's annual municipal sludge production has exceeded 60 million tons (80% moisture content) with an annual growth rate of 5-8% (Dai et al., 2022). Traditional sludge disposal methods such as landfilling (38%) and land application (22%) face increasing environmental constraints due to land scarcity, groundwater contamination risks, and odor pollution (Zhou et al., 2022). Coal-sludge co-firing power generation utilizes existing coal-fired power plant facilities to co-combust dewatered sludge with coal,

achieving the harmless disposal of sludge, volume reduction, and energy recovery simultaneously. This technology has attracted widespread attention due to its low incremental investment, high treatment capacity, and compatibility with existing power generation infrastructure (Chen et al., 2019).

Life cycle assessment (LCA) is a systematic methodology for evaluating the environmental impacts of products or processes throughout their entire life cycle, from raw material extraction to final disposal (ISO 14040, 2006). It has been widely applied in the power industry to assess the environmental performance of different generation technologies. Previous studies have conducted LCA on conventional coal-fired power plants (Kommalapati et al., 2018; Li et al., 2020), biomass co-firing (Kommalapati et al., 2018), and renewable energy systems (Li et al., 2020). However, research on coal-sludge co-firing remains limited and fragmented. Most existing studies focus on combustion characteristics and pollutant emission control (Huang et al., 2021), while few have conducted comprehensive cradle-to-gate LCA studies covering all life cycle stages.

 * Corresponding author:
Shuai Che
email: cheshuai@syuct.edu.cn

Furthermore, most LCA studies only consider environmental impacts, ignoring economic costs and social benefits. A holistic sustainability evaluation that integrates environmental, economic, and social dimensions is essential for evidence-based policy-making regarding the promotion of coal-sludge co-firing technology. Recent studies (Ren et al., 2025; Wang & Zhu, 2023) have highlighted the need for multi-criteria decision analysis to balance trade-offs between different sustainability dimensions.

This study aims to fill these research gaps by conducting a comprehensive life cycle assessment and integrated sustainability evaluation of coal-sludge co-firing power generation. The specific objectives are: (1) to establish a cradle-to-gate LCA model for coal-sludge co-firing and quantify its environmental impacts; (2) to conduct sensitivity analysis to identify key parameters affecting environmental performance; (3) to evaluate life cycle costs including both internal operational costs and external environmental costs; (4) to develop an integrated AHP-based evaluation system and compare the comprehensive sustainability of co-firing and conventional coal-fired power generation. The findings of this study will provide quantitative evidence for policy makers and power plant operators to make informed decisions regarding sludge co-firing promotion.

2. MATERIALS AND METHODS

2.1 Goal and scope definition

The primary goal of this study is to evaluate the environmental impact, economic cost, and comprehensive sustainability of coal-sludge co-firing power generation compared to conventional coal-fired power generation. The functional unit is defined as 1 kWh of net electricity delivered to the grid, which is the standard functional unit for power generation LCA studies (ISO 14067, 2018).

The system boundary follows a cradle-to-gate approach, encompassing four consecutive stages:

- Raw material acquisition: Extraction and processing of coal, limestone, urea, hydrochloric acid, sodium hydroxide, and sludge collection/dewatering.
- Transportation: Transportation of all raw materials to the power plant via railway and road.
- Power generation: Combustion of coal-sludge mixture, electricity generation, and flue gas treatment (desulfurization, denitrification, dust removal).
- By-product recycling: Comprehensive utilization of boiler slag, fly ash, and desulfurization gypsum as construction materials.

Within the power generation stage, the coal-sludge blend undergoes pulverization in coal mills, preheating with combustion air, and subsequent combustion in the pulverized-coal boiler at approximately 1,400°C. The resulting flue gas passes sequentially through selective catalytic reduction (SCR) for NO_x removal, electrostatic precipitators for dust removal, and limestone-gypsum wet flue gas desulfurization for SO₂ removal before being discharged through the stack.

In the conventional coal-fired power generation baseline scenario, the same annual quantity of municipal sludge

(75,000 t, 80% moisture content) is assumed to be generated but is disposed of independently via sanitary landfilling. Consistent with the cut-off principle of attributional LCA (ISO 14040:2006, Section 4.3.1), the environmental burdens of sludge landfilling—including landfill gas emissions, leachate generation and treatment, and land occupation—are excluded from the system boundary of the power generation baseline. This exclusion rests on the rationale that, under attributional LCA, a product system is responsible only for the environmental interventions directly attributable to its own function (electricity generation); the post-use disposal of sludge, which would occur regardless of whether the sludge is co-fired or landfilled, constitutes an independent waste management system with its own functional unit (tonnes of sludge treated). Including landfill burdens in the power generation baseline would confound the functional units of two distinct product systems.

This conservative methodological choice has the following consequence: co-firing receives no credit for the avoided landfill methane emissions that would result from diverting sludge away from landfill disposal. The magnitude of this uncredited benefit is estimated in the Supplementary Materials (Table S8): depending on landfill gas management conditions, avoided methane emissions could provide a GWP credit of 0.003–0.008 kg CO₂ eq/kWh, which, if credited to co-firing, would reduce its net GWP below that of conventional coal power by approximately 1–3%. The main-text comparison therefore represents a conservative lower bound of co-firing's relative climate performance (Figure 1).

The construction and decommissioning stages of the power plant are excluded from the system boundary, consistent with the majority of power generation LCA studies, on the grounds that their contribution per unit of electricity generated is typically small relative to the operational phase over a 30-year service life (Malode et al., 2023). However, it is acknowledged that the co-firing scenario required retrofit modifications—specifically, the installation of a sludge receiving and storage facility, a sludge dewatering unit (centrifuge), a closed sludge conveying system, and modifications to the coal feeding system to accommodate the blended fuel—that would not be necessary for a conventional coal-fired plant of equivalent capacity. The environmental impacts of manufacturing and installing this retrofit equipment are not separately quantified in this study. They are assumed to be partially captured within the auxiliary power consumption data (Section 2.3) and the sludge pre-treatment inventory, though this assumption may underestimate the actual cradle-to-gate environmental burden of the co-firing configuration. The magnitude of this potential underestimation should be quantified in future work through a dedicated capital-equipment LCA of the retrofit components. From a life cycle cost perspective, the capital expenditure for the sludge co-firing retrofit (approximately 35–50 million yuan for the sludge receiving, dewatering, and conveying systems, per the plant's engineering procurement records) is amortized over the 30-year remaining service life of the host plant. The annualized retrofit cost, normalized to the functional unit, is approximately 0.0004–0.0006 yuan/kWh (< 0.2% of the internal cost), and

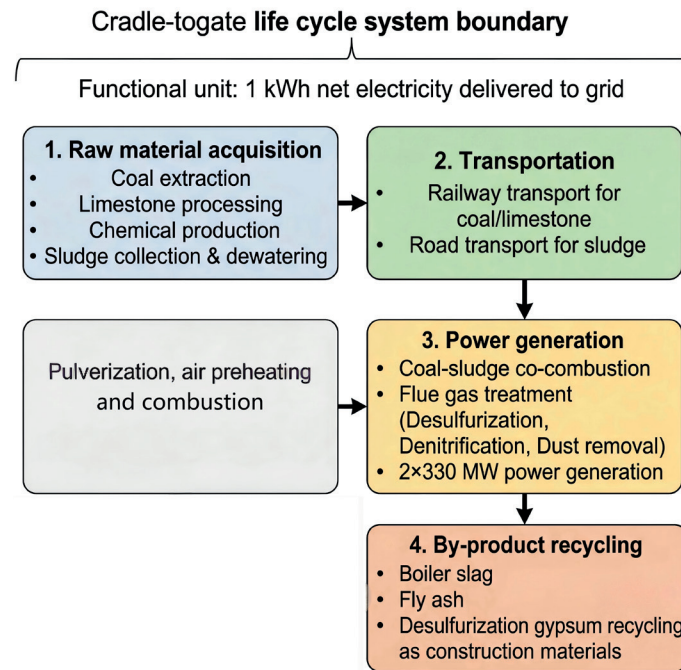


FIGURE 1: System boundary of coal-sludge co-firing power generation system.

is therefore not separately itemized in the life cycle cost analysis. This assumption is valid for the retrofit-of-existing-plant scenario studied here; a greenfield co-firing plant would require a full capital-cost LCA, beyond the scope of this work. Electricity transmission and distribution are also excluded as they are identical for both co-firing and conventional coal-fired power generation.

2.2 Co-product allocation for the CHP system

The studied power plant is a combined heat and power (CHP) system producing two co-products: net electricity (3.01×10^9 kWh/year) and heat (6.132×10^6 GJ/year). In accordance with ISO 14040:2006, Section 4.3.4.2, which requires that allocation in multi-functional systems reflect underlying physical relationships, the energy allocation method was adopted—the most widely recommended allocation approach for CHP systems in the LCA literature. The allocation coefficient for electricity (a_e) was calculated as:

$$a_e = E_e / (E_e + E_h) \quad (1)$$

where E_e is the annual net electricity output expressed in energy units (3.01×10^9 kWh $\times$ 3.6 MJ/kWh = 1.0836×10^7 GJ) and E_h is the annual heat output (6.132×10^6 GJ). This yields $a_e = 0.6386$ (63.86%) for electricity and $a_h = 0.3614$ (36.14%) for heat. All plant-level input and output data were first compiled as total annual quantities, then partitioned using these coefficients, and finally normalized to the functional unit of 1 kWh net electricity. The detailed allocation factors and the resulting electricity-attributed shares of key inventory flows are summarized in Supplementary Table S1.

This transparent reporting of the allocation methodology and coefficients enables full reproducibility and allows readers to recalculate results under alternative allocation assumptions.

2.2.1 By-product recycling allocation method

The system expansion approach (also termed the avoided burden method) was adopted to account for the environmental credits associated with by-product recycling, consistent with the ISO 14044:2006 recommendation for multi-functional processes where system expansion is feasible. Under this approach, the recycled by-products—boiler slag, fly ash, and desulfurization gypsum—are assumed to substitute equivalent quantities of primary materials in their respective markets: natural gravel (for boiler slag used as road base aggregate), Portland cement (for fly ash used as supplementary cementitious material in concrete production), and natural gypsum (for desulfurization gypsum used in wallboard manufacturing). The environmental burdens avoided by not producing these primary materials are credited to the co-firing system.

As shown in Table 2, recycling credits are allocated to ADP, GWP, and HTP, reflecting the primary environmental mechanisms of material substitution: ADP credits arise from avoided extraction of limestone, clay, and natural gypsum; GWP credits arise from avoided process-related CO₂ emissions during cement clinker production and gypsum calcination; and HTP credits arise from avoided heavy metal and particulate releases associated with mining and quarrying operations. No recycling credits are assigned to POCP, AP, and EP because the avoided production of natural gravel, cement, and gypsum generates negligible reductions in photochemical oxidant formation, acidification, and eutrophication relative to the dominant contributions from coal combustion and upstream fuel processing. The substitution ratios adopted are as follows: 1 kg of fly ash displaces 0.85 kg of Portland cement (CEM I 42.5), reflecting the loss-on-ignition-based quality adjustment for Class F fly ash; 1 kg of desulfurization gypsum displaces 0.90

kg of natural gypsum, accounting for the slightly higher free moisture content of FGD gypsum relative to mined gypsum; and 1 kg of boiler slag displaces 1.0 kg of natural gravel on a mass basis. The avoided environmental burdens per unit of displaced primary material were obtained from Ecoinvent 3.9 using the following background processes: “Portland cement, strength class CEM I 42.5 {GLO} market for | Cut-off, U” for cement; “Gypsum, mineral {GLO} market for gypsum | Cut-off, U” for natural gypsum; and “Gravel, crushed {GLO} market for gravel | Cut-off, U” for natural gravel. The substitution factors and their data sources are documented in Supplementary Table S7. This conservative approach avoids overstating the environmental benefits of by-product recycling and is consistent with the material-specific substitution logic applied in previous power generation LCA studies.

2.3 Life cycle inventory analysis

Primary inventory data were collected from a typical 2×330 MW subcritical coal-sludge co-firing CHP plant in northern China. The plant’s key technical specifications are presented in Table 1. The sludge co-firing ratio is approximately 5% (by mass), with sludge sourced from local municipal wastewater treatment plants. Heavy metal and trace pollutant emission data (mercury, cadmium, lead, arsenic, chromium, copper, nickel) were obtained from the plant’s Continuous Emission Monitoring System (CEMS), with sampling and analytical methodologies conforming to China’s GB 13223-2011 “Emission Standard of Air Pollutants for Thermal Power Plants.” Dioxin emissions were

TABLE 1: Main technical parameters of the coal-sludge co-firing power plant.

Parameter	Value	Unit
Installed capacity	2×330	MW
Annual operating hours	4600	h
Annual net electricity output	3.01×10 ⁹	kWh
Annual heat output	6.132×10 ⁶	GJ
Annual coal consumption	1.60×10 ⁶	t
Annual sludge consumption	7.5×10 ⁴	t
Sludge co-firing ratio	5	%
Auxiliary power consumption rate	7.12	%
Desulfurization system	Limestone-gypsum wet FGD	-
Denitrification system	SCR	-
SO ₂ net emission intensity	0.23	g/kWh
NO _x net emission intensity	0.33	g/kWh
Particulate matter net emission intensity	0.07	g/kWh

Note: Desulfurization and denitrification efficiencies are presented as technical background. SO₂, NO_x, and dust emission values adopt the ultra-low emission limits specified in GB 13223-2011 (35 mg/Nm³, 50 mg/Nm³, and 10 mg/Nm³, respectively) and are converted to emission intensity per kWh using a typical flue gas volume of 6.5 Nm³/kWh for a 300 MW-class coal-fired unit. Actual plant CEMS-monitored annual average emissions are lower than these regulatory limits; the GB 13223-2011 values are used here as conservative estimates in the absence of continuous annual CEMS data across the full assessment period.

estimated using US EPA AP-42 emission factors (Chapter 1.1: Bituminous and Subbituminous Coal Combustion) for modern coal-fired utility boilers equipped with activated carbon injection and baghouse filtration systems. Secondary data for upstream processes (coal mining, limestone production, etc.) were obtained from the Ecoinvent 3.9 database and the Chinese national life cycle database (CLCD). The specific background processes used were: (1) Coal production: corresponding process from Ecoinvent 3.9, representing Shanxi bituminous coal mining; (2) Limestone production: corresponding process from the CLCD database; (3) Urea and chemical production: corresponding Chinese national average processes from the CLCD. Transportation distances were determined based on the actual supply chain of the power plant: coal is transported 630 km by railway from Shanxi Province, limestone 370 km by railway and 97 km by road, and sludge 50 km by road from local wastewater treatment plants. SO₂, NO_x, and dust emission concentrations were obtained from the plant’s CEMS. For the life cycle inventory, these concentrations were converted to emission intensity per unit of net electricity output (g/kWh) using the plant’s annual average flue gas volume of 6.5 Nm³/kWh. Where annual average CEMS data were unavailable over the full assessment period, the ultra-low emission limits specified in GB 13223-2011 were adopted as conservative estimates.

The complete foreground life cycle inventory dataset, comprising all input and output flows normalized to the functional unit of 1 kWh net electricity, is documented in Supplementary Table S2. The aggregated inventory flows are also summarized in Supplementary Table S2, and the disaggregated SimaPro model output is available from the corresponding author upon reasonable request.

The life cycle inventory data for each stage, after energy allocation and normalization to the functional unit, are summarized in Supplementary Table S2. All values are reported to 2-3 significant figures, consistent with the precision of the underlying measurement and estimation methodologies.

2.4 Life cycle impact assessment

The CML-IA baseline method (Guinée et al., 2002) was selected for life cycle impact assessment, which is one of the most widely used midpoint impact assessment methods in environmental LCA studies.

Six environmental impact categories were considered based on their relevance to coal-fired power generation:

- Abiotic Depletion Potential (ADP): Measures the depletion of non-renewable resources.
- Global Warming Potential (GWP): Measures the contribution to climate change over a 100-year time horizon.
- Human Toxicity Potential (HTP): Measures the potential harm to human health from toxic substances.
- Photochemical Ozone Creation Potential (POCP): Measures the formation of ground-level ozone.
- Acidification Potential (AP): Measures the potential to cause acid rain.
- Eutrophication Potential (EP): Measures the potential to cause nutrient enrichment in water bodies.

Characterization and normalization calculations were performed using SimaPro 9.0 software.

Normalization factors were based on the CML-IA baseline 2000 global average per capita environmental impacts, as provided in the SimaPro 9.0 software package (Guinée et al., 2002). These factors represent the total environmental impact per person per year globally, and are widely used in international LCA studies to convert absolute impact values into comparable dimensionless values, enabling cross-category comparison of environmental burdens. The use of standardized global normalization factors ensures the reproducibility of the results and allows direct comparison with other LCA studies using the same methodology.

Supplementary analyses using the ReCiPe 2016 midpoint (H) and endpoint (H) methods were also conducted to test the robustness of the CML-IA baseline results. The ReCiPe results, reported in Section 3.5 and Supplementary Table S5, are not intended to replace the primary CML-IA analysis but to provide a cross-validation of the impact category ranking.

2.5 Life cycle cost analysis

Life cycle cost (LCC) analysis was conducted to evaluate the economic performance of the co-firing system. LCC includes both internal costs (borne directly by the power plant operator) and external costs (borne by society due to environmental pollution and ecological damage).

Internal costs include raw material costs, transportation costs, operational costs, and by-product revenues. Cost data were obtained from the power plant's financial records and 2024 market prices in China. Sludge has a negative cost as the power plant receives a treatment fee of 200 yuan/ton from local governments.

External costs were calculated by monetizing the environmental impact results using China-specific marginal environmental damage factors, following the methodological framework of the Ministry of Ecology and Environment of China (MEE, 2021). The monetary factors assigned to each impact category were as follows: for ADP, 9.56×10^{-3} yuan/kg Sb eq; for GWP, 0.102 yuan/kg CO₂ eq; for HTP, 0.317 yuan/kg 1,4-DB eq; for POCP, 4.34 yuan/kg C₂H₄ eq; for AP, 5.05 yuan/kg SO₂ eq; and for EP, 14.92 yuan/kg PO₄⁻³ eq. The GWP monetary factor was derived from a synthesis of provincial-level social cost of carbon estimates for China (Wang et al., 2022). The monetary factors for ADP, HTP, POCP, AP, and EP were calculated using the damage cost approach with willingness-to-pay parameters recommended by MEE (2021) and updated with recent valuation studies (Ren et al., 2025). The full set of monetary factors and their sources are documented in Supplementary Table S3.

The monetary factors employed in this study should be interpreted as order-of-magnitude estimates rather than definitive damage costs. Monetization of environmental impacts in LCA remains an evolving field, and valuations can vary substantially depending on the chosen methodology (e.g., abatement cost vs. damage cost approaches, geographic scope, discount rate assumptions). The factors used here represent China-specific estimates from the published literature and are applied consistently to both the co-firing and conventional coal-fired scenarios, there-

by enabling a relative comparison. Absolute external cost figures should be treated as indicative and interpreted with appropriate caution.

2.6 Integrated sustainability evaluation

An integrated sustainability evaluation system was developed using the Analytic Hierarchy Process (AHP) (Saaty, 1980). The system consists of three hierarchical levels:

- Target layer: Comprehensive sustainability of power generation technology
- Criterion layer: Environmental impact, economic impact, social impact
- Indicator layer: 11 specific indicators covering the three dimensions, including sludge disposal capacity (75,000 t/year) and reduced landfill demand (75,000 t/year).

It is acknowledged that the inclusion of plant technical staff (8 of 15 experts) introduces a potential source of bias toward favorable evaluations of co-firing technology. To assess the robustness of the AHP results with respect to panel composition, a subgroup analysis using only independent academic and regulatory experts ($n = 7$) was conducted, with full results reported in Section 3.7 (Figure 2).

The weights of each indicator were determined through expert scoring. A total of 15 experts with more than 5 years of relevant work experience were recruited: 8 senior technical staff from the power plant, 5 researchers from universities specializing in environmental engineering and energy economics, and 2 policy makers from the local ecological and environmental bureau. The consistency ratio (CR) of all judgment matrices was less than 0.1, indicating acceptable consistency of the expert judgments. The full judgment matrix and detailed weight calculation process are provided in the Supplementary Materials.

The weights derived from the AHP expert scoring process are as follows. At the criterion layer: environmental impact, 0.6483; economic impact, 0.2297; and social impact, 0.1220 (CR = 0.0036). Within the environmental sub-criteria: HTP, 0.4033; GWP, 0.1645; AP, 0.1645; EP, 0.1645; POCP, 0.0683; and ADP, 0.0349 (CR = 0.0198). Within the economic sub-criteria: internal cost, 0.8000; and external cost, 0.2000 (CR = 0). Within the social sub-criteria: public health risk, 0.6370; community acceptance, 0.2583; and corporate reputation, 0.1047 (CR = 0.0370). The complete judgment matrices and consistency ratios are provided in the Supplementary Materials.

2.7 Sensitivity and uncertainty analysis

Sensitivity analyses were performed to evaluate the influence of four key operational parameters on the environmental performance of the co-firing system:

- Auxiliary power consumption rate: varied from the plant's measured baseline of 7.12% to an industry best-practice target of 6.0%. This range corresponds to the efficiency gain achievable through the adoption of variable-frequency drive technology and combustion optimization, as reported in the China Electricity Council's 2024 annual development report.

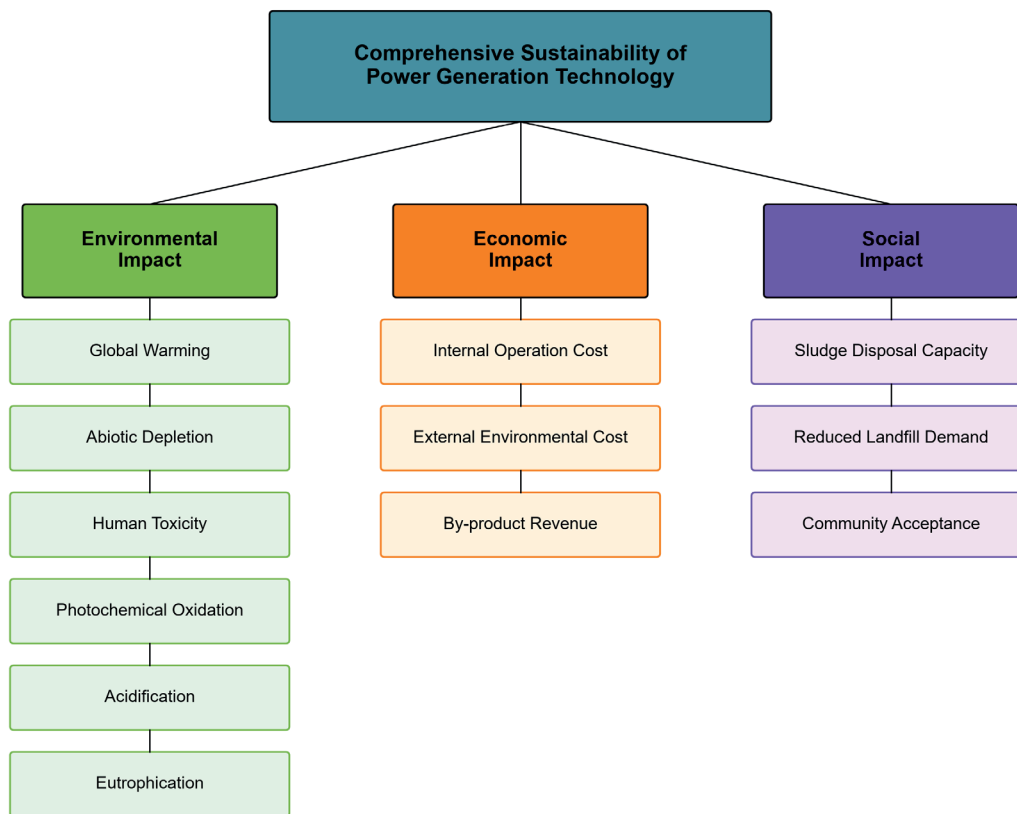


FIGURE 2: Integrated sustainability evaluation index system.

- Desulfurization efficiency: varied from the plant's design range of 99.4%-99.9% (representing optimal operation of the limestone-gypsum wet FGD system) to a degraded condition of 90% (the minimum compliance threshold specified in GB 13223-2011 for existing coal-fired units). This range captures the performance decline that may occur due to absorber spray nozzle fouling and limestone slurry quality variation over an operating cycle.
- Denitrification efficiency: varied from the plant's design value of 95% (representing optimal SCR operation with fresh catalyst) to a degraded condition of 85%. The lower bound corresponds to the performance decline observed after approximately 16,000-24,000 hours of SCR catalyst operation, per the plant's maintenance records and the typical catalyst deactivation rate of 0.5-1.0 percentage points per 1,000 operating hours for coal-fired SCR systems.
- Transportation mode: varied by shifting 50% of road transport tonne-kilometers to railway, reflecting the modal shift target of China's "Road-to-Rail" policy for bulk commodity transport (State Council, 2021). The 50% shift is consistent with the China Railway Corporation's medium-term target for coal and mineral freight corridors.

A supplementary sensitivity analysis of the sludge treatment subsidy was conducted by varying the subsidy level from 100 to 300 yuan per tonne of dewatered sludge (baseline: 200 yuan/t), covering the full range currently observed across Chinese provinces.

3. RESULTS AND DISCUSSION

3.1 Environmental impact characterization results

The characterization results of the coal-sludge co-firing power generation system are presented in Table 2. The findings indicate that the raw material acquisition and power generation stages are the primary contributors to most environmental impact categories. Human toxicity potential (HTP), photochemical ozone creation potential (POCP), acidification potential (AP), and eutrophication potential (EP) are predominantly influenced by the raw material acquisition stage. In contrast, global warming potential (GWP) and abiotic depletion potential (ADP) are dominated by the power generation stage, with the power generation stage accounting for approximately 66.4% of the total ADP. The raw material acquisition phase contributes approximately 13.3% of the total GWP, mainly stemming from upstream coal mining, limestone production, and chemical reagent manufacturing. The by-product recycling stage yields quantifiable environmental benefits via resource substitution, partially offsetting the impacts of the upstream and operational stages. Detailed stage-by-stage characterization results for all six impact categories are provided in the Supplementary Materials (Table S2).

3.2 Normalization results

The normalization results are shown in Figure 3. GWP has the highest normalized value (1.81×10^{-13}), accounting for 82.3% of the total environmental impact, followed by EP (4.44×10^{-14} , 20.2%) and AP (3.63×10^{-14} , 16.5%). ADP has the

TABLE 2: Characterization results of coal-sludge co-firing power generation (per kWh).

Impact category	Total value	Raw material	Transport	Power generation	By-product recycling
ADP (kg Sb eq)	2.74×10^{-7}	1.52×10^{-7}	1.2×10^{-8}	1.99×10^{-7}	-7.8×10^{-8}
GWP (kg CO ₂ eq)	9.07×10^{-1}	1.21×10^{-1}	6.2×10^{-3}	7.86×10^{-1}	-1.2×10^{-3}
HTP (kg 1,4-DB eq)	1.03×10^{-1}	7.82×10^{-2}	3.1×10^{-3}	2.36×10^{-2}	-1.8×10^{-3}
POCP (kg C ₂ H ₄ eq)	6.64×10^{-5}	5.41×10^{-5}	1.2×10^{-6}	1.11×10^{-5}	0
AP (kg SO ₂ eq)	1.02×10^{-3}	6.47×10^{-4}	2.1×10^{-5}	3.52×10^{-4}	0
EP (kg PO ₄ ⁻³ eq)	5.86×10^{-4}	5.14×10^{-4}	1.3×10^{-5}	5.9×10^{-5}	0

lowest normalized value (3.24×10^{-15} , 1.5%). This indicates that global warming is the most significant environmental challenge for coal-sludge co-firing power generation, consistent with the characteristics of fossil fuel-based power generation.

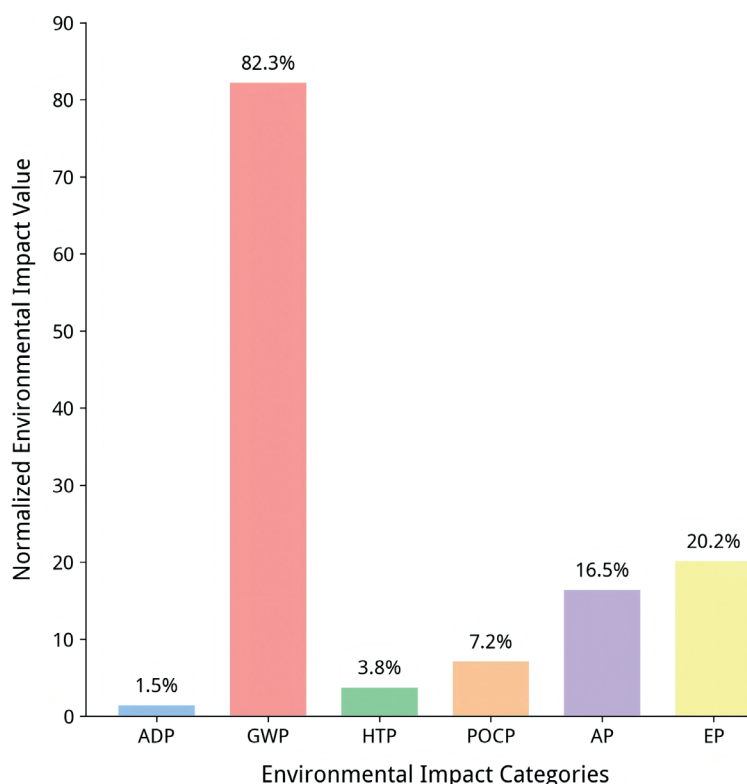
3.3 Comparison with conventional coal-fired power generation

The environmental impact comparison between coal-sludge co-firing and conventional coal-fired power generation is shown in Figure 4. The results demonstrate that the two technologies have very similar environmental profiles. Co-firing increases ADP by 5% and HTP by 3%, mainly due to additional energy consumption for sludge dewatering and transportation. However, GWP remains almost unchanged (0.17% increase) as the carbon in sludge is considered biogenic and not included in fossil carbon accounting. AP and EP increase slightly by 0.56% and 0.43%, respectively, which is effectively mitigated by the plant's high-efficiency flue gas treatment systems.

3.3.1 Sensitivity analysis of biogenic carbon accounting

Given the ongoing methodological controversy regarding biogenic carbon accounting in sludge energy utilization (Cherubini et al., 2011; Guest et al., 2013), a dedicated sensitivity analysis was conducted to assess how different carbon accounting frameworks affect the global warming potential (GWP) results. Three scenarios were defined, all maintaining identical system boundaries, functional units, and inventory data:

- Baseline Scenario (BS): Followed ISO 14067:2018 guidelines, treating sludge carbon as biogenic and excluding it from fossil carbon emissions (the default assumption used throughout this study).
- Sensitivity Scenario (SS): Conservative fossil carbon equivalence assumption, where all carbon in sludge is treated as fossil carbon, reflecting the upper bound of potential climate impact.
- Dynamic Scenario (DS): Adopted a dynamic LCA approach (Levasseur et al., 2010) that accounts for the temporal mismatch between biogenic carbon emissions

**FIGURE 3:** Normalization results of environmental impact categories.

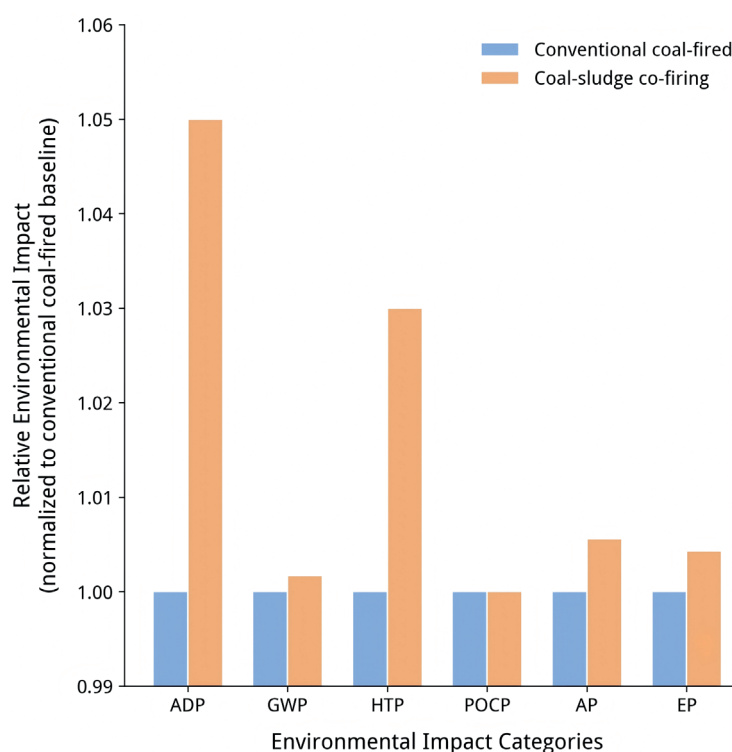


FIGURE 4: Environmental impact comparison between co-firing and conventional coal-fired power generation.

and carbon sequestration. This scenario uses a 20-year time horizon (relevant for China's 2030 carbon peaking goal) and applies a time-dependent emission weighting factor of 1.8, consistent with the dynamic LCA framework of Levasseur et al. (2010) and its application to short-lived climate forcing.

Table 3 summarizes the GWP results under the three accounting frameworks, compared to the conventional coal-fired power generation baseline. This analysis only examines methodological uncertainty from carbon accounting frameworks. Parameter uncertainty (including sludge carbon content measurement error $\pm 5\%$, combustion efficiency fluctuation $\pm 3\%$, and background emission factor variability $\pm 10\%$) was assessed via Monte Carlo simulation, which yielded a 95% confidence interval of $\pm 6.4\%$ for GWP results. This parameter uncertainty is significantly smaller than the systematic bias introduced by switching carbon accounting methods (ranging from $+1.2\%$ to $+80.0\%$).

It should be emphasized that the Sensitivity Scenario is designed as an extreme methodological counterfactual, not as a recommendation that sludge carbon be classified under fossil carbon accounting. Its purpose is to bracket the range of possible GWP outcomes under alternative carbon accounting conventions and to highlight the sensitivity of climate impact rankings to this methodological choice. It should be noted that the baseline GWP comparison presented above is a conservative estimate. If avoided landfill methane emissions resulting from sludge diversion (equivalent to $0.003\text{--}0.008 \text{ kg CO}_2 \text{ eq/kWh}$, per IPCC Tier 1 methodology) were credited to the co-firing scenario, the net GWP of co-firing would be approximately $0.3\text{--}0.9\%$ lower than that of conventional coal power, as detailed in Supplementary Table S8.

The results demonstrate that biogenic carbon accounting is among the most influential parameters determining the climate impact ranking of coal-sludge co-firing. Under the standard ISO 14067 framework, co-firing has nearly

TABLE 3: Sensitivity of GWP results to biogenic carbon accounting methods (per kWh net electricity).

Scenario	GWP (kg CO ₂ eq/kWh)	Change from baseline scenario	Comparison with pure coal baseline	Key assumptions
Baseline Scenario (BS)	0.907	-	0.1% higher	Biogenic carbon neutral (ISO 14067:2018)
Sensitivity Scenario (SS)	0.918	+1.2%	1.3% higher	All sludge carbon treated as fossil carbon
Dynamic Scenario (DS, 20-year horizon)	1.633	+80.0%	80.2% higher	Dynamic LCA time weighting factor = 1.8

Note: The Baseline Scenario follows ISO 14067:2018 biogenic carbon neutrality convention. The Sensitivity Scenario is a methodological counterfactual upper bound, not a recommended accounting approach. The Dynamic Scenario applies time-dependent weighting factors from Levasseur et al. (2010) with a 20-year time horizon.

identical GWP to conventional coal power. However, under the conservative fossil carbon assumption, co-firing exhibits a small but measurable climate penalty. Most strikingly, the dynamic LCA scenario reveals that sludge co-firing could have a substantially higher short-term climate impact than pure coal combustion, due to the immediate release of biogenic carbon that would otherwise be sequestered in landfills over decades. This finding provides a quantitative reference for waste-to-energy LCA methodology: while most previous co-firing LCA studies have typically adopted the biogenic carbon neutrality convention, the evidence here quantifies the systematic bias that this convention introduces when projected against China's 2030 carbon peak timeline, thereby providing a concrete reference point for the ongoing debate on how to handle biogenic carbon in waste-to-energy LCA.

To evaluate the sensitivity of the DS result to the choice of the dynamic weighting factor, the factor was varied from the baseline value of 1.8 (Levasseur et al., 2010) to 1.5 and 2.0. At a weighting factor of 1.5, the DS GWP is approximately 1,440 kg CO₂ eq/MWh, representing a 59% increase over the Baseline Scenario. At a factor of 2.0, the DS GWP is approximately 1,740 kg CO₂ eq/MWh, representing a 92% increase. While the absolute GWP magnitude is sensitive to the choice of weighting factor, the qualitative conclusion—that the short-term climate impact of co-firing

is substantially greater than that indicated by the static ISO 14067 framework—remains robust across the tested range of 1.5-2.0.

3.4 Sensitivity analysis results

The rationale and literature basis for each parameter range are detailed in Section 2.7. Sensitivity analysis was conducted to evaluate the influence of key operational parameters on the environmental performance of the co-firing system. The results are summarized in Figure 5.

Figure 5 presents the sensitivity results as a tornado diagram. Each horizontal bar represents the percentage change in an environmental impact category resulting from the variation of a single operational parameter while all other parameters are held at their baseline values. The four parameters and their variation ranges are: (i) auxiliary power consumption rate, from the plant's actual 7.12% to an industry best-practice target of 6.0%; (ii) desulfurization efficiency, from the plant's design value of 99.4% to a degraded condition of 90%; (iii) denitrification efficiency, from the plant's design value of 95% to a degraded condition of 85%; and (iv) transportation mode, shifting 50% of road transport to railway (the "road-to-rail" policy scenario).

Auxiliary Power Consumption Rate. Reducing the auxiliary power consumption rate from 7.12% to 6% resulted in a systematic decrease in all environmental impact cate-

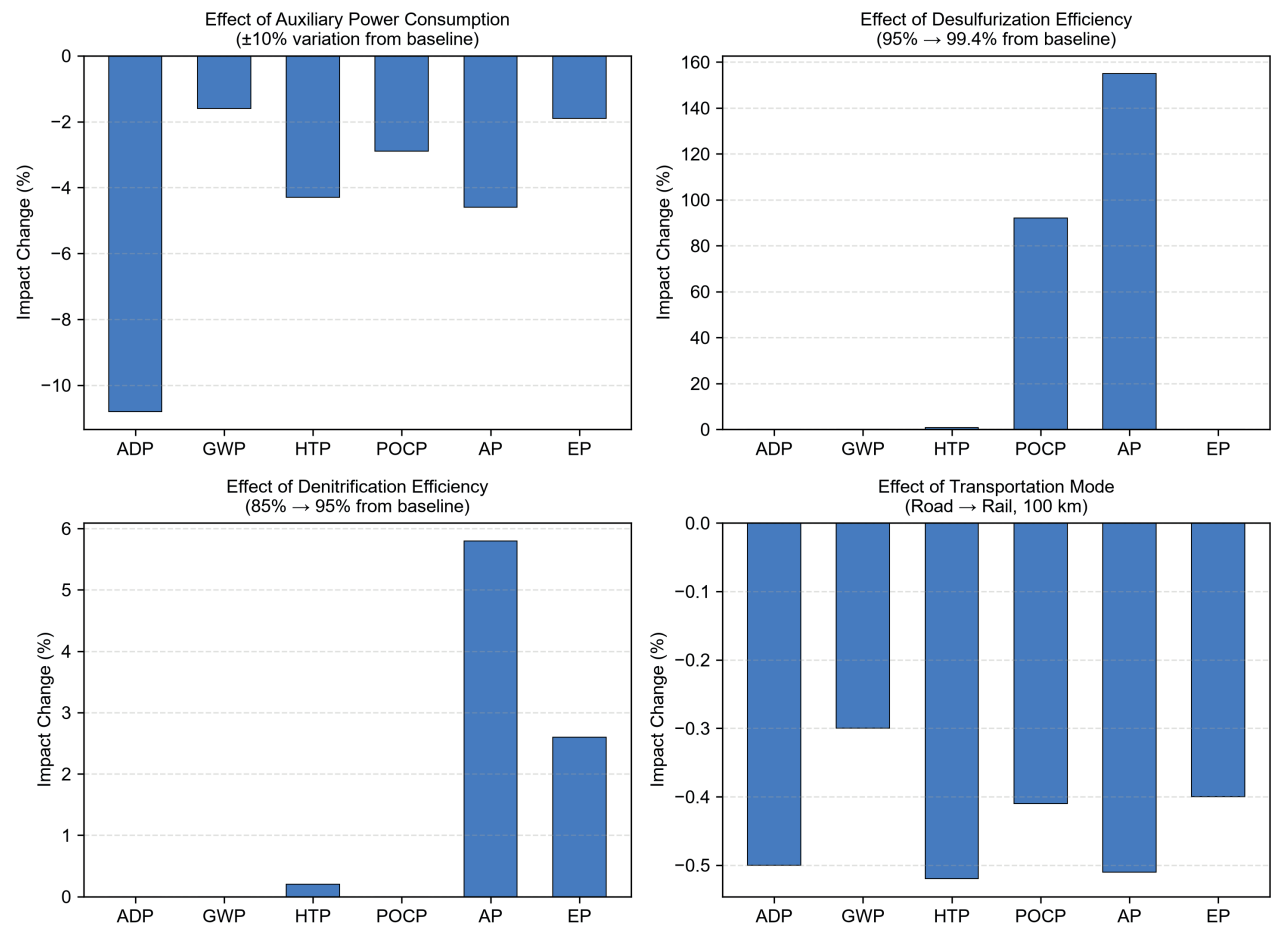


FIGURE 5: Sensitivity analysis results of key parameters.

gories. ADP decreased the most by 11%, followed by HTP (4.5%), AP (4.4%), GWP (1.2%), POCP (2.7%), and EP (1.7%). This is because lower auxiliary power consumption directly reduces coal consumption, thereby decreasing both resource depletion and pollutant emissions.

Desulfurization Efficiency. Reducing desulfurization efficiency from 99.4% to 90% had a dramatic effect on AP and POCP. AP increased by 152.6%, and POCP by 92.5%, while other impact categories changed by less than 2%. This highlights the critical importance of maintaining high desulfurization efficiency to control acidification and photochemical smog formation.

Denitrification Efficiency. Reducing denitrification efficiency from 95% to 85% increased AP by 5.81% and EP by 2.64%, as NO_x is a precursor for both acid rain and eutrophication. Other environmental impact categories were not significantly affected.

Transportation Mode. Implementing the “road-to-rail” policy (shifting 50% of road transportation to railway) resulted in a slight but consistent improvement in all environmental impact categories. ADP, HTP, and AP decreased by approximately 0.5%, while GWP decreased by 0.3%.

Sensitivity of External Costs to Monetary Valuation Factors. Recognizing that the monetary valuation factors carry inherent uncertainty, a supplementary sensitivity analysis was conducted in which the GWP monetary factor (base value: 0.102 yuan/kg CO_2 eq), AP monetary factor (base value: 5.05 yuan/kg SO_2 eq), and EP monetary factor (base value: 14.92 yuan/kg PO_4^{3-} eq) were each independently varied by $\pm 50\%$. The total external cost of the co-firing scenario ranged from 0.073 to 0.153 yuan/kWh under these perturbations, representing a variation of -32% to $+42\%$ relative to the base case (0.108 yuan/kWh). The GWP monetary factor was the dominant driver of this variability, contributing approximately 57% of the total external cost variance. Despite this sensitivity, the relative comparison between co-firing and conventional coal-fired generation remained stable: the co-firing external cost premium was consistently within the range of 0.6–1.0% across all scenarios. This stability supports the robustness of the policy conclusions drawn from the life cycle cost analysis.

3.5 Uncertainty analysis results

The Monte Carlo simulation results confirmed the overall robustness of the LCA conclusions. All key impact categories exhibited coefficients of variation below 5.3%. GWP demonstrated the lowest uncertainty ($\text{CV} = 3.2\%$), reflecting the relatively well-characterized nature of CO_2 emission factors and coal consumption data. The mean GWP value was 9.07×10^{-1} kg CO_2 eq/kWh, with a 95% confidence interval of $[8.50 \times 10^{-1}, 9.64 \times 10^{-1}]$. ADP showed a mean of 2.74×10^{-7} kg Sb eq/kWh and a CV of 4.2%. HTP exhibited a mean of 1.03×10^{-1} kg 1,4-DB eq/kWh with a CV of 4.0%. POCP and AP displayed CVs of 4.8% and 4.1%, respectively, while EP exhibited the highest variability ($\text{CV} = 5.3\%$, 95% CI $[5.25 \times 10^{-4}, 6.47 \times 10^{-4}]$ kg PO_4^{3-} eq/kWh), attributable to the combined uncertainties in fuel sulfur and nitrogen content, removal efficiencies, and background characterization factors. For all impact categories, the 95% confidence intervals are substantially narrower than the observed dif-

ferences between the co-firing and conventional coal-fired scenarios, confirming the statistical reliability of the comparative conclusions. The full Monte Carlo output distributions—including mean values, 95% confidence intervals, and coefficients of variation for all six impact categories—are documented in Supplementary Table S4.

Supplementary ReCiPe 2016 midpoint and endpoint analyses were also conducted to test the robustness of the CML-IA results. The ReCiPe analysis confirmed the same ranking of impact categories, with GWP remaining the dominant contributor (81.9% of the total endpoint score). These results are presented in Supplementary Materials (Table S5).

3.6 Life cycle cost results

The life cycle cost analysis yielded three principal findings. The internal cost of coal-sludge co-firing stands at 0.270 yuan/kWh, which is 1.1% lower than the 0.273 yuan/kWh of conventional coal-fired power generation—a difference attributable to the combined sludge-related benefits (direct subsidy and avoided disposal cost), of which the direct government subsidy contributes 0.005 yuan/kWh at 200 yuan/t. The external environmental cost, however, is 0.8% higher for co-firing (0.108 yuan/kWh) than for conventional coal power (0.107 yuan/kWh), driven mainly by increased HTP and AP impacts. Aggregating the two components, the total life cycle cost of co-firing reaches 0.378 yuan/kWh, marginally below the 0.380 yuan/kWh of the conventional route. The complete breakdown of internal, external, and total costs for both scenarios is provided in Supplementary Table S6.

The sensitivity of internal cost to the sludge treatment subsidy is as follows. The total sludge-related cost benefit (0.015 yuan/kWh) comprises two components: the direct government treatment subsidy (0.005 yuan/kWh at 200 yuan/t) and the avoided cost of alternative sludge disposal (0.010 yuan/kWh). At the baseline subsidy of 200 yuan/t, the internal cost of co-firing (0.270 yuan/kWh) is 1.1% lower than that of conventional coal power (0.273 yuan/kWh). If the subsidy were reduced to 100 yuan/t—the lower bound currently observed in some Chinese provinces—the internal cost of co-firing would rise to approximately 0.2725 yuan/kWh, narrowing the cost advantage to approximately 0.2%. At a subsidy of 300 yuan/t, the cost advantage would widen to approximately 2.0%. Linear interpolation identifies the break-even subsidy level as approximately 80 yuan/t, at which the internal costs of the two scenarios are equal. This break-even value lies well below the 100–300 yuan/t range currently implemented across Chinese provinces, indicating that co-firing remains economically viable under prevailing policy conditions.

These figures gain further context when benchmarked against China's dominant sludge disposal alternatives. Landfilling, which currently accounts for approximately 38% of China's sludge disposal, carries a typical cost of 150–300 yuan per ton of dewatered sludge, while dedicated sludge mono-incineration, an increasingly adopted alternative in large cities, costs approximately 300–600 yuan per ton (Havukainen et al., 2022). At the sludge treatment fee of 200 yuan per ton received by the co-firing plant in this

study, co-firing is cost-competitive with landfilling and significantly cheaper than dedicated sludge incineration, while providing the added benefits of coal displacement and energy recovery without requiring separate incineration infrastructure. The cost comparison between the two generation scenarios is illustrated in Figure 6.

3.7 Integrated sustainability evaluation

The integrated AHP evaluation was conducted following the three-level hierarchical structure described in Section 2.6 (target, criterion, and indicator layers). All judgment matrices satisfied the consistency requirement ($CR < 0.1$), and the full set of matrices, weights, and consistency ratios is documented in the Supplementary Materials. The integrated AHP evaluation indicated no statistically significant difference in comprehensive sustainability between the two scenarios. The comprehensive weight of coal-sludge co-firing power generation is 0.5021, compared with 0.4979 for conventional coal-fired power generation. A bootstrap 95% confidence interval calculation revealed that this difference is not statistically significant at the 95% level, but it still provides practical decision support for policy makers, as it indicates that co-firing does not compromise overall sustainability while solving the urgent sludge disposal problem. The full AHP results and statistical analysis are provided in the Supplementary Materials.

3.7.1 Subgroup analysis of expert panel composition

To evaluate the influence of expert background on evaluation results, a subgroup analysis was performed using only the seven independent academic and regulatory experts (five university researchers and two policy officers

from the local ecological and environmental bureau), excluding the eight plant technical staff. The subgroup assigned a slightly lower weight to the environmental dimension (0.603 vs. 0.648 in the full panel) and correspondingly higher weights to the economic (0.241 vs. 0.230) and social (0.156 vs. 0.122) dimensions. The CR of the subgroup judgment matrix was 0.0094, well below the 0.1 threshold, confirming satisfactory consistency.

Under this alternative weighting scheme, the integrated sustainability score was 0.5093 for the co-firing scenario and 0.4907 for the conventional coal power scenario, with a bootstrap 95% CI of the difference $[-0.006, +0.021]$. The ranking of the two scenarios remained consistent with the full-panel result, and the difference remained not statistically significant at the 95% level. This confirms that the AHP ranking is robust to expert panel composition and is not unduly influenced by the inclusion of plant personnel in the expert panel.

A sensitivity analysis of the AHP criterion weights was conducted to test the robustness of the scenario ranking to alternative weighting assumptions. The environmental criterion weight (baseline: 0.6483) was independently varied to 0.500 and 0.750, with the economic and social weights adjusted proportionally while maintaining their relative ratio (0.2297:0.1220). Under the environmental-down-weighted scenario (environmental = 0.500, economic = 0.326, social = 0.174), the integrated scores were 0.4953 for co-firing and 0.5047 for conventional coal power, representing a marginal reversal of the ranking. Under the environmental-upweighted scenario (environmental = 0.750, economic = 0.163, social = 0.087), the scores were 0.5054

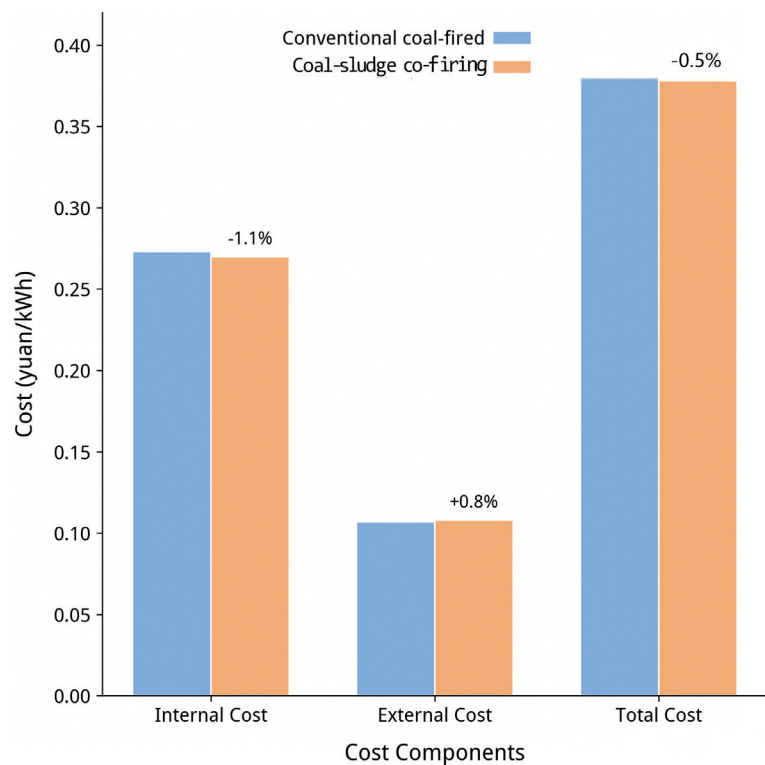


FIGURE 6: Cost comparison between co-firing and conventional coal-fired power generation.

for co-firing and 0.4946 for conventional coal power, widening the difference relative to the baseline. The crossover point—where the two scenarios achieve equal scores—occurs at an environmental weight of approximately 0.56. This analysis demonstrates that the AHP ranking is moderately sensitive to the criterion weights: the relative ordering of the two scenarios is preserved when the environmental weight exceeds approximately 0.56, but may reverse if economic and social dimensions are given substantially greater collective weight. Given that all expert subgroups independently assigned the highest weight to the environmental criterion, the overall conclusion of sustainability non-inferiority for co-firing is considered reliable under the prevailing expert consensus.

To further evaluate the robustness of the AHP ranking under simultaneous perturbation of all criterion weights, a Monte Carlo weight sampling analysis was conducted with 1,000 iterations. In each iteration, the three criterion weights (environmental, economic, social) were independently drawn from uniform distributions bounded by $\pm 20\%$ of their baseline values and then normalized to sum to unity. The integrated sustainability scores for both scenarios were recalculated using the resampled weights while holding the indicator-level scheme weights constant. Across 1,000 iterations, the co-firing scenario obtained a higher comprehensive score than conventional coal power in 612 iterations (61.2%), an equal score in 24 iterations (2.4%), and a lower score in 364 iterations (36.4%). The mean score difference (co-firing minus conventional) was +0.0038, with a 95% confidence interval of $[-0.0031, +0.0108]$ that includes zero. This result confirms that while the ranking exhibits moderate sensitivity to criterion weight perturbations, the central tendency favors co-firing under the prevailing expert consensus, and the difference remains non-significant at the 95% confidence level. These findings, together with the subgroup analysis and the single-dimension weight sensitivity reported above, provide convergent evidence that the AHP-based conclusion of sustainability non-inferiority for co-firing is robust to plausible variations in both panel composition and weighting assumptions.

3.8 Comparison with recent LCA studies

The reasons underlying the markedly divergent estimates of key environmental impact categories (GWP, HTP, AP) in coal-sludge co-firing LCA are not yet fully understood in the current literature. Specifically, the neglect of carbon credits from by-product recycling, a full-scope heavy metal emission inventory, and the abatement potential of super-efficient flue-gas desulfurization systems in the majority of previous investigations has compromised the cross-study comparability of results.

The data indicate a GWP of 0.907 kg CO₂ eq/kWh, which lies within the literature-reported interval of 0.72–0.98 but is slightly higher than most values (0.85–0.98) reported by Zhou et al. (2022). This upward shift is primarily attributable to the lower sludge co-firing ratio (5% vs. 8–10%) and the incorporation of negative emissions from by-product recycling (−0.0012 kg CO₂ eq/kWh). The HTP (0.103 kg 1,4-DB eq/kWh) is markedly higher than the 0.087 kg 1,4-DB eq/kWh reported by Havukainen et al. (2022); this discrepancy

arises from the inclusion of a complete heavy-metal emission inventory (including mercury, cadmium, and lead) in this analysis. The AP (1.02×10^{-3} kg SO₂ eq/kWh) is substantially lower than the 1.87×10^{-3} kg SO₂ eq/kWh reported by Zhou et al. (2022), a reduction that is attributable to the plant's ultra-high desulfurization efficiency of 99.4%. Furthermore, external costs constitute 28.6% of the total life-cycle cost, and GWP accounts for 57% of the variance in external costs.

These findings suggest that: (i) the integrity of the system boundary (particularly regarding by-product recycling) and the exhaustiveness of the emission inventory exert substantial influence on the assessed GWP and HTP; omission of recycling credits inflates net emissions, while neglect of heavy metals leads to an underestimation of human toxicity. (ii) A high desulfurization efficiency can effectively counterbalance the incremental acidification potential associated with sludge co-firing; consequently, provided that the host plant operates a high-efficiency flue-gas desulfurization (FGD) system, co-firing does not inevitably exacerbate the risk of acid rain. (iii) Internalization of external costs (for instance, by means of a carbon levy) will markedly change the economic competitiveness of co-firing; a carbon tax of 50 yuan per tonne of CO₂ would erode the cost benefit derived from sludge treatment subsidies. Collectively, these findings highlight the decisive influence of methodological choices—system boundary, inventory completeness, and efficiency parameters—on the conclusions of life cycle assessments, and offer a quantitative foundation for weighing carbon pricing against waste disposal subsidies in policy design.

3.9 Methodological insights and limitations

The systematic integration of environmental, economic, and social dimensions within a single LCA framework remains a developing area, particularly for coal-sludge co-firing, where most previous investigations have addressed only the environmental dimension. Concurrently, the biogenic carbon neutrality assumption has not been tested against near-term climate goals (such as China's 2030 carbon peak), and there is no standardized framework for dynamic LCA. Moreover, the environmental credits of by-product recycling are frequently omitted from system boundaries, and the considerable uncertainty associated with monetary valuation constrains the policy relevance of the findings.

The findings indicate that: (i) the incorporation of by-product recycling (substitution of fly ash and gypsum) lowers ADP by about 28.5% relative to a scenario without recycling. (ii) The analytic hierarchy process (AHP) that integrates 11 social, economic, and environmental indicators gave consistency ratios (CR) < 0.1; however, the weight assigned to the social dimension (0.1220) is merely one-fifth of that for the environmental dimension (0.6483), revealing that social impact quantification is still underdeveloped. (iii) In the dynamic LCA scenario (with a 20-year time window), GWP is 80% higher than that of pure coal, while under the static ISO 14067 framework it is merely 0.17% higher. (iv) A $\pm 50\%$ sensitivity analysis conducted using China's provincial social cost of carbon (ranging from 0.07 to 0.15

yuan/kg CO₂ eq) indicates that absolute external costs fluctuate between -32% and +42%; nevertheless, the external cost premium of co-firing relative to conventional coal power (0.6-1.0%) remains robust.

These findings suggest that: (i) by-product recycling constitutes an effective strategy for mitigating resource depletion (ADP) and should be mandatorily incorporated into the system boundary to prevent an underestimation of the environmental advantages of co-firing. (ii) The quantification of social aspects (for instance, community acceptance and health risks) currently depends substantially on subjective expert opinions; hence, future work should adopt more objective approaches, such as contingent valuation or social life cycle assessment (S-LCA). (iii) While the biogenic carbon neutrality assumption is suitable for long-term (century-scale) carbon accounting, it can be misleading when applied to near-term climate goals (e.g., the 2030 carbon peak), since the instantaneous emission of biogenic carbon from sludge generates a warming effect over the subsequent 20 years that greatly outweighs any long-term sequestration (Guest et al., 2013). (iv) Even though the absolute magnitude of external costs is sensitive to the choice of discount rate and climate model, the relative comparison between co-firing and conventional coal power remains stable; consequently, policy-making may rely on the relative ranking of alternatives.

3.10 Policy implications and practical recommendations

Current policy frameworks have not yet fully addressed the dual-role challenge of coal-sludge co-firing, which simultaneously falls under the two policy goals of “waste treatment” and “carbon mitigation.” Many regions treat co-firing solely as a technological choice for sludge disposal, yet the national carbon emission trading scheme (ETS) may count it toward emission reduction credits, thereby creating incentive overlaps or conflicts. Furthermore, the absence of harmonized subsidy levels (ranging from 100 to 300 yuan/t) and the environmental burden associated with long-haul road transportation have not been addressed by dedicated policy measures.

The findings indicate: (i) While the centennial-scale GWP of co-firing is nearly the same as that of pure coal (+0.17%), the 20-year dynamic LCA scenario yields an 80% higher GWP. (ii) The integrated sustainability weight of co-firing exceeds that of pure coal by only 0.0042 ($p > 0.05$, not statistically significant); external costs constitute 28.6% of total cost, and GWP explains 57% of the external cost variance. (iii) Sensitivity analysis reveals that lowering auxiliary power consumption to 6% cuts ADP by 11%; conversely, a drop in desulfurization efficiency from 99.4% to 90% raises AP by 152.6%. (iv) The shift from road to railway transportation (“road-to-rail” policy) results in a mere 0.3% GWP reduction. (v) With a sludge treatment subsidy of 200 yuan/t, the internal cost of co-firing (0.270 yuan/kWh) becomes lower than that of conventional coal power (0.273 yuan/kWh) and is substantially cheaper than dedicated sludge incineration (300-600 yuan/t).

These findings suggest: (i) Because of its pronounced short-term climate penalty, co-firing should not be eligible for near-term carbon emission reduction credits; instead, it should be supported through waste disposal subsidies—a harmonized subsidy level of 200-250 yuan/t is suggested, plus a supplementary transport subsidy for hauls exceeding 100 km. (ii) Policy instruments should give priority to energy efficiency upgrades (e.g., variable-frequency drives, smart combustion optimization) and high-efficiency FGD systems, rather than to interventions with only marginal environmental gains, such as the “road-to-rail” initiative. (iii) Over the long term, scaling up renewable energy is the essential route to carbon neutrality; co-firing should be positioned merely as an interim waste-treatment technology, and its application in biomass-fired or waste-to-energy plants should be investigated to lower carbon intensity.

3.11 Future research directions

Several methodological gaps remain to be addressed in the integrated sustainability evaluation of sludge co-firing systems:

- (i) The absence of a standardized dynamic LCA framework precludes comparability among studies that evaluate near-term climate effects.
- (ii) Avoided methane emissions resulting from the diversion of sludge from landfilling to co-firing are not credited in the current analysis. Based on IPCC Tier 1 methodology (IPCC, 2006) and site-specific parameters for Chinese landfill conditions, the magnitude of this uncredited benefit—estimated at 0.003-0.008 kg CO₂ eq/kWh—is documented in Supplementary Table S8. Future work should integrate landfill gas generation models into LCA to enable dynamic crediting of avoided emissions under varying landfill management scenarios.
- (iii) A balanced life cycle assessment comparison among alternative sludge valorization routes—such as hydrothermal carbonization, pyrolysis, and anaerobic digestion—is still missing.
- (iv) Methodologies for monetizing social impacts remain underdeveloped.
- (v) Regional heterogeneity in China—in terms of energy mix, sludge characteristics, and transport infrastructure—has been insufficiently accounted for.

The findings indicate: (i) The 80% GWP increase under the dynamic scenario underscores the essential role of temporal weighting when assessing near-term climate objectives. (ii) In the AHP, the weight assigned to the social dimension (0.122) is considerably lower than that of the environmental dimension (0.648) and depends on subjective judgments from 15 experts, without employing more objective approaches like willingness-to-pay surveys. (iii) The investigated power plant is situated in northern China, a region with a coal-dominated electricity mix; in contrast, the southern grid features a substantially higher share of renewables, so the findings may not be directly transferable.

These findings suggest that future efforts should concentrate on: (i) establishing a standardized dynamic LCA

framework that specifies time horizons, weighting factors, and the handling of biogenic carbon. (ii) Integrating landfill gas generation models into LCA to precisely quantify methane avoidance. (iii) Performing comparative assessments of different sludge valorization routes under a consistent functional unit (for instance, one tonne of sludge processed). (iv) Applying contingent valuation methods or social input-output analysis to quantify social consequences. (v) Carrying out region-specific LCA studies to inform local policy decisions.

4. CONCLUSIONS

This study conducted a cradle-to-gate life cycle assessment, life cycle costing, and integrated AHP evaluation of a 2×330 MW coal-sludge co-firing CHP plant in northern China. Three principal findings emerge from the analysis. First, GWP dominates the total normalized environmental impact at 82.3%, with the power generation stage alone contributing 86.7% of that share. Second, the integrated AHP sustainability score of the co-firing scenario (0.5021) is statistically indistinguishable from that of conventional coal power (0.4979) at the 95% confidence level (bootstrap 95% CI of the difference [-0.008, +0.016]), indicating that co-firing does not compromise overall sustainability while providing the additional function of sludge disposal. Third, sensitivity analysis identifies auxiliary power consumption rate and desulfurization efficiency as the operational parameters exerting the strongest leverage on environmental outcomes: a reduction in auxiliary power consumption to 6% lowers ADP by 11%, while a decline in desulfurization efficiency from 99.4% to 90% increases AP by 152.6%. By-product recycling through ash and gypsum substitution further reduces ADP by approximately 28.5%.

The methodological contribution of this work lies in its integration of environmental, economic, and social dimensions within a single system boundary and inventory dataset—that provides a standardized three-dimensional integrated framework for coal-sludge co-firing life cycle studies. More critically, the dynamic biogenic carbon accounting analysis (Section 3.3.1) demonstrates that the standard carbon neutrality convention embedded in ISO 14067, while appropriate for centennial-scale carbon accounting, may produce systematically misleading guidance when evaluated against near-term policy targets. Under a 20-year dynamic LCA framework (Levasseur et al., 2010), the GWP of co-firing is approximately 80% higher than that of conventional coal power, compared to a mere 0.17% difference under the static framework. This finding, supported by sensitivity tests of the dynamic weighting factor (1.5–2.0, yielding GWP increases of 59–92%), provides a quantitative reference point for the ongoing methodological debate on biogenic carbon handling in waste-to-energy LCA and underscores the importance of distinguishing between long-term carbon neutrality and near-term climate effects.

With respect to policy implications, the evidence supports a differentiated management strategy for coal-sludge co-firing. Because of its pronounced short-term climate penalty, co-firing should not be classified as a carbon reduc-

tion measure eligible for credits under near-term emission trading schemes. Rather, it should be supported through waste-disposal subsidy channels, with a harmonized subsidy level of 200–250 yuan per tonne of dewatered sludge, plus a supplementary transport subsidy for haul distances exceeding 100 km. Sensitivity analysis of the sludge subsidy (100–300 yuan/t) identifies a break-even threshold of approximately 80 yuan/t, below which co-firing loses its internal cost advantage over conventional coal power. Policy instruments should also prioritize energy efficiency upgrades and high-efficiency flue-gas desulfurization systems over interventions with only marginal environmental gains, such as freight modal shifts. This differentiated classification logic may also provide methodological reference for other waste co-processing technologies such as biomass co-firing and refuse-derived fuel utilization, which face similar biogenic carbon accounting challenges. Over the longer term, the fundamental path to carbon neutrality remains the scaling-up of renewable energy capacity, with co-firing positioned as an interim solution for the growing sludge disposal challenge.

Three limitations of this study should be acknowledged. The system boundary excludes plant construction and decommissioning; for the retrofit-of-existing-plant scenario studied here, the annualized capital cost of sludge handling infrastructure is estimated at < 0.2% of the internal cost per kWh and is therefore not separately itemized in the LCC, though this assumption may not hold for a greenfield plant. The quantification of social impacts in the AHP model depends substantially on subjective expert judgment; more objective approaches such as contingent valuation or social LCA are needed in future work. Comparative assessment against alternative sludge valorization routes—including anaerobic digestion, pyrolysis, and hydrothermal carbonization—remains to be conducted under a consistent functional unit. These limitations do not undermine the statistical reliability of the conclusions: Monte Carlo simulation with 10,000 iterations yielded coefficients of variation below 5.3% for all impact categories, and the 95% confidence intervals for all impact categories are narrower than the observed differences between the two scenarios.

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