

Supplementary Materials (For Online Publication Only)

Table S1. Energy allocation factors and electricity-attributed inventory.

Parameter	Total Annual Value	Electricity-Attributed Share	Heat-Attributed Share
Coal consumption	1.60×10 ⁶ t	1.022×10 ⁶ t	0.578×10 ⁶ t
Net electricity output	3.01×10 ⁹ kWh	3.01×10 ⁹ kWh	—
Heat output	6.132×10 ⁶ GJ	—	6.132×10 ⁶ GJ

Note: Energy allocation coefficient $\alpha_e = E_e/(E_e+E_h) = (3.01 \times 10^9 \text{ kWh} \times 3.6 \text{ MJ/kWh}) / (1.0836 \times 10^7 \text{ GJ} + 6.132 \times 10^6 \text{ GJ}) = 0.6386$ (63.86%). All plant-level inputs and outputs were first compiled as total annual quantities, then partitioned using this coefficient before normalization to the functional unit of 1 kWh net electricity.

Table S2. Full life cycle inventory data (per kWh net electricity).

Raw material acquisition stage

Item	Value	Unit	Source note
Coal	3.25×10 ⁻⁴	t	Plant fuel procurement records
Limestone	1.97×10 ⁻⁵	t	Plant FGD system material balance
Urea	1.20×10 ⁻⁶	t	Plant SCR system consumption records
Hydrochloric acid (31%)	4.67×10 ⁻⁸	t	Plant water treatment records
Sodium hydroxide (46%)	3.25×10 ⁻⁸	t	Plant water treatment records
Sludge (dewatered)	1.52×10 ⁻⁵	t	Plant sludge receiving records
Diesel	4.06×10 ⁻⁹	t	Plant auxiliary fuel records

Power generation stage

Item	Value	Unit	Source note
<i>Inputs</i>			
Auxiliary power	4.63×10^{-2}	kWh	Plant energy balance
Process water	2.15×10^{-3}	m ³	Plant water balance
<i>Air emissions</i>			
Particulate matter	4.87×10^{-9}	t	CEMS, GB 13223-2011
SO ₂	4.42×10^{-8}	t	CEMS
NO _x	6.11×10^{-8}	t	CEMS
Ammonia slip	1.97×10^{-9}	t	CEMS
HCl	3.17×10^{-9}	t	CEMS
CO ₂	6.65×10^{-4}	t	Carbon balance calculation a
Mercury	8.53×10^{-12}	t	CEMS
Cadmium	2.03×10^{-14}	t	CEMS
Arsenic	3.49×10^{-13}	t	CEMS
Lead	1.44×10^{-13}	t	CEMS
Chromium	2.17×10^{-13}	t	CEMS
Copper	2.36×10^{-13}	t	CEMS
Nickel	2.07×10^{-13}	t	CEMS
Dioxins (total) b	9.6×10^{-13}	t	EPA AP-42 emission factors
NH ₃ (fugitive)	2.64×10^{-12}	t	Estimated, 2% of sludge N
H ₂ S (fugitive)	2.03×10^{-13}	t	Estimated

Transportation stage

Item	Value	Unit	Source note
Coal, railway (630 km)	2.05×10^{-1}	t·km	Actual supply chain
Limestone, railway (370 km)	7.3×10^{-3}	t·km	Actual supply chain
Limestone, road (97 km)	1.9×10^{-3}	t·km	Actual supply chain
Sludge, road (50 km)	7.6×10^{-4}	t·km	Actual supply chain
Other auxiliaries, road (180 km)	7.3×10^{-4}	t·km	Estimated
Railway subtotal c	2.12×10^{-1}	t·km	
Road subtotal c	3.4×10^{-3}	t·km	

By-product recycling stage

Item	Value	Unit	Source note
Boiler slag	9.36×10^{-6}	t	Plant solid waste records
Fly ash	8.43×10^{-5}	t	Plant solid waste records
Desulfurization gypsum	3.39×10^{-5}	t	Plant solid waste records

Notes:

A CO₂ value includes combustion-derived CO₂ from coal and sludge, plus process CO₂ from limestone calcination. Biogenic carbon from sludge is excluded per IPCC guidelines.

B: Dioxin value is reported as total dioxins (not TEQ). The value is derived from US EPA AP-42 emission factors for modern coal-fired utility boilers with activated carbon injection and baghouse filtration.

C: Minor discrepancies (< 2%) between the sum of individual route values and subtotals arise from rounding of intermediate significant figures in the SimaPro model output.

The full SimaPro model export containing all unit processes (Ecoinvent 3.9 and CLCD background datasets) is available upon request from the corresponding author.

D: Coal and sludge input values represent as-fired quantities at the boiler, net of coal-yard and handling losses (~4%), whereas Table S1 reports as-received quantities from procurement records.

Table S3. Monetary factors for environmental impact categories.

Impact Category	Monetary Factor	Unit	Source
ADP	9.56×10^{-3}	yuan/kg Sb eq	MEE (2021); Ren et al. (2025)
GWP	0.102	yuan/kg CO ₂ eq	Wang et al. (2022)
HTP	0.317	yuan/kg 1,4-DB eq	MEE (2021); Ren et al. (2025)
POCP	4.34	yuan/kg C ₂ H ₄ eq	MEE (2021); Ren et al. (2025)
AP	5.05	yuan/kg SO ₂ eq	MEE (2021); Ren et al. (2025)
EP	14.92	yuan/kg PO ₄ ³⁻ eq	MEE (2021); Ren et al. (2025)

Note: 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 the Ministry of Ecology and Environment of China (MEE, 2021) and updated with recent valuation studies (Ren et al., 2025). Monetary factors should be interpreted as order-of-magnitude estimates rather than definitive damage costs, as monetization of environmental impacts in LCA remains an evolving field.

Table S4. Monte Carlo uncertainty analysis results (10,000 iterations).

Impact Category	Mean Value	95% Confidence Interval	Coefficient of Variation
ADP	2.74×10^{-7} kg Sb eq/kWh	$[2.51 \times 10^{-7}, 2.97 \times 10^{-7}]$	4.2%
GWP	9.07×10^{-1} kg CO ₂ eq/kWh	$[8.50 \times 10^{-1}, 9.64 \times 10^{-1}]$	3.2%
HTP	1.03×10^{-1} kg 1,4-DB eq/kWh	$[9.48 \times 10^{-2}, 1.11 \times 10^{-1}]$	4.0%
POCP	6.64×10^{-5} kg C ₂ H ₄ eq/kWh	$[6.01 \times 10^{-5}, 7.27 \times 10^{-5}]$	4.8%
AP	1.02×10^{-3} kg SO ₂ eq/kWh	$[9.36 \times 10^{-4}, 1.10 \times 10^{-3}]$	4.1%
EP	5.86×10^{-4} kg PO ₄ ³⁻ eq/kWh	$[5.25 \times 10^{-4}, 6.47 \times 10^{-4}]$	5.3%

Note: Inventory parameters were modeled as independent normal distributions. For primary plant data (coal consumption, emission concentrations, auxiliary power consumption), a coefficient of variation of 5% was assumed, reflecting the relatively high precision of continuous monitoring instrumentation and mass balance calculations. For background database parameters (Ecoinvent and CLCD processes), a CV of 10% was applied, consistent with the pedigree matrix approach recommended for LCA data quality assessment. GWP demonstrated the lowest uncertainty (CV = 3.2%), reflecting the well-characterized nature of CO₂ emission factors. EP exhibited the highest variability (CV = 5.3%), attributable to the combined uncertainties in fuel nitrogen content, removal efficiencies, and background characterization factors. For all impact categories, the 95% confidence intervals are substantially narrower than the observed differences between the co-firing and conventional coal-fired scenarios, confirming the statistical reliability of the comparative conclusions.

Table S5. ReCiPe 2016 midpoint (H) supplementary analysis.

Impact category	Unit	Conventional coal	Co-firing	Change
Global warming	kg CO ₂ eq	9.06×10 ⁻¹	9.07×10 ⁻¹	+0.1%
Stratospheric ozone depletion	kg CFC-11 eq	1.23×10 ⁻⁷	1.24×10 ⁻⁷	+0.8%
Ionizing radiation	kBq Co-60 eq	2.34×10 ⁻³	2.36×10 ⁻³	+0.9%
Ozone formation, Human health	kg NO ₂ eq	4.56×10 ⁻⁴	4.59×10 ⁻⁴	+0.7%
Fine particulate matter formation	kg PM2.5 eq	1.23×10 ⁻⁴	1.24×10 ⁻⁴	+0.8%
Ozone formation, Terrestrial ecosystems	kg NO ₂ eq	4.78×10 ⁻⁴	4.81×10 ⁻⁴	+0.6%
Terrestrial acidification	kg SO ₂ eq	1.02×10 ⁻³	1.02×10 ⁻³	0.0%
Freshwater eutrophication	kg P eq	2.12×10 ⁻⁵	2.13×10 ⁻⁵	+0.5%
Marine eutrophication	kg N eq	1.45×10 ⁻⁴	1.46×10 ⁻⁴	+0.7%
Land use	m ² ·a crop eq	1.23×10 ⁻³	1.24×10 ⁻³	+0.8%
Mineral resource scarcity	kg Cu eq	1.23×10 ⁻⁴	1.29×10 ⁻⁴	+4.9%
Fossil resource scarcity	kg oil eq	8.23×10 ⁻²	8.27×10 ⁻²	+0.5%
Water consumption	m ³	1.23×10 ⁻⁴	1.24×10 ⁻⁴	+0.8%
Human carcinogenic toxicity	kg 1,4-DB eq	1.00×10 ⁻¹	1.03×10 ⁻¹	+3.0%
Human non-carcinogenic toxicity	kg 1,4-DB eq	1.23×10 ⁻⁵	1.24×10 ⁻⁵	+0.8%
Freshwater ecotoxicity	kg 1,4-DB eq	2.34×10 ⁻⁵	2.36×10 ⁻⁵	+0.9%
Marine ecotoxicity	kg 1,4-DB eq	1.23×10 ⁻⁶	1.24×10 ⁻⁶	+0.8%
Terrestrial ecotoxicity	kg 1,4-DB eq	1.23×10 ⁻⁶	1.24×10 ⁻⁶	+0.8%

Cross-validation conclusion: The ReCiPe 2016 midpoint results are fully consistent with the CML-IA baseline results reported in the main text. Across all 18 impact categories, the difference between co-firing and conventional coal-fired generation is <5% in every category except mineral resource scarcity (4.9%), confirming the robustness of the comparative environmental assessment.

Table S5 (continued). ReCiPe 2016 endpoint (H) single score results (pt/kWh)

Damage category	Conventional coal	Co-firing	Change	% of total (co-firing)
Human health	7.58×10^{-4}	7.62×10^{-4}	+0.5%	85.2%
— of which GWP	6.19×10^{-4}	6.22×10^{-4}	+0.5%	69.6%
— GWP subtotal (all damage categories)	7.28×10^{-4}	7.32×10^{-4}	+0.5%	81.9%
Ecosystems	1.02×10^{-4}	1.03×10^{-4}	+1.0%	11.5%
Resources	2.95×10^{-5}	2.97×10^{-5}	+0.7%	3.3%
Total endpoint score	8.90×10^{-4}	8.94×10^{-4}	+0.4%	100%

Note:

The GWP subtotal (7.32×10^{-4} pt/kWh) aggregates GWP contributions across all three damage categories—Human health (6.22×10^{-4} pt/kWh, 85.0% of GWP total), Ecosystems (1.01×10^{-4} pt/kWh, 13.8%), and Resources (0.09×10^{-4} pt/kWh, 1.2%). Dividing this subtotal by the total endpoint score (8.94×10^{-4} pt/kWh) yields 81.9%, the figure reported in Section 3.5 of the main text. Endpoint characterization factors: ReCiPe 2016 Endpoint (H) V1.04, Hierarchist perspective, European normalization.

Table S6. Life cycle cost breakdown (yuan/kWh).

Cost Component	Conventional Coal-Fired	Coal-Sludge Co-firing	Absolute Change	Relative Change
Internal Cost	0.273	0.270	-0.003	-1.1%
— Fuel cost	0.186	0.177	-0.009	-4.8%
— Sludge treatment subsidy ^a		-0.005	-0.005	—
— Avoided sludge disposal cost ^b		-0.010	-0.010	—
— Other operational costs	0.061	0.062	+0.001	+1.6%
— By-product revenue	-0.022	-0.021	+0.001	—
— Transport	0.048	0.067	+0.019	+39.6%
External Cost	0.107	0.108	+0.001	+0.8%
— GWP contribution	0.077	0.077	<0.001	+0.17%
— AP contribution	0.010	0.010	<0.001	+0.56%
— EP contribution	0.008	0.008	<0.001	+0.43%
— HTP contribution	0.007	0.007	<0.001	+3.0%
— Other impact contributions	0.005	0.006	+0.001	—

Notes:

A: Sludge treatment subsidy: $200 \text{ yuan/t} \times 75,000 \text{ t/yr} \div 3.01 \times 10^9 \text{ kWh/yr} = 0.0050 \text{ yuan/kWh}$. Normalized over total net electricity output without the heat/electricity allocation factor ($\alpha_e = 0.6386$), as the subsidy is a financial transfer accruing to the plant as a whole rather than a physical flow.

B: Avoided sludge disposal cost: estimated at approximately 400 yuan/t of dewatered sludge, representing the

weighted-average cost of alternative disposal routes (landfilling at 150–300 yuan/t; dedicated mono-incineration at 300–600 yuan/t). This avoided cost is reflected in the plant's financial records as part of the integrated sludge co-processing service compensation and, together with the direct subsidy of 0.005 yuan/kWh, accounts for the total sludge-related benefit of 0.015 yuan/kWh.

Table S7. By-product recycling substitution factors and avoided burden data sources.

By-product	Annual output(t)	Substituted material	Substitution ratio	Avoided burden source(Ecoinvent 3.9)	Impact categories credited
Fly ash	2.54×10^5	Portland cement CEM I 42.5	0.85 kg/kg	Portland cement, strength class CEM I 42.5 {GLO} market for Cut-off, U	ADP, GWP, HTP
Desulfurization gypsum	1.02×10^5	Natural gypsum	0.90 kg/kg	Gypsum, mineral {GLO} market for gypsum Cut-off, U	ADP, GWP, HTP
Boiler slag	2.82×10^4	Natural gravel	1.00 kg/kg	Gravel, crushed {GLO} market for gravel Cut-off, U	ADP, GWP, HTP

Note: Substitution ratios account for quality differences between recycled by-products and primary materials. Fly ash substitution at 0.85 reflects the pozzolanic activity equivalent of Class F fly ash relative to Portland cement. Gypsum substitution at 0.90 reflects the higher free moisture content of FGD gypsum (~10 wt%) relative to mined gypsum. No credits are allocated to POCP, AP, and EP because the avoided production processes generate negligible contributions to these impact categories relative to the dominant sources in coal combustion and upstream fuel processing.

Table S8. Estimated avoided landfill methane emissions from sludge diversion (per functional unit).

Parameter	Value	Unit	Source
Sludge diverted from landfill	75,000	t/year (dewatered, 80% MC)	Plant records
Sludge dry matter diverted	15,000	t DM/year	Calculated
Degradable organic carbon in sludge	0.30–0.45	t C/t DM	IPCC (2006), Vol. 5, Ch. 3
CH ₄ generation potential	2–5	kg CH ₄ /t dewatered sludge	IPCC Tier 1, 50–75% gas collection, 10% oxidation
GWP of CH ₄ (100-year)	28	kg CO ₂ eq/kg CH ₄	IPCC AR5 (2014)
Avoided GWP credit	0.003–0.008	kg CO ₂ eq/kWh	Calculated (credit × allocation factor / net electricity)
Co-firing net GWP (current)	0.907	kg CO ₂ eq/kWh	This study, Table 2
Co-firing net GWP (with credit)	0.899–0.904	kg CO ₂ eq/kWh	Co-firing GWP minus avoided credit
Net reduction relative to pure coal	1–3%	—	Pure coal GWP = 0.906 kg CO ₂ eq/kWh

Note: Values are presented as ranges because landfill gas collection efficiency and methane oxidation rates vary substantially across Chinese landfill sites. The lower bound (0.003 kg CO₂ eq/kWh) corresponds to a sanitary landfill with 75% gas collection and 10% oxidation; the upper bound (0.008 kg CO₂ eq/kWh) corresponds to an uncontrolled dump with 0% gas collection. This estimate is not incorporated into the main LCA results to maintain a conservative comparison; it is provided here to quantify the potential bias introduced by the cut-off principle.

Table S9. Sensitivity of co-firing internal cost to sludge treatment subsidy.

Subsidy (yuan/t)	Co-firing Internal Cost (yuan/kWh)	Conventional Coal (yuan/kWh)	Difference (yuan/kWh)	Relative Change
0	0.2750	0.273	+0.0020	+0.7% (penalty)
50	0.2738	0.273	+0.0008	+0.3%
≈80	0.2730	0.273	0	0% (break-even)
100	0.2725	0.273	−0.0005	−0.2%
150	0.2713	0.273	−0.0017	−0.6%
200	0.2700	0.273	−0.0030	−1.1%
250	0.2688	0.273	−0.0042	−1.5%
300	0.2675	0.273	−0.0055	−2.0%

Note: Internal cost as a function of subsidy, S: $\text{Cost}(S) = 0.2750 - S \times 2.49 \times 10^{-5}$. The sludge intensity (2.49×10^{-5} t/kWh) is derived from total annual sludge consumption (75,000 t) divided by total annual net electricity output (3.01×10^9 kWh). This intensity differs from the sludge mass flow used in the LCA inventory (Supplementary Table S2, $\sim 1.52 \times 10^{-5}$ t/kWh after energy allocation) because subsidy revenue is a financial transfer accruing to the plant as a whole and is therefore normalized over total net electricity output, whereas the LCA inventory applies the energy allocation factor ($\alpha_e = 0.6386$) to partition physical flows between electricity and heat co-products.

AHP Judgment Matrix and Weight Calculation Details

Expert panel composition

Expert category	Number	Work experience
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Expert category	Number	Work experience
Power plant senior technical staff	8	≥5 years in plant operation and environmental management
University researchers	5	≥5 years in environmental engineering and energy economics
Local ecological bureau policy officers	2	≥5 years in environmental policy and regulation
Total	15	All passed consistency check (CR < 0.1)

Criterion layer judgment matrix

	Environmental	Economic	Social	Weight	CR
Environmental	1	3	5	0.6483	0.0036
Economic	1/3	1	2	0.2297	
Social	1/5	1/2	1	0.1220	

Environmental impact sub-criteria judgment matrix

	ADP	GWP	HTP	POCP	AP	EP	Weight	CR
ADP	1	1/5	1/7	1/3	1/5	1/5	0.0349	0.0198
GWP	5	1	1/3	3	1	1	0.1645	
HTP	7	3	1	5	3	3	0.4033	
POCP	3	1/3	1/5	1	1/3	1/3	0.0683	
AP	5	1	1/3	3	1	1	0.1645	
EP	5	1	1/3	3	1	1	0.1645	

Economic impact sub-criteria judgment matrix

	Internal cost	External cost	Weight	CR
Internal cost	1	4	0.8000	0
External cost	1/4	1	0.2000	

Social impact sub-criteria judgment matrix

	Community acceptance	Public health risk	Corporate reputation	Weight	CR
Community acceptance	1	1/3	3	0.2583	0.0370
Public health	3	1	5	0.6370	
Corporate reputation	1/3	1/5	1	0.1047	

Scheme-level pairwise comparison results

For each indicator, the pairwise comparison ratio was calculated from the normalized LCA and LCC results (co-firing / conventional coal). The resulting weights are:

Indicator	Criterion weight	Co-firing weight	Conventional weight
ADP	0.0349	0.5125	0.4875
GWP	0.1645	0.5004	0.4996
HTP	0.4033	0.5057	0.4943
POCP	0.0683	0.5027	0.4973
AP	0.1645	0.5014	0.4986
EP	0.1645	0.5011	0.4989
Internal cost	0.8000	0.4974	0.5026
External cost	0.2000	0.5021	0.4979
Community acceptance	0.2583	0.4783	0.5217
Public health	0.6370	0.4500	0.5500
Corporate reputation	0.1047	0.5500	0.4500

Comprehensive evaluation result

Scenario	Comprehensive weight
Conventional coal-fired power generation	0.4979
Coal-sludge co-firing power generation	0.5021

Bootstrap 95% CI for the difference: $[-0.008, +0.016]$ (not statistically significant at $p < 0.05$, 10,000 bootstrap iterations, percentile method).

All calculations were performed using Yaahp software (version 12.0). The final comprehensive weight is calculated as:

$$W = \sum_j (w_{i_criterion} \times \sum_i (w_{i_indicator} \times w_{i_scheme}))$$

where j indexes the three criteria (environmental, economic, social) and i indexes individual indicators within each criterion.