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Parameter-Level Attribution of Uncertainty in Electricity Carbon Footprint Factors: A Case Study of Coal-Fired and Hydropower Plants in a Chinese Province

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Abstract

Provincial carbon footprint factors of electricity underpin product carbon footprints, green certificate trading, and carbon border adjustment, yet their uncertainty is usually reported as one aggregate interval that does not show which part better measurement could reduce and which part an accounting convention fixes. This case study examines eight plants in one Chinese province with original 2025 accounting workbooks (four coal-fired, four hydropower). Each is rebuilt into a normalized parametric model reproducing the original total. Measurable quantities are propagated by Monte Carlo sampling and apportioned with variance-based sensitivity indices; database choices and accounting conventions are enumerated as discrete scenarios and compared with, rather than added to, the probabilistic interval. For the coal-fired plants, the measurement-driven 95% interval is about −11% to +12%, dominated by coal input; the background database shifts the factor by a comparable amount, whereas every accounting convention shifts it by less than 30% of the interval half-width. For the hydropower plants, the interval is wider, yet harmonizing the amortization horizon of civil works alone moves the factor by 1.5 to 2.8 times that half-width. The findings are specific to the sample and suggest differentiating data collection and factor publication by generation type.

Keywords: carbon footprint of electricity; life cycle assessment; parametric model; sensitivity analysis; Monte Carlo; Sobol' indices; amortization horizon; reservoir greenhouse gas; coal-fired power; hydropower

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Academic Editor: Fernando Rubiera

Received: 31 August 2026
Revised: 7 October 2026
Accepted: 13 October 2026
Published: 12 November 2026

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1. Introduction

The carbon footprint factor of electricity is the single largest parameter in most product carbon footprint calculations, and it is the common basis for green certificate trading, export carbon declarations and compliance with carbon border adjustment mechanisms [1,2]. Because a growing share of corporate and product-level disclosure is settled against a published regional factor rather than against metered plant data, the credibility of that one number propagates into a large number of derived claims [3].

Unlike an emission factor, which counts only on-site direct emissions, a carbon footprint factor is quantified on a life-cycle basis and includes fuel extraction and washing, raw material transport, plant construction and equipment manufacturing [4,5]. Its magnitude therefore depends on the declared system boundary, the allocation rule and the choice of background database, as well as on data quality. Recent syntheses of power-sector life

cycle assessment report that the dispersion across studies of nominally the same technology is driven mainly by upstream process assumptions, siting conditions and boundary definitions rather than by measurement error in the foreground inventory [4,5].

The treatment of uncertainty in life cycle assessment is a mature subfield. Quantitative approaches have been surveyed and classified [6], guidance exists on which technique suits which class of uncertainty [7], and propagation methods have been compared systematically [8]. A long-standing typology distinguishes parameter uncertainty from scenario uncertainty, which arises from normative choices such as allocation rules and time horizons, and from model uncertainty [9]. Where foreground data quality is the concern, the pedigree approach converts qualitative data-quality judgements into distributions [10]. Most applied studies, however, report an aggregate output distribution, which indicates how wide the interval is but not which parameter the next field campaign should measure.

Sensitivity analysis is the natural complement. A systematic review found that most published analyses vary one factor at a time over an arbitrary and usually uniform range, a design that cannot detect interactions and that encodes the analyst's choice of range into the ranking of importance [11]. Within life cycle assessment, variance-based global methods have been formalized and benchmarked [12], applied to background inventories at scale [13], and extended to energy systems [14]. Global methods require a probability distribution for every input, which is not available when the quantity is a convention—an amortization horizon, or a decision on whether reservoir emissions fall inside the boundary. Hybrid designs therefore treat parameter uncertainty probabilistically and choices as discrete scenarios [15,16].

Two gaps remain for electricity factors. First, the accounting workbook of a plant is rarely rebuilt into an analytical model from which each parameter's effect can be derived and traced back to a cell of the original sheet; the closest precedents parameterize a generic technology inventory rather than an audited plant workbook [17]. Second, for infrastructure-intensive sources, the dominant variation often comes from boundary declarations and amortization conventions rather than from missing data. The assumed lifetime of long-lived infrastructure is known to dominate life-cycle results for buildings [18], and capital goods have been identified as a structural problem for environmental product declarations [19], waste management systems [20], and ocean energy technologies [21]. For hydropower the reservoir term adds a further convention: a physically based modelling framework exists [22], but which plant configurations should declare reservoir emissions remains open [23]. When both kinds of uncertainty are merged into one interval, they cannot be told apart, although they call for different remedies.

The aim of this study is to identify and classify, at the parameter level, the sources of variability in the carbon footprint factors of a set of case-study coal-fired and hydropower plants and to quantify how the part that measurement can reduce compares with the part fixed by the choice of background database and by accounting conventions. The study makes three contributions.

1. The accounting workbook of each plant is rebuilt into a normalized parametric model whose baseline reproduces the original total and whose terms are traced to individual workbook cells; the models and the code are provided as Supplementary Materials.
2. Parameters are assigned to three classes—measurable quantities, background-database choice and accounting conventions—with explicit screening and perturbation rules. Measurable quantities are propagated probabilistically; the other two classes are enumerated as scenarios and compared with the probabilistic interval instead of being added to it.
3. The analysis is repeated for every plant with an original workbook, so that each result is reported as a range across plants rather than for a single plant.

Because every result is expressed in relative terms, the method and the findings do not depend on the absolute value of any factor, which allows them to be published while the plant data remain confidential.

The remainder of the paper is organized as follows. Section 2 describes the sample, the system boundary, the parametric models and the treatment of the three classes. Section 3 reports the factor dispersion and block composition, the treatment of reservoir emissions, the probabilistic results for measurable quantities, and the scenario results for database choice and conventions. Section 4 discusses the implications for data collection and factor publication, relates the approach to hybrid uncertainty methods, and states the limitations. Section 5 concludes.

2. Materials and Methods

2.1. Sample, Anonymization and Data Sources

The sample consists of the nine plants whose 2025 carbon footprint accounting was completed: five coal-fired and four hydropower. Between them they cover the three coal-fired technology routes present in the province (subcritical pulverized coal, circulating fluidized bed and ultra-supercritical pulverized coal) and the four hydropower development modes (storage, mixed, run-of-river, and diversion). These case-study plants were not selected as a statistically representative sample of the provincial fleet. The modelling additionally requires the original accounting workbook, which is available for eight of the nine plants; C4 is described in Table 1 but not modelled. Every modelled quantity is read from a cell of the original workbook, no secondary summary sheet is used, and each retrieved value is recorded with its worksheet and cell address.

Table 1. Sample composition and relative dispersion of the carbon footprint factors.

No.	Type	Technology or Development Mode	Key Accounting Conventions	Factor vs. Type Mean (%)	Modelled
C1	Coal	Circulating fluidized bed (subcritical + supercritical)	In-furnace limestone desulfurization; condensing	+12.6	yes
C2	Coal	Pulverized coal (subcritical)	Minor heat supply, fully borne by power	+8.0	yes
C3	Coal	Pulverized coal (subcritical)	Cogeneration, allocated by heat ratio	−3.4	yes
C4	Coal	Pulverized coal (subcritical)	Cogeneration, not allocated	−4.7	no
C5	Coal	Pulverized coal (ultra-supercritical)	Condensing	−12.5	yes
H1	Hydro	Storage type, embankment dam	Civil 100 yr/equipment 40 yr; reservoir GHG included	−36.4	yes
H2	Hydro	Mixed type, embankment dam	Civil 50 yr/equipment 40 yr; reservoir GHG excluded	−20.1	yes
H3	Hydro	Run-of-river, gravity dam	Civil 100 yr/equipment 40 yr; reservoir GHG excluded	−14.5	yes
H4	Hydro	Diversion type, embankment dam	Civil 100 yr/equipment 40 yr; reservoir GHG included	+71.0	yes

Note: each factor is given as a deviation from the arithmetic mean of its generation type. The inter-plant spread, defined throughout as the ratio of the highest to the lowest factor, is 1.29 for the five coal-fired plants and 2.69 for the four hydropower plants. Each deviation is computed from the headline total of the plant's own workbook; for C2, whose workbook contains two totals differing by 0.68% (Section 2.3), this is the production-unit total, whereas the life-cycle-stage total is used as the modelling baseline. C4 has no original workbook; its factor is taken from provincial summary data.

Plant production data are commercially confidential. Plants are therefore labelled C1 to C5 and H1 to H4, and no absolute quantity is reported—neither carbon footprint factors nor installed capacity, electricity delivered to the grid, reservoir water surface or fuel assay values. Results are given as relative changes with respect to the baseline, as shares of the baseline total, as deviations from the mean of the generation type, or as ratios. Two

disclosure rules—no plant name and no absolute value—are checked automatically over the manuscript source and over the Supplementary Materials.

2.2. System Boundary and Functional Unit

With reference to the association standards of the China Electricity Council [24,25] and the corresponding national standards [26,27], and on the principle that the boundary must be the same for both generation types, the system boundary comprises three blocks: raw material acquisition and transport; plant construction (civil works and equipment acquisition, plus a pre-construction stage for hydropower); and operation and maintenance. Transmission and distribution are excluded. The functional unit is 1 kW·h delivered to the grid, and all greenhouse gases are accounted for, consistent with ISO 14067 [28]. One-off investments are converted into annual figures by dividing by an amortization horizon.

The identical boundary is a deliberate choice. Boundary identification is a recognized source of divergence in life cycle assessment [29], and a comparison between technologies is only meaningful if the same blocks are included for both.

2.3. Parametric Models

Both accounting sheets share the same structure: one-off investments divided by an amortization horizon, plus annual activity data multiplied by emission factors, divided by the electricity delivered to the grid, and scaled by an allocation coefficient for non-power products:

$$EF = \frac{E}{W}(1-\alpha) \tag{1}$$

In Equation (1), EF is the plant factor in $kgCO_2e/(kW{\cdot}h)$, E the annual total emissions in $kgCO_2e/a$, W the annual electricity delivered to the grid in kW·h/a and α the allocation coefficient. For coal-fired plants α is the heat allocation coefficient and $W = G(1-r)$, with gross generation G and auxiliary power rate r. For hydropower α is the share allocated to non-power functions and $W = W_0\, g$, with normal-year output W_0 and wet/dry-year coefficient g.

For coal-fired plants,

$$E = \underbrace{Mf}_{\text{coal upstream}} + \underbrace{M\,\omega C\eta + Q\textstyle\sum_i e_i\gamma_i}_{\text{combustion}} + E_\mathrm{t} + E_\mathrm{s} + \frac{B}{N} + E_\mathrm{x} \tag{2}$$

and for hydropower plants,

$$E = \frac{\lambda\left(C_\mathrm{p} + C_\mathrm{c}\right)}{N_\mathrm{c}} + \frac{C_\mathrm{e}}{N_\mathrm{e}} + E_\mathrm{o} + \delta E_\mathrm{r} + E_\mathrm{w}. \tag{3}$$

The symbols are defined in Table A1 (Appendix A). In Equation (2), coal input M drives coal upstream emissions, combustion and coal transport E_t; limestone consumption acts on the flue-gas term E_s; and E_x collects the items that are not linked to any parameter. In Equation (3), the completeness coefficient λ scales the one-off emissions of the pre-construction stage and civil works, and δ indicates whether the reservoir term E_r lies inside the boundary. Reservoir emissions are computed with the IPCC default factors for flooded land [30] and the hundred-year methane global warming potential of the Sixth Assessment Report [31]; background factors are taken from ecoinvent [32] and, where a localized dataset exists, from the Chinese Life Cycle Database (CLCD) [33]; direct-emission quantities follow the national inventory guidelines [34].

Dividing each term by the baseline total gives a normalized model in which every term is a share of the baseline total multiplied by the relative change of its parameters.

The normalized models of the eight plants are provided in the Supplementary Materials and contain no absolute value.

Reproduction of the workbooks. Each term of Equations (2) and (3) is read from the workbook cells that the original sheet uses for that item, and automated checks in the code verify that the model returns the original total at the baseline. For hydropower the stage values close the balance exactly. For the coal-fired plants, the unattributed term E_x (natural gas and diesel supply, consumables, hazardous waste, and other minor items) accounts for 0.4% to 0.8% of the total and is kept constant.

Two inconsistencies in the source workbooks. The C2 workbook contains a second, production-unit table whose factor is 0.68% lower than that of the stage table. The difference is fully reconciled by the cell formulas: the production-unit table applies the 1.43% heat allocation, counts coal transport a second time (+0.70% of the total) and adds the natural-gas items of one unit (+0.06%), which the stage table treats as already contained in the unit CO_2 figure; $(1 + 0.0076)(1 - 0.0143) - 1 = -0.68\%$. The stage table, which does not apply the allocation and counts transport once, is used as the baseline. In the C1 workbook, coal transport also enters the total twice (+0.49%); this is retained so that the model reproduces the reported factor, and it affects no conclusion.

2.4. Parameter Screening

Parameters enter the analysis under three rules: (1) any block contributing more than 1% of the factor is included; (2) a parameter with a small share but a large leverage is included—the auxiliary power rate and the annual output sit in the denominator of Equation (1) and act on every term; (3) boundary and convention parameters are always included, because their values are fixed by a standard rather than by data. The rules select six measurable coal-fired parameters and three measurable hydropower parameters, together with the database and convention items of Section 2.5.

Excluded items are those whose shares are too small to affect any conclusion. For the coal-fired plants, all items not linked to a parameter (E_x) together account for at most 0.8% of any factor; the largest of them is the supply of consumables. For hydropower, solid-waste disposal ($\leq$2%) is kept as a constant. Reservoir water surface, year of impoundment and similar quantities act only through the single term δE_r and are therefore covered by the reservoir boundary item. Dam type, boiler type and installed capacity are discrete plant attributes and are examined by comparison across plants.

2.5. Three Classes of Uncertainty and Their Treatment

Each parameter is assigned to one of three classes according to how its uncertainty could be reduced. The class describes the origin of the uncertainty and is independent of the strength of the parameter's effect, which is described separately by the sensitivity grade below.

Class (i) concerns measurable quantities. Their uncertainty can be reduced through measurement or inventory completion. For coal-fired plants, these are coal input M, as-received carbon content C, carbon oxidation rate η, auxiliary power rate r, coal transport activity and limestone consumption; for hydropower, annual generation g, completeness of the construction bill of materials λ, and operation and maintenance emissions E_o. Each is perturbed over its credible domain: the range observed in the plant records for the coal input ($\pm$10%) and carbon content ($\pm$5%), the physical range 0.98 to 1.00 for the oxidation rate, the customary industry limits for the auxiliary power rate ($-$12.5% to +16.6% of the baseline, applied to each plant's own value), $\pm$30% for transport activity and limestone consumption, $\pm$20% for g and λ, and $\pm$50% for E_o. The domains for g and λ are modelling assumptions that have not been calibrated against plant records (Section 4.4).

For each class-(i) parameter the local sensitivity coefficient

$$S = \frac{\Delta EF\,\%}{\Delta X\,\%} \tag{4}$$

is computed at the baseline, where $\Delta X\%$ is the relative change of the parameter and $\Delta EF\%$ that of the factor; S is a local elasticity [35]. Parameters are graded as highly, moderately or weakly sensitive for $|S| \geq 0.5$, $0.1 \leq |S| < 0.5$ and $|S| < 0.1$. For probabilistic propagation, the class-(i) parameters are assigned independent uniform distributions over the adopted domains. These distributions, independence and domain limits are modelling assumptions, rather than fitted distributions of plant observations. The resulting class-(i) intervals and total-order Sobol' indices are conditional on all three assumptions; different distributions, dependencies or domains can change both the interval widths and the variance attribution. Class-(ii) and class-(iii) choices are held at their baseline values during this propagation.

Monte Carlo propagation uses 200,000 draws per plant. Let $Y = 100(EF/EF_0 - 1)$ be the relative change from the plant's baseline factor EF_0, and let q_p denote its empirical quantile at probability p. The equal-tail class-(i) 95% interval is $[q_{0.025}, q_{0.975}]$ and

$$h_{95} = \frac{q_{0.975} - q_{0.025}}{2}.$$

Quantiles are calculated by linear interpolation between adjacent sorted draws (the NumPy 1.26.4 `percentile` function, linear method): for n ordered draws $y_{(1)}, \ldots, y_{(n)}$, set $r = (n-1)p$, $k = \lfloor r \rfloor$ and $a = r - k$, and use $q_p = (1-a)y_{(k+1)} + a y_{(k+2)}$. Thus h_{95} is half the interval's total span, in percentage points; the interval need not be symmetric around zero or the median. It is a model-derived uncertainty interval, not a confidence interval estimated from repeated plant observations. The variance contribution is measured by the total-order Sobol' index

$$S_{\mathrm{T},j} = \frac{\mathrm{E}\left[\mathrm{Var}\left(EF \mid X_{\sim j}\right)\right]}{\mathrm{Var}(EF)}, \tag{5}$$

estimated with the design of Saltelli et al. [36] and the estimator of Jansen [37]. Two independent random input matrices A and B each contain 2^{16} rows; for each parameter, a hybrid matrix replaces its column of A with that of B. This is a pick-and-freeze design with pseudo-random uniform sampling.

Numerical stability was assessed by repeating the calculations with three independent root seeds and doubling the Monte Carlo draws from 200,000 to 400,000 and the base size of each Sobol input matrix from 2^{16} to 2^{17}. Within each seed, the smaller design was a prefix of the larger design. Across the eight plants, the largest paired change of a baseline 95% interval endpoint was 0.073 percentage points, and that of a total-order index was 0.0054. At the doubled sizes, the largest between-seed ranges were 0.167 percentage points and 0.0086, respectively. All total-order parameter rankings were unchanged. The script, seeds and per-plant checks are included in Supplementary Files S2 and S3.

Class (ii) concerns background-database choice. Agreement on a database resolves this uncertainty; additional plant data do not. Here it concerns the upstream factor of coal mining and washing, for which the two databases used in the batch differ by a factor of 11.7. It is treated as a discrete model-choice scenario: the localized database value replaces the ecoinvent value used in the workbooks.

Class (iii) concerns accounting conventions. Their values are prescribed by a standard, so additional plant data do not resolve this uncertainty. They are enumerated as discrete scenarios at the values that occur in the present batch or in current practice: heat allocation (C2 allocated by its heat ratio; C3 fully borne by power), the construction amortization horizon of coal-fired plants (30 to 50 or 25 years), the global warming potential set (AR6

100-year and 20-year values for fossil methane), the civil-works amortization horizon of hydropower (harmonized between the 100 and 50 years that both occur in the batch), the equipment horizon (40 to 25 years) and the reservoir boundary. For H1 and H4, which include reservoir emissions, the reservoir scenario removes them. For H2 and H3, which have no artificial impoundment, applying the default factors to the tabulated water surface is shown only as a hypothetical case in Section 3.2, because the configuration does not qualify. Allocation to non-power functions of a multi-purpose project reduces the factor by exactly α; no allocation basis is documented for any of the plants, so it is not enumerated.

Comparison between classes. Class-(ii) and class-(iii) shifts are reported individually and are never added to the class-(i) interval or to each other, because a shift from a discrete choice and a percentile of a probability distribution are not commensurable. Instead, each shift ΔEF_s is compared with the class-(i) interval through the ratio

$$R_s = \frac{|\Delta EF_s|}{h_{95}}. \quad (6)$$

Here, $\Delta EF_s = 100(EF_s/EF_0 - 1)$ is the scenario shift relative to the same baseline, expressed in percent. $R_s < 1$ or $R_s > 1$ means that the magnitude of this shift is smaller or larger than the class-(i) interval half-width, respectively. This is a comparison of scales, not a test of whether the shifted value lies inside the possibly asymmetric interval, nor a test of statistical significance.

3. Results

3.1. Factor Dispersion and Block Composition

The spread among the five coal-fired plants is 1.29, and every plant lies above the national coal-fired carbon footprint factor. The ultra-supercritical unit (C5) lies below the subcritical pulverized-coal units (C2 to C4), which lie below the subcritical circulating fluidized bed (C1); C5 is 22.3% below C1. This ordering reproduces, on an independent provincial sample, the ranking of clean coal routes reported for another Chinese province [38]. The cogeneration plants C3 and C4 lie below C2, which supplies only a marginal heat load; the size of this effect depends on the allocation rule, itself a recognized source of uncertainty in combined heat and power accounting [39]. The spread among the four hydropower plants is 2.69.

The block composition separates the two technologies (Figure 1). In all four coal-fired plants the fuel supply chain (coal upstream and transport) accounts for 14% to 15% of the factor, operation for 84% to 86%, and plant construction for less than 0.3%, so the factor is determined by the fuel burned in the year. In the four hydropower plants, plant construction accounts for 57% to 99.6%, with civil works alone contributing 36% to 91%; the factor is determined by a stock built decades ago and distributed over each kilowatt-hour by an amortization rule. For C2 the life-cycle factor is 18.5% above the factor that counts on-site direct emissions only, and 14.3 of those percentage points come from upstream coal mining and washing, consistent with life-cycle modelling of Chinese coal-fired power [40,41] and with the methane burden of Chinese coal mining [42].

3.2. Treatment of Reservoir Greenhouse Gases

H1 and H4 include net reservoir greenhouse gas emissions, which represent 26.9% and 39.1% of their factors; H2 and H3 do not. The omission is consistent with the plant configurations: H2 regulates a natural lake, and H3 is a run-of-river plant without a storage reservoir, so neither has a water surface created by impoundment. For H1 and H4, however, the inclusion itself is a convention, and removing the term is a scenario of class (iii) (Section 3.4).

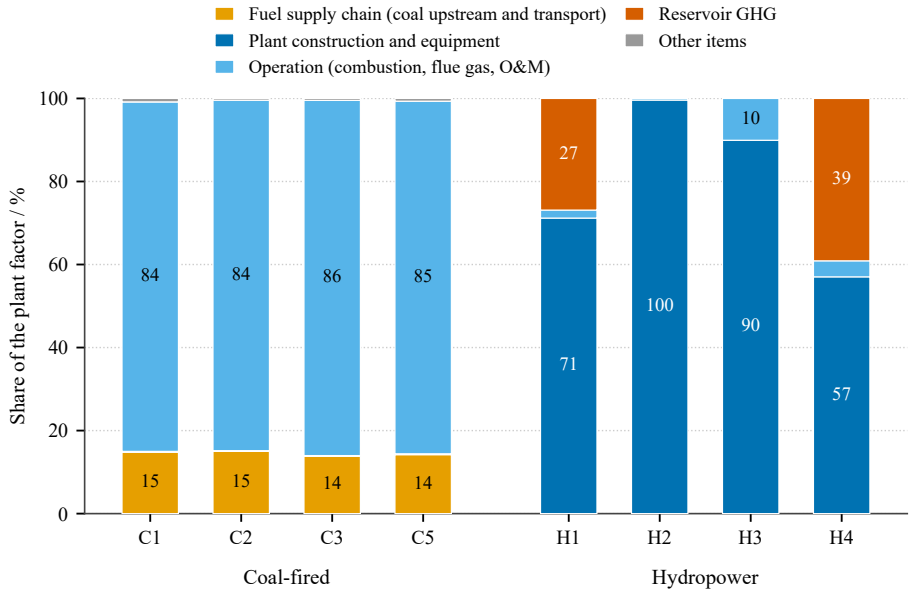


Figure 1. Life-cycle block composition of the eight modelled plants, as shares of each plant's factor. Absolute factors are withheld; for orientation, the hydropower factors are about two orders of magnitude smaller than the coal-fired factors. "Other items" are the unattributed term E_x of Equation (2).

The influence of the missing declaration rule can be illustrated by a hypothetical case. If the default factors were applied to the tabulated water surface of every plant regardless of configuration, the factor of H3 would rise by 120.0%, whereas that of H2 would rise by only 6.0%; the difference follows from the ratio of water surface to annual output, which is about 21 times larger for H3. This case does not describe an omission to be corrected and is excluded from all other results; it shows how far a boundary declaration alone can move a factor. The physical basis of the term is not in dispute: reservoir surfaces are a significant greenhouse gas source [43], their emissions depend on age and latitude [44], the processes are increasingly well characterized [45,46], the drivers across Chinese reservoirs have been quantified [47], and a framework that resolves pre-impoundment baselines and allocates the footprint across reservoir services is in operational use [22]. What is missing is a rule stating which configurations must declare the term.

3.3. Measurable Quantities

Table 2 gives the local sensitivity of the class-(i) parameters for the two plants shown in Figure 2, C2 and H3, together with the range of S and of the total-order index over the four plants of each type. Table 3 gives the class-(i) 95% intervals of all eight plants.

For coal-fired generation, the four plants behave almost identically. Coal input has a coefficient of 0.965 to 0.991: in this accounting structure it drives coal upstream emissions, transport and combustion together, so its relative change is passed almost proportionally to the factor. This coefficient applies to the modelled plants; efficiency measures that change coal quality or auxiliary consumption act through other terms. Within the model, the same coefficient quantifies the carbon cost of a higher coal consumption rate, as under the deep peak-shaving operation that coal-fired units increasingly provide [48] and for which accounting methods are being developed [49]: a 10% rise raises the factor by 9.7% to 9.9%. The carbon content and the oxidation rate have coefficients of 0.81 to 0.85. The total-order indices show that coal input alone explains 83% to 85% of the class-(i) variance and carbon content about 15%; every other parameter contributes at most 1.3%. The resulting 95% interval is −10.7% to −11.0% at the lower end and +11.5% to +11.8% at the upper end

in all four plants. The limestone coefficient is seven to eight times higher in the circulating fluidized bed plant C1 (0.024) than in the pulverized-coal plants, but still low.

Table 2. Class (i): local sensitivity and variance contribution of the measurable quantities.

Parameter	Symbol	Domain	ΔEF (%)	S	S (All)	Grade	S_T (All)
Coal-fired generation (C1, C2, C3, C5; columns 4, 5 and 7 for C2)							
Coal input/coal consumption rate	M	±10%	−9.91/+9.91	0.991	0.965–0.991	high	0.83–0.85
As-received carbon content	C	±5%	−4.18/+4.18	0.837	0.813–0.848	high	0.15
Carbon oxidation rate	η	0.98–1.00	−0.84/+0.85	0.837	0.813–0.848	high	0.01
Auxiliary power rate	r	−12.5%/+16.6%	−0.92/+1.24	0.074	0.049–0.083	low	0.004–0.013
Coal transport activity	E_t	±30%	−0.21/+0.21	0.007	0.006–0.010	low	<0.01
Limestone consumption	E_s	±30%	−0.10/+0.10	0.003	0.003–0.024	low	<0.01
Hydropower (H1 to H4; columns 4, 5 and 7 for H3)							
Annual generation (wet/dry year)	g	±20%	+25.00/−16.67	−1.000	−1.000	high	0.55–0.77
Completeness of construction bill of materials	λ	±20%	−17.06/+17.06	0.853	0.562–0.931	high	0.24–0.46
Operation and maintenance emissions (excl. reservoir)	E_o	±50%	−5.02/+5.02	0.100	0–0.100	moderate	≤0.04

Note: ΔEF: change of the factor with the parameter at the low/high end of its domain. S: local sensitivity coefficient of Equation (4) at the baseline; the grade refers to $|S|$. "All": range over the four plants of the type. The grade describes the strength of a parameter's effect and is independent of its class, which describes the origin of its uncertainty. S_T is the total-order Sobol' index of Equation (5) within class (i), conditional on the adopted uniform distributions, independence and domains. For the auxiliary power rate the low end of the domain lowers the factor; for annual generation the low end raises it.

Table 3. Class-(i) 95% intervals and shifts of the factor under the class-(ii) and class-(iii) scenarios (%).

Item	Class	Plant			
Coal-fired		**C1**	**C2**	**C3**	**C5**
95% interval of class (i)	(i)	−10.7/+11.5	−11.0/+11.8	−10.9/+11.7	−10.9/+11.7
Upstream coal factor from the localized database	(ii)	−12.6	−13.1	−12.0	−12.2
Heat allocation (C2: allocated; C3: fully borne by power)	(iii)	n/a	−1.4	+3.3	n/a
Construction amortization horizon 30 → 50 yr	(iii)	−0.10	−0.06	−0.07	−0.09
Construction amortization horizon 30 → 25 yr	(iii)	+0.05	+0.03	+0.03	+0.04
GWP set: AR6 100-year (fossil CH_4)	(iii)	−0.05	−0.05	−0.05	−0.05
GWP set: AR6 20-year (fossil CH_4)	(iii)	−0.01	−0.01	−0.01	−0.01
Hydropower		**H1**	**H2**	**H3**	**H4**
95% interval of class (i)	(i)	−22.4/+31.2	−26.0/+35.7	−25.5/+35.0	−21.2/+29.6
Civil-works amortization horizon harmonized (100 ↔ 50 yr)	(iii)	+66.5	−46.5	+85.3	+56.2
Equipment amortization horizon 40 → 25 yr	(iii)	+2.8	+3.9	+2.8	+0.50
Reservoir GHG removed from the boundary	(iii)	−26.9	n/a	n/a	−39.1

Note: shifts are relative to each plant's baseline and are not additive. For H2 the civil-works horizon is changed from 50 to 100 years, for the other plants from 100 to 50 years. n/a: not applicable (no heat supply, or no reservoir term in the baseline).

For hydropower, annual generation enters as a reciprocal ($S = -1$), and the completeness of the bill of materials has a coefficient equal to the share of pre-construction and civil works, from 0.56 (H4) to 0.93 (H2). Together they explain more than 96% of the class-(i) variance in every plant, and the 95% interval is −21.2% to −26.0% at the lower end and +29.6% to +35.7% at the upper end, 2.2 to 2.8 times as wide as for coal. Because the hydropower civil-works stage is reported as a single lump of emissions without an itemized bill of materials, λ cannot at present be attributed to cement, steel or earthwork; completing the itemized bill is a precondition for narrowing this term and for applying pedigree-based data-quality assessment to it [10].

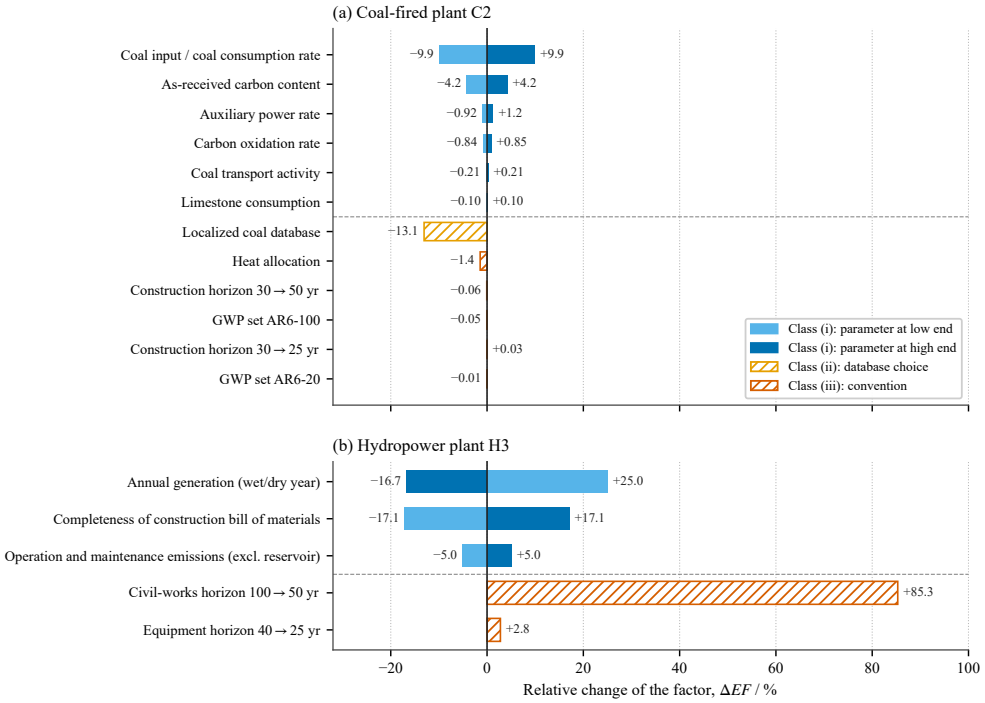


Figure 2. Tornado charts for C2 (**a**) and H3 (**b**) on a common abscissa. Solid bars: class-(i) parameters at the low and high ends of their domains; hatched bars: class-(ii) and class-(iii) scenarios, shown below the dashed line. Every bar is labelled with its value. The hypothetical reservoir scenario for H3 is discussed separately in Section 3.2.

3.4. Database Choice and Accounting Conventions

Table 3 lists the shift produced by every class-(ii) and class-(iii) scenario in every modelled plant, next to the class-(i) 95% interval of the same plant.

For coal-fired generation, the database choice lowers the factor by 12.0% to 13.1%, which is 1.06 to 1.15 times the half-width of the class-(i) interval. The upstream coal factor thus has a low local coefficient (0.13 to 0.14, equal to its share of the factor), but the two databases differ by a factor of 11.7, producing a model-choice effect slightly larger than the class-(i) interval half-width. The shifts caused by accounting conventions are much smaller. The largest is the heat allocation of the cogeneration plant C3, +3.3% ($R_s = 0.29$), because its heat ratio is only about 3%; for C2 it is −1.4%. The construction horizon and the global warming potential set change the factor by 0.10% or less. These items are among the most time-consuming to document in a site survey, despite their small effects on the factor.

For hydropower, harmonizing the civil-works horizon moves the factor by +56.2% to +85.3% in the three plants currently at 100 years and by −46.5% in H2, currently at 50 years—1.5 to 2.8 times the half-width of the class-(i) interval. The response is nonlinear because the horizon enters as a reciprocal: halving it raises the factor of H3 by 85.3%, whereas a linear extrapolation of the local coefficient would give 42.7%. For the two plants that declare reservoir emissions, removing them lowers the factor by 26.9% and 39.1% ($R_s = 1.0$ and 1.5). The equipment horizon changes the factor by 3.9% or less.

Figure 3 shows the joint effect of the amortization horizon and hydrological variability for H3. Over horizons of 30 to 120 years and generation deviations of ±30%, the factor varies between 66% and 427% of the baseline, a span of 6.5 times; the plant controls neither parameter. The two horizons applied in the batch, 100 and 50 years, are marked, together with the 40-year design life that one plant reports in its general information sheet, although its calculation applies 100 years.

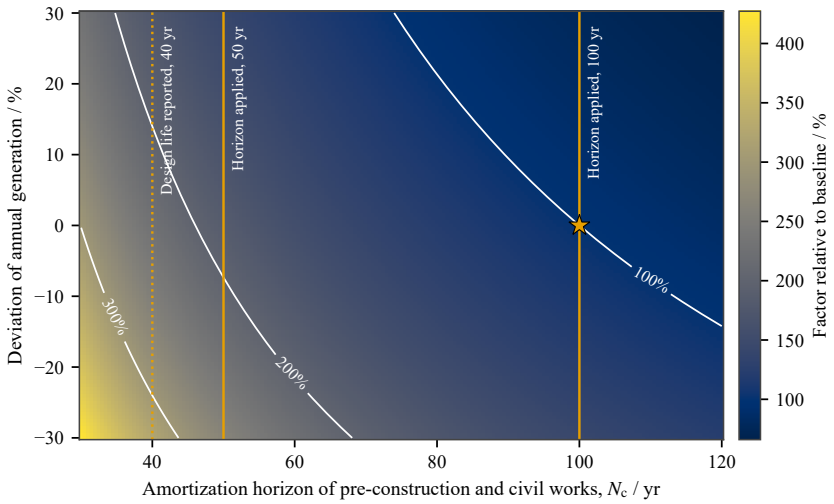


Figure 3. Factor of H3 relative to its baseline as a function of the amortization horizon of pre-construction and civil works and of the deviation of annual generation. Contours at 100%, 200% and 300%; the star marks the baseline. Solid vertical lines: the two horizons applied in the batch (100 and 50 years); dotted line: the 40-year design life reported in one plant's general information sheet.

3.5. Comparison Across the Eight Plants

Figure 4 places every class-(ii) and class-(iii) shift against the class-(i) interval of the same plant. Two regularities hold in all eight plants. In the coal-fired plants, every accounting convention produces a shift no greater than 0.29 times the class-(i) interval half-width, whereas the database shift is 1.06 to 1.15 times that half-width. In the hydropower plants, the civil-works horizon shift is 1.5 to 2.8 times the interval half-width in every plant, and the reservoir boundary shift is about 1.0 to 1.5 times where applicable. The two generation types therefore sit at opposite ends of the same axis: in the coal-fired plants the factor is limited mainly by the precision of fuel data and by the database choice; in the hydropower plants mainly by conventions. This mirrored structure is established here for the eight case-study plants; it is a comparison of positions on a common axis, not a decomposition of total uncertainty into additive shares.

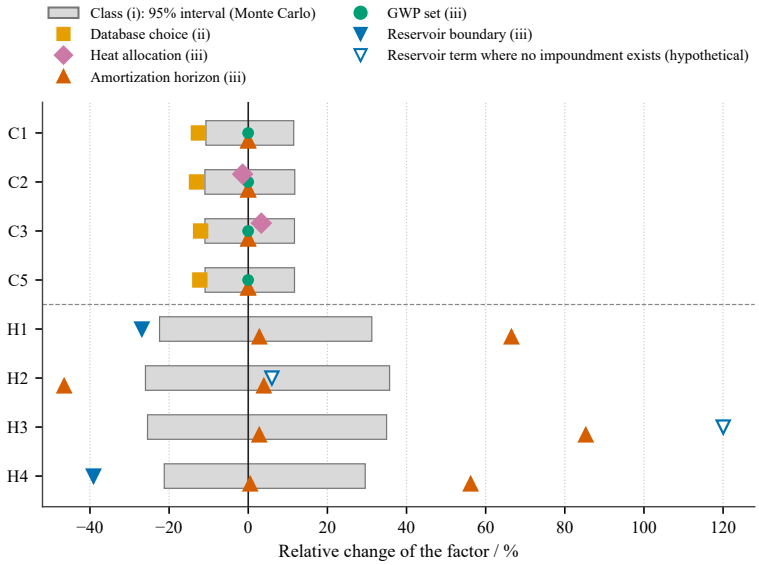


Figure 4. Class-(i) 95% interval (grey bar, Monte Carlo) and class-(ii) and class-(iii) scenario shifts (markers) for each modelled plant, on a common abscissa. Shifts are shown individually and are not additive. The hollow markers are the hypothetical reservoir case for the two plants without impoundment (Section 3.2). The horizontal dashed line separates the coal-fired and hydropower plants; the vertical dotted lines are gridlines.

4. Discussion

4.1. Differentiated Data Collection

For the coal-fired plants, coal input and carbon content explain almost all of the class-(i) variance. The mandatory parameters are therefore those of the fuel records: as-received elemental carbon content, net calorific value, coal input, oxidation rate, auxiliary power rate and heat supply. They come from assay records and production reports, are obtained by reading monthly meters and are held by the generation and chemistry departments. Construction data, the global warming potential set, and limestone consumption together change the factor by a fraction of a percentage point and deserve little survey time. The one item that measurement cannot settle is the database choice, which should be fixed by the campaign before data collection starts.

For the hydropower plants, the mandatory items are the itemized bill of materials of civil works and of the pre-construction stage, the reservoir characteristics (flooded water surface, year of impoundment, downstream degassing), the documentary basis of the amortization horizon, a ten-year series of annual output, and the allocation basis of any multi-purpose project. They come from as-built accounts, construction plans and reservoir management records held by the construction management unit and the reservoir dispatch office. Site selection for hydropower should therefore favour plants whose as-built documentation has been preserved, a criterion that does not arise for coal-fired plants.

4.2. Implications for Factor Publication

For coal-fired generation, a factor range by technology route can be published under the present conventions, with a measurement-driven 95% interval of about −11% to +12% for each plant of the sample, provided that the background database is declared: replacing the ecoinvent upstream coal factor by the localized value lowers the factor by 12% to 13%, so the database choice is a decision that shifts the published number materially [13,32,33,50].

For hydropower, a single point factor is not recommended until the reservoir boundary and the amortization convention have been unified. Until then, factors could be published as variants that state the boundary and the horizon, with reservoir emissions reported as a separate term. As a hypothesis for future testing, stratification by development mode and by the ratio of reservoir surface area to annual energy production may help explain between-plant variation. The present four hydropower cases do not establish suitable strata or validate a factor-publication rule based on that ratio. The proposal requires confirmation with a larger, representative sample, using plant configurations to which reservoir emissions apply and consistent boundary and amortization conventions. Four items require a decision at the standards level:

1. the plant configurations for which reservoir greenhouse gases must be declared, and how they are computed;
2. the amortization horizon of the construction stage;
3. the allocation rule for multi-purpose projects, for which service-based concepts exist [22,51];
4. the methane global warming potential, for which two values differing by nearly a factor of three coexist in the present batch.

None of these can be settled by collecting more plant data.

4.3. Relation to Published Work and to Hybrid Approaches

The magnitude and ordering of the coal-fired results are consistent with the life-cycle literature on Chinese coal-fired power [40,41] and with the comparative assessment of clean coal routes [38]. For hydropower, construction dominating at 57% to 99.6% matches reviews of hydropower life cycle assessment [23] and studies of small hydropower schemes [52].

Methodologically, the present design belongs to the family of hybrid approaches that treat parameter uncertainty probabilistically and normative choices as scenarios [9,15]. Such studies commonly propagate the parameter distribution separately under each scenario and report the scenarios side by side, as in comparative assessments where scenario choices can reverse a ranking that parameter uncertainty alone would not [16]. The present analysis follows this logic but differs in two respects. First, it attributes the variation to individual parameters of an audited workbook rather than to aggregate inventory flows, so each item can be traced to the department and document that would resolve it. Second, it compares each scenario with the probabilistic interval through the ratio R_s instead of merging both into one distribution, which keeps visible whether a given item can be resolved by measurement. Work on electricity emission factors that propagate fuel-factor uncertainty [53] and grid-level life-cycle modelling [54] addresses the size of the interval; the present analysis addresses its composition. Because green certificate and carbon market designs increasingly use regional factors for settlement [55], a factor whose dominant variation is convention-driven will not become more reliable as metering improves.

4.4. Limitations

First, this is a case study of eight plants in one province and one accounting year. The sample covers the technology routes and development modes present in the province but was not drawn to be representative, so the results describe these plants and cannot be generalized to the coal-fired or hydropower sector without confirmation on a larger and representative sample. C4 is not modelled.

Second, the class-(i) parameters are treated as independent and uniformly distributed. Coal input, carbon content and calorific value are physically correlated, and the domains for hydrological variability and bill-of-materials completeness ($\pm$20%) have not been calibrated against plant records. Calibrated or correlated distributions would change the width of the class-(i) intervals and the total-order Sobol' indices. The numerical stability checks assess sampling error under the adopted assumptions; they do not validate those assumptions. Holding the civil-works scenarios fixed, an interval half-width of 1.5 to 2.8 times the present value would make the corresponding scale ratios no greater than one; this comparison does not establish robustness to all alternative input distributions.

Third, the conventions are enumerated at the values that occur in the batch or in current practice; other values are possible, and the shifts should be read as illustrations of the effect of each convention rather than as bounds. The multi-purpose allocation of hydropower is not enumerated because no allocation basis is documented.

Fourth, the models reproduce the workbooks as they stand, including the double counting of coal transport in C1 and the unattributed terms of 0.4% to 0.8% in the coal-fired plants. Correcting these would change the factors by less than 1% and would not affect the classification.

Finally, whether other infrastructure-intensive technologies, such as wind and photovoltaic generation, show a sensitivity structure similar to that of hydropower is a question for future research; the corresponding analyses are in progress.

5. Conclusions

For the eight case-study plants analysed here, and under the adopted class-(i) distribution, independence and domain assumptions, the following conclusions are drawn.

1. A plant accounting workbook can be rebuilt into a normalized parametric model that reproduces the original total, traces each term to workbook cells and can be published without disclosing absolute plant data. The rebuild also exposes inconsistencies in the source workbooks, two of which are reconciled here.

2. In the four coal-fired plants, the measurement-driven 95% interval is about −11% to +12%, and coal input and carbon content explain almost all of its variance. The choice of background database shifts the factor by 12% to 13%, comparable to that interval, whereas every accounting convention shifts it by less than 30% of the interval half-width. A low local sensitivity coefficient therefore does not imply a small model-choice effect.
3. In the four hydropower plants the measurement-driven interval is wider, but harmonizing the amortization horizon of civil works alone shifts the factor by 1.5 to 2.8 times its half-width, and removing the declared reservoir term shifts it by 1.0 to 1.5 times its half-width.
4. Within this sample the two generation types sit at opposite ends of the axis from measurement-reducible to convention-fixed uncertainty. Data collection should be differentiated accordingly; the background database should be declared with every coal-fired factor, and hydropower factors should be published only with an explicit boundary and amortization declaration until these conventions are unified. Whether this structure holds for larger samples and other technologies remains to be tested.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19225458/s1, File S1: Normalized parametric models of the eight modelled plants (shares of the baseline total and relative perturbation domains, JSON). File S2: Python 3.12.7 code, using NumPy 1.26.4, to reproduce Tables 2 and 3 and Figures 1 to 4 from File S1 and to check numerical stability with increased sample sizes and independent seeds. File S3: Per-plant baseline results and numerical stability results (JSON and CSV). The files contain no plant name and no absolute plant-level quantity.

Author Contributions: Conceptualization, H.Z. and H.L.; methodology, H.Z.; software, H.Z.; validation, F.L. and Y.W.; formal analysis, H.Z. and H.L.; investigation, L.C. and H.L.; resources, H.L.; data curation, L.C., W.T., and H.L.; writing—original draft preparation, H.Z. and H.L.; writing—review and editing, F.L., Y.W., and H.L.; visualization, H.Z.; supervision, H.L.; project administration, W.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Science and Technology Project of State Grid Corporation of China (521999250044-633-RC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article and in the Supplementary Materials. The normalized parametric models, the code and the per-plant results required to reproduce every table and figure are provided as Files S1–S3. Restrictions apply to the availability of the underlying plant-level accounting workbooks: these were obtained from the operators of the eight modelled plants and contain commercially confidential production data (fuel assay records, generation and heat supply quantities, reservoir characteristics). They are available from the corresponding author on reasonable request and with the permission of the data owners.

Conflicts of Interest: The authors are employed by State Grid Sichuan Electric Power Research Institute. This study received funding from State Grid Corporation of China. The authors declare no conflicts of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CFB	Circulating fluidized bed
CLCD	Chinese Life Cycle Database
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
OAT	One-at-a-time
PCF	Product carbon footprint
USC	Ultra-supercritical

Appendix A. Nomenclature

Table A1. Symbols used in Equations (1)–(6).

Symbol	Meaning	Class/Unit
EF	Carbon footprint factor of the plant	$kgCO_2e/(kW{\cdot}h)$
E, W	Annual total emissions; electricity delivered to the grid	$kgCO_2e/a$; kW·h/a
α	Allocation coefficient (heat, or non-power functions)	(iii);–
G, r	Gross generation; auxiliary power rate	–; (i)
W_0, g	Normal-year output; wet/dry-year coefficient	–; (i)
M	Annual coal input	(i); kg/a
f	Upstream factor of coal mining and washing	(ii); $kgCO_2e/kg$
ω	Ratio of molecular weights of CO_2 and C (44/12)	constant
C, η	As-received carbon content; carbon oxidation rate	(i);–
Q	Annual heat input	TJ/a
e_i, γ_i	Energy-specific emission factor and GWP of non-CO_2 gas i	–; (iii)
E_t, E_s	Coal transport; flue-gas treatment (limestone)	(i); $kgCO_2e/a$
B, N	One-off construction emissions; amortization horizon	–; (iii)
E_x	Items not linked to a parameter (kept constant)	$kgCO_2e/a$
C_p, C_c, C_e	One-off emissions of pre-construction, civil works, equipment	$kgCO_2e$
λ	Completeness coefficient of the construction bill of materials	(i);–
N_c, N_e	Amortization horizons of civil works and of equipment	(iii); a
E_o	Operation and maintenance emissions, excluding reservoir	(i); $kgCO_2e/a$
δ, E_r	Reservoir boundary indicator; reservoir emissions	(iii); $kgCO_2e/a$
E_w	Solid-waste disposal emissions	$kgCO_2e/a$
S, $S_{T,j}$	Local sensitivity coefficient; total-order Sobol' index	–
h_{95}, R_s	Half-width of the class-(i) 95% interval; ratio of Equation (6)	percentage points;–

References

1. Bertolini, M.; Duttilo, P.; Lisi, F. Accounting carbon emissions from electricity generation: A review and comparison of emission factor-based methods. *Appl. Energy* **2025**, *392*, 125992. https://doi.org/10.1016/j.apenergy.2025.125992.
2. Garcia, R.; Freire, F. Carbon footprint of particleboard: A comparison between ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. *J. Clean. Prod.* **2014**, *66*, 199–209. https://doi.org/10.1016/j.jclepro.2013.11.073.
3. Suer, J.; Traverso, M.; Ahrenhold, F. Carbon footprint of scenarios towards climate-neutral steel according to ISO 14067. *J. Clean. Prod.* **2021**, *318*, 128588. https://doi.org/10.1016/j.jclepro.2021.128588.
4. Wang, X.; Guo, L.; Xue, G.; Tan, J.; Niu, W.; Wu, Y. Toward low-carbon power systems: Reviewing life cycle carbon footprints of diverse generation pathways. *Energies* **2025**, *18*, 6413. https://doi.org/10.3390/en18246413.
5. Marchi, B.; Bertagna, E.; Zavanella, L.E. Life cycle assessment of power plants: A systematic review of environmental impacts across electricity generation technologies. *Sustainability* **2026**, *18*, 1994. https://doi.org/10.3390/su18041994.
6. Lloyd, S.M.; Ries, R. Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: A survey of quantitative approaches. *J. Ind. Ecol.* **2007**, *11*, 161–179. https://doi.org/10.1162/jiec.2007.1136.
7. Igos, E.; Benetto, E.; Meyer, R.; Baustert, P.; Othoniel, B. How to treat uncertainties in life cycle assessment studies? *Int. J. Life Cycle Assess.* **2019**, *24*, 794–807. https://doi.org/10.1007/s11367-018-1477-1.
8. Groen, E.A.; Heijungs, R.; Bokkers, E.A.M.; de Boer, I.J.M. Methods for uncertainty propagation in life cycle assessment. *Environ. Model. Softw.* **2014**, *62*, 316–325. https://doi.org/10.1016/j.envsoft.2014.10.006.

9. Huijbregts, M.A.J. Application of uncertainty and variability in LCA. Part I: A general framework for the analysis of uncertainty and variability in life cycle assessment. *Int. J. Life Cycle Assess.* **1998**, *3*, 273–280. https://doi.org/10.1007/BF02979835.
10. Ciroth, A.; Muller, S.; Weidema, B.; Lesage, P. Empirically based uncertainty factors for the pedigree matrix in ecoinvent. *Int. J. Life Cycle Assess.* **2016**, *21*, 1338–1348. https://doi.org/10.1007/s11367-013-0670-5.
11. Saltelli, A.; Aleksankina, K.; Becker, W.; Fennell, P.; Ferretti, F.; Holst, N.; Li, S.; Wu, Q. Why so many published sensitivity analyses are false: A systematic review of sensitivity analysis practices. *Environ. Model. Softw.* **2019**, *114*, 29–39. https://doi.org/10.1016/j.envsoft.2019.01.012.
12. Groen, E.A.; Bokkers, E.A.M.; Heijungs, R.; de Boer, I.J.M. Methods for global sensitivity analysis in life cycle assessment. *Int. J. Life Cycle Assess.* **2017**, *22*, 1125–1137. https://doi.org/10.1007/s11367-016-1217-3.
13. Kim, A.; Mutel, C.L.; Froemelt, A.; Hellweg, S. Global sensitivity analysis of background life cycle inventories. *Environ. Sci. Technol.* **2022**, *56*, 5874–5885. https://doi.org/10.1021/acs.est.1c07438.
14. Jaxa-Rozen, M.; Pratiwi, A.S.; Trutnevyte, E. Variance-based global sensitivity analysis and beyond in life cycle assessment: An application to geothermal heating networks. *Int. J. Life Cycle Assess.* **2021**, *26*, 1008–1026. https://doi.org/10.1007/s11367-021-01921-1.
15. Huijbregts, M.A.J.; Gilijamse, W.; Ragas, A.M.J.; Reijnders, L. Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling. *Environ. Sci. Technol.* **2003**, *37*, 2600–2608. https://doi.org/10.1021/es020971+.
16. Mendoza Beltran, A.; Prado, V.; Font Vivanco, D.; Henriksson, P.J.G.; Guinée, J.B.; Heijungs, R. Quantified uncertainties in comparative life cycle assessment: What can be concluded? *Environ. Sci. Technol.* **2018**, *52*, 2152–2161. https://doi.org/10.1021/acs.est.7b06365.
17. Ghezzi, D.; Rocco, M.V. Parametric life cycle assessment of carbon footprint of electricity generation from floating offshore wind farms. *Sustain. Energy Technol. Assess.* **2026**, *90*, 105063. https://doi.org/10.1016/j.seta.2026.105063.
18. Aktas, C.B.; Bilec, M.M. Impact of lifetime on US residential building LCA results. *Int. J. Life Cycle Assess.* **2012**, *17*, 337–349. https://doi.org/10.1007/s11367-011-0363-x.
19. Tokede, O.; Rouwette, R. Problematic consequences of the inclusion of capital goods inventory data in environmental product declarations. *Int. J. Life Cycle Assess.* **2024**, *29*, 1–24. https://doi.org/10.1007/s11367-023-02231-4.
20. Brogaard, L.K.; Christensen, T.H. Life cycle assessment of capital goods in waste management systems. *Waste Manag.* **2016**, *56*, 561–574. https://doi.org/10.1016/j.wasman.2016.07.037.
21. Uihlein, A. Life cycle assessment of ocean energy technologies. *Int. J. Life Cycle Assess.* **2016**, *21*, 1425–1437. https://doi.org/10.1007/s11367-016-1120-y.
22. Prairie, Y.T.; Mercier-Blais, S.; Harrison, J.A.; Soued, C.; del Giorgio, P.; Harby, A.; Alm, J.; Chanudet, V.; Nahas, R. A new modelling framework to assess biogenic GHG emissions from reservoirs: The G-res tool. *Environ. Model. Softw.* **2021**, *143*, 105117. https://doi.org/10.1016/j.envsoft.2021.105117.
23. Gemechu, E.; Kumar, A. A review of how life cycle assessment has been used to assess the environmental impacts of hydropower energy. *Renew. Sustain. Energy Rev.* **2022**, *167*, 112684. https://doi.org/10.1016/j.rser.2022.112684.
24. *T/CEC 1048-2024*; Greenhouse Gases—Product Carbon Footprint—Quantification Methods and Requirements—Coal-Fired Power Generation. China Electricity Council: Beijing, China, 2024.
25. *T/CEC 1050-2024*; Greenhouse Gases—Product Carbon Footprint—Quantification Methods and Requirements—Hydropower Generation. China Electricity Council: Beijing, China, 2024.
26. *GB/T 47657-2026*; Greenhouse Gases—Product Carbon Footprint—Quantification Methods and Requirements—Coal-Fired Power Generation. Standardization Administration of China: Beijing, China, 2026.
27. *GB/T 47660-2026*; Greenhouse Gases—Product Carbon Footprint—Quantification Methods and Requirements—Hydropower Generation. Standardization Administration of China: Beijing, China, 2026.
28. *ISO 14067:2018*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. International Organization for Standardization: Geneva, Switzerland, 2018.
29. Li, T.; Zhang, H.; Liu, Z.; Ke, Q.; Alting, L. A system boundary identification method for life cycle assessment. *Int. J. Life Cycle Assess.* **2014**, *19*, 646–660. https://doi.org/10.1007/s11367-013-0654-5.
30. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Chapter 7: Wetlands; IPCC: Geneva, Switzerland, 2019; Volume 4.
31. IPCC. The Earth's energy budget, climate feedbacks and climate sensitivity. In *Climate Change 2021: The Physical Science Basis*; Chapter 7; Cambridge University Press: Cambridge, UK, 2021.
32. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

33. Sichuan University; IKE Environmental Technology Co., Ltd. *Chinese Life Cycle Database (CLCD)*; Sichuan University and IKE Environmental Technology: Chengdu, China, n.d. Available online: https://ghgprotocol.org/Third-Party-Databases/CLCD (accessed on 21 August 2026).
34. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy*; IGES: Hayama, Japan, 2006.
35. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. *Global Sensitivity Analysis: The Primer*; Wiley: Chichester, UK, 2008. https://doi.org/10.1002/9780470725184.
36. Saltelli, A.; Annoni, P.; Azzini, I.; Campolongo, F.; Ratto, M.; Tarantola, S. Variance based sensitivity analysis of model output. Design and estimator for the total sensitivity index. *Comput. Phys. Commun.* **2010**, *181*, 259–270. https://doi.org/10.1016/j.cpc.2009.09.018.
37. Jansen, M.J.W. Analysis of variance designs for model output. *Comput. Phys. Commun.* **1999**, *117*, 35–43. https://doi.org/10.1016/S0010-4655(98)00154-4.
38. Wu, H.; Fang, W.; Zhang, L.; Ye, Y.; Yang, L.; Dong, Z. Comparative life cycle assessment of four clean coal power generation technologies in Anhui province, China. *Int. J. Life Cycle Assess.* **2025**, *30*, 3072–3086. https://doi.org/10.1007/s11367-025-02544-6.
39. Tereshchenko, T.; Nord, N. Uncertainty of the allocation factors of heat and electricity production of combined cycle power plant. *Appl. Therm. Eng.* **2015**, *76*, 410–422. https://doi.org/10.1016/j.applthermaleng.2014.11.019.
40. Wang, N.; Ren, Y.; Zhu, T.; Meng, F.; Wen, Z.; Liu, G. Life cycle carbon emission modelling of coal-fired power: Chinese case. *Energy* **2018**, *162*, 841–852. https://doi.org/10.1016/j.energy.2018.08.054.
41. Rasheed, R.; Javed, H.; Rizwan, A.; Sharif, F.; Yasar, A.; Tabinda, A.B.; Ahmad, S.R.; Wang, Y.; Su, Y. Life cycle assessment of a cleaner supercritical coal-fired power plant. *J. Clean. Prod.* **2021**, *279*, 123869. https://doi.org/10.1016/j.jclepro.2020.123869.
42. Cheng, Y.P.; Wang, L.; Zhang, X.L. Environmental impact of coal mine methane emissions and responding strategies in China. *Int. J. Greenh. Gas Control* **2011**, *5*, 157–166. https://doi.org/10.1016/j.ijggc.2010.07.007.
43. Deemer, B.R.; Harrison, J.A.; Li, S.; Beaulieu, J.J.; DelSontro, T.; Barros, N.; Bezerra-Neto, J.F.; Powers, S.M.; dos Santos, M.A.; Vonk, J.A. Greenhouse gas emissions from reservoir water surfaces: A new global synthesis. *BioScience* **2016**, *66*, 949–964. https://doi.org/10.1093/biosci/biw117.
44. Barros, N.; Cole, J.J.; Tranvik, L.J.; Prairie, Y.T.; Bastviken, D.; Huszar, V.L.M.; del Giorgio, P.; Roland, F. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nat. Geosci.* **2011**, *4*, 593–596. https://doi.org/10.1038/ngeo1211.
45. Wang, Z.; Chan, F.K.S.; Feng, M.; Johnson, M.F. Greenhouse gas emissions from hydropower reservoirs: Emission processes and management approaches. *Environ. Res. Lett.* **2024**, *19*, 073002. https://doi.org/10.1088/1748-9326/ad560c.
46. Shi, W.; Maavara, T.; Chen, Q.; Zhang, J.; Ni, J.; Tonina, D. Spatial patterns of diffusive greenhouse gas emissions from cascade hydropower reservoirs. *J. Hydrol.* **2023**, *619*, 129343. https://doi.org/10.1016/j.jhydrol.2023.129343.
47. Li, H.; Liu, Q.; Tang, X.; Ai, L.; Chen, H.; Xiong, J.; Pan, H. Uncovering the drivers of greenhouse gas emissions from hydropower reservoirs in China based on machine learning. *Water* **2026**, *18*, 1610. https://doi.org/10.3390/w18131610.
48. Wang, J.; Huo, J.; Zhang, S.; Teng, Y.; Li, L.; Han, T. Flexibility transformation decision-making evaluation of coal-fired thermal power units deep peak shaving in China. *Sustainability* **2021**, *13*, 1882. https://doi.org/10.3390/su13041882.
49. Chen, H.; Chen, X.; Zhou, G.; Zheng, L.; Xu, M.; Yu, L.; Zhang, H. Carbon emission accounting method for coal-fired power units of different coal types under peak shaving conditions. *Energy* **2025**, *320*, 135314. https://doi.org/10.1016/j.energy.2025.135314.
50. Peng, S.; Pfister, S. Regionalizing the supply chain in process life cycle inventory with multiregional input–output data: An implementation for ecoinvent with EXIOBASE. *J. Ind. Ecol.* **2024**, *28*, 680–694. https://doi.org/10.1111/jiec.13491.
51. Branche, E. The multipurpose water uses of hydropower reservoir: The SHARE concept. *C. R. Phys.* **2017**, *18*, 469–478. https://doi.org/10.1016/j.crhy.2017.06.001.
52. Varun; Prakash, R.; Bhat, I.K. Life cycle greenhouse gas emissions estimation for small hydropower schemes in India. *Energy* **2012**, *44*, 498–508. https://doi.org/10.1016/j.energy.2012.05.052.
53. Lee, K.M.; Lee, M.H. Uncertainty of the electricity emission factor incorporating the uncertainty of the fuel emission factors. *Energies* **2021**, *14*, 5697. https://doi.org/10.3390/en14185697.
54. Zuffi, C.; Rossi, F.; Fiaschi, D.; Manfrida, G. Energy modeling and life cycle assessment of the Italian electricity grid and energy storage system: Comparison of current state and forecast to 2030. *Int. J. Life Cycle Assess.* **2025**, *30*, 1827–1843. https://doi.org/10.1007/s11367-025-02500-4.
55. Yan, S.; Wang, W.; Li, X.; Lv, H.; Fan, T.; Aikepaer, S. Stochastic optimal scheduling strategy of cross-regional carbon emissions trading and green certificate trading market based on Stackelberg game. *Renew. Energy* **2023**, *219*, 119268. https://doi.org/10.1016/j.renene.2023.119268.

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