Supplementary Material

Cryptocurrency Mining in European Electricity Systems: A Critical Review of Carbon Accounting, Operational Flexibility and Environmental Trade-Offs

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Supporting information for the review. Reference numbers match the main manuscript.

This document supplies the source inputs, accounting boundaries, calculation rules, selected-source appraisal and source-verification queries supporting the three research questions. Sections S1–S3 and S5 support the accounting comparison in RQ2; Section S4 documents the evidence appraisal used for RQ1 and RQ3. Section S6 gives the fixed-load procurement example for RQ2 and the assumed dispatch illustration informing RQ3. Sections S7 and S8 document evidence identification and the accompanying formula-based calculation workbook. The procurement and dispatch scenarios do not represent original facility measurements.

S1. Country-level inputs and geographic coverage

The principal frame uses AIB European residual mixes 2024, version 1.1 dated 11 August 2025: production factors from Table 5 and residual factors from Table 2 [18]. Published values are retained at two decimal places. Austria and the Netherlands have no numerical residual factor in the selected table; neither is assigned zero. The all-island Ireland domain includes Northern Ireland and is used only in the separate geographic sensitivity. Table S1 provides the resulting 24-country frame, excluded entries and ascending ranks.

Table S1. AIB 2024 factors, country contrasts and ranks.

Country/domain	Production	Residual	Difference	Ratio	Production rank	Residual rank
Austria (AT; excluded)	86.53	NA	NA	NA	—	—
Belgium (BE)	104.82	131.73	26.91	1.257	9	3
Bulgaria (BG)	310.74	379.53	68.79	1.221	18	10
Cyprus (CY)	586.55	613.08	26.53	1.045	23	22
Czechia (CZ)	529.13	584.07	54.94	1.104	22	20
Germany (DE)	311.58	724.56	412.98	2.325	19	23
Denmark (DK)	51.18	421.89	370.71	8.243	6	13
Estonia (EE)	364.28	611.96	247.68	1.680	21	21
Spain (ES)	100.66	292.20	191.54	2.903	8	6
Finland (FI)	33.20	405.59	372.39	12.217	3	12
France (FR)	18.07	23.52	5.45	1.302	2	1

Country/domain	Production	Residual	Difference	Ratio	Production rank	Residual rank
Greece (GR)	231.97	367.07	135.10	1.582	16	9
Croatia (HR)	224.38	573.17	348.79	2.554	15	19
Hungary (HU)	177.20	318.64	141.44	1.798	12	7
Ireland (all-island) (IE; sensitivity only)	245.57	365.61	120.04	1.489	—	—
Italy (IT)	235.24	441.20	205.96	1.876	17	15
Lithuania (LT)	118.76	567.91	449.15	4.782	10	18
Luxembourg (LU)	46.18	213.07	166.89	4.614	5	4
Latvia (LV)	145.65	504.22	358.57	3.462	11	17
Malta (MT)	345.33	398.45	53.12	1.154	20	11
Netherlands (NL; excluded)	228.58	NA	NA	NA	—	—
Poland (PL)	634.03	808.30	174.27	1.275	24	24
Portugal (PT)	43.30	501.76	458.46	11.588	4	16
Romania (RO)	216.47	233.02	16.55	1.076	14	5
Sweden (SE)	5.05	85.52	80.47	16.935	1	2
Slovenia (SI)	212.22	429.45	217.23	2.024	13	14
Slovakia (SK)	99.13	334.33	235.20	3.373	7	8

Note: Production, residual and difference are in g CO_2/kWh; the difference is residual minus production and the ratio is residual divided by production. Rank 1 is the lowest factor among the 24 included national domains. NA denotes no applicable numerical residual value in the selected AIB table, not zero emissions. Ranks are not assigned to excluded or sensitivity-only entries. The values are annual direct CO_2 descriptors, not marginal or full life-cycle factors [18].

The two columns have different accounting boundaries. A production factor represents domestic generation. The residual factor represents attributes remaining for untracked consumption after explicit tracking and attribute balancing. The comparison does not establish that either factor is freely selectable for a facility inventory. AIB national results become official disclosure values when adopted by the competent authority; actual procurement, national implementation and reporting year remain relevant [10,18].

S2. Calculation definitions

The principal 2024 statistics retain equal country weights. Calculations use the published two-decimal inputs without intermediate rounding; display rounding is applied only to the resulting values. Table S2 gives the definitions and native equations used in the secondary accounting benchmark. The consumption-weight comparison is defined in Section S5. No mining-capacity weighting, zero imputation or interpolation of missing country factors is applied.

Table S2. Definitions used in the secondary accounting analysis.

Quantity	Definition or implementation
Paired difference	$D_i=R_i-P_i$; g CO_2/kWh.
Paired ratio	$Q_i=\frac{R_i}{P_i}$; dimensionless. All included P_i are positive.
Mean and population SD	$\overline{x}=\frac{1}{n}\sum_{i=1}^{n} x_i$; SD$=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i-\overline{x})^2}$. The denominator n describes the included frame. Here x_i is an included country value and $\overline{x}$ is its cross-country mean.
Quartiles	Type-7 linear interpolation: with sorted values and probability p, $h=1+(n-1)p$; interpolate between the surrounding order statistics. Here h is the fractional position in the ordered data and p is the quantile probability, distinct from the indexed electricity price p_t.

Quantity	Definition or implementation
Relative dispersion	$\mathrm{CV}=\frac{\mathrm{SD}}{\bar{x}}$; not an inventory uncertainty estimate. The abbreviation CV denotes the coefficient of variation.
Spearman correlation	Pearson correlation of the two ascending factor ranks. No tied values occur in the main frame. The Spearman coefficient is denoted by ρ.
Kendall's tau	$\tau=\frac{N_\mathrm{c}-N_\mathrm{d}}{N_\mathrm{pairs}}$, because no ties occur. Here N_c and N_d count concordant and discordant pairs, and $N_\mathrm{pairs}=\frac{n(n-1)}{2}$.
Pair inversion	$(P_i-P_j)(R_i-R_j)<0$; 68 of 276 distinct pairs in the main frame.
Facility illustration	$E=LH$ in MWh; $A=\frac{LHF}{1000}$ in tonnes CO_2. Load L is in MW, duration H in hours and factor F in g CO_2/kWh; E is electricity use and A is attributed direct emissions.
Operating-year convention	Calendar 2024 is a leap year: $366\times24=8784$ hours. A 1 MW facility uses 8784 MWh$=8.784$ GWh at full-year operation.
Time-resolved quantities	$E=\sum_t L_t\,\Delta t$; $K=\sum_t L_t\,p_t\Delta t$; $C=\sum_t L_t\,m_t\Delta t$. Index t denotes an interval, Δt its duration in hours, L_t load in MW, p_t price in EUR/MWh and m_t a marginal factor in tonnes CO_2/MWh. K is electricity cost in EUR and C the first-order emissions approximation in tonnes CO_2.
Small-change approximation	$\Delta C\approx\sum_t \Delta L_t m_t\Delta t$. The symbol Δ denotes a change: ΔL_t is a small load change and ΔC the approximated emissions change under fixed marginal factors.
Load-emissions covariance	$\overline{Lm}=\bar{L}\,\bar{m}+\mathrm{Cov}(L,m)$ for equal-duration intervals. The overbar denotes the arithmetic interval mean; $\mathrm{Cov}(L,m)$ is the population covariance over the same intervals.
Volume-intensity decomposition	$C_1-C_0=(E_1-E_0)I_0+E_1(I_1-I_0)$. Subscripts 0 and 1 identify baseline and alternative; I_0 and I_1 are load-weighted emission intensities. The identity holds with $C_0=E_0I_0$ and $C_1=E_1I_1$.

Note: Facility load is measured at the facility boundary, including its auxiliary consumption. Applying an additional auxiliary-load multiplier to the same quantity would count that consumption twice. Population standard deviations and type-7 quantiles describe the included frame. The direct CO_2 illustration does not include upstream impacts, non-CO_2 gases or hardware manufacture.

Table S2a provides worked checks for rank comparison and consumption weighting using the published 2024 inputs. The country factors and ranks are in Table S1; the matched annual consumption volumes are in Table S5.

Table S2a. Worked checks using the published 2024 inputs.

Calculation	Procedure and numerical check
Identification of a discordant pair	Sweden has a lower production factor than France (5.05 < 18.07 g CO_2/kWh) and a higher residual factor (85.52 > 23.52 g CO_2/kWh). This pair is discordant. Each distinct country pair is counted once.
Spearman rank correlation	For the 24 matched countries in Table S1, the sum of squared differences between the two ascending ranks is 760. With no tied ranks, multiply 760 by 6, divide by 24 times the difference between 24 squared and 1, and subtract the quotient from 1. This gives a Spearman correlation of 0.669565…, reported as 0.6696.
Consumption-weighted production mean	Using the 2024 factors and consumption volumes in Table S5, the sum of the 24 factor–consumption products is 454,240.3457 (g CO_2/kWh)·TWh. Dividing this sum by the total consumption of 2,344.24 TWh gives a weighted production mean of 193.768703… g CO_2/kWh, reported as 193.77 g CO_2/kWh.

S3. Numerical verification and sensitivity checks

Table S3 retains the numerical checks for the principal 2024 frame and its geographic, omission and input-rounding sensitivities. The additional 2025 factors and annual consumption weights are reported in Table S5.

Table S3. Arithmetic verification and sensitivity interpretation.

Check	Result
Main frame: sums of factors	5,145.12 (P); 9,964.24 (R); 4,819.12 (difference).
Main frame: direction and ratios	$24/24$ residual factors exceed production factors; $12/24$ ratios exceed 2; $4/24$ exceed 5.
Hungary: full-year direct CO_2	Production: 1,556.5248 t; residual: 2,798.93376 t; difference: 1,242.40896 t.
Hungary: relative accounting difference	$\left(\frac{318.64}{177.20}\text{-}1\right)\times100$=79.8194%. No operating characteristic changes.
Main frame pair check	$\frac{24\times23}{2}$=276 pairs; 68 discordant and 208 concordant; $\tau=\frac{208\text{-}68}{276}$=0.507246.
Geographic sensitivity pair check	With all-island IE: $\frac{25\times24}{2}$=300 pairs; 77 discordant; τ=0.486667.
Leave-one-country-out	Twenty-four separate 23-country recalculations. The resulting ranges for the 2024 frame are reported in the main manuscript; they are not sampling confidence intervals.
Input-rounding check	Allowing each displayed factor to differ by at most 0.005 g/kWh gives a maximum absolute change of 0.01 g/kWh in the mean paired difference.
Hungary ratio rounding limits	Lower: $\frac{318.64\text{-}0.005}{177.20+0.005}$=1.798115; upper: $\frac{318.64+0.005}{177.20\text{-}0.005}$=1.798273.

Note: Input-rounding limits describe reported numerical precision only. They do not quantify uncertainty in source inventories, contracts, unobserved facility operation or causal emissions models. Country omission ranges are descriptive selection checks, not sampling confidence intervals.

Verification compared all 24 countries' production factors, residual factors and consumption volumes in both years between the AIB spreadsheets and the printed document Tables 2, 4 and 5. All 144 cells agreed at the stated two-decimal precision. The Italian 2025 correction and Dutch exclusion were resolved from the authoritative residual table as specified in Section S5; inconsistent summary-sheet entries were not substituted.

S4. Six-criterion evidence-to-claim appraisal

The same six questions are documented for nine cases spanning inventories, prospective scenarios, operational flexibility, heat recovery, methane, exposure, European electricity accounting and operator-reported implementation. The cases are retained for direct relevance to the research questions and complementary claim types, methods and access conditions. The five cases in the manuscript's Table 10 form a presentation subset of this matrix, rather than a separate sample. This selection demonstrates how claims are bounded; it is not a representative sample of studies or a numerical validation of the framework. Table S4a and S4b record:

C1, what is measured or modelled;

C2, period and geography;

C3, physical and accounting boundaries;

C4, counterfactual or comparison;

C5, conditioning assumptions and reported validation or uncertainty; and

C6, European transfer and the permissible claim.

Access codes describe the material inspected for the cited publication: PA = original publisher or author-institution abstract and bibliographic record; FT = full text of the published study; IR = substantive official institutional material; OR = an operator's public account. Cambridge is assessed from the substantive official report summary. Abstract-only details remain unassessed. These are access categories, not quality scores.

The appraisal separates access from methodological credibility. Design, input provenance and coverage are evaluated through C1–C3, the comparison through C4, reported validation and uncertainty through C5, and external validity through C6. Validation of an input or submodel does not validate the entire environmental claim. Where a validation procedure or uncertainty assessment cannot be checked in the inspected material, it remains unassessed rather than presumed adequate or absent. The published studies [23,50,53,54] provide the methodological basis for the C5 entries on validation and uncertainty. In Menati et al. [50], recorded load associations and simulated system effects are treated as separate evidence types.

Table S4a. Selected-source appraisal: quantities, coverage and boundaries.

Case and access	C1: quantity/design	C2: period/geography	C3: boundary
Köhler and Pizzol (2019) [20]; PA	Estimates Bitcoin electricity use and life-cycle greenhouse-gas emissions.	Global network, 2018.	Electricity and mining-equipment life cycle; detailed inventory cannot be rechecked from the inspected abstract.
Cambridge Centre for Alternative Finance (2025) [38]; IR	Operator-reported electricity, energy sourcing and curtailment, with extrapolated network indicators.	2025 report; 49 firms operating in 23 countries; includes 2023 curtailment. The official summary identifies a US-heavy sample.	Surveyed operators and modelled network coverage; self-reported activity differs from independently metered system effects.
Jiang et al. (2021) [37]; FT	Models Bitcoin energy demand, emissions and economic dynamics under policy scenarios.	China; model horizon 2014–2030, published in 2021.	China's mining electricity and associated operational emissions under regional coal/hydropower assumptions.
Menati et al. (2023) [50]; FT	Reports associations between recorded flexible load, prices and system demand, and separately simulates grid, price and emissions effects.	Texas; SCADA records January 2021–December 2022; synthetic 2,000-bus grid with 2020 zonal profiles.	Power-system operational effects of added loads, separated from observed load associations.
Chen and You (2025) [53]; FT	Models greenhouse energy use and operating economics under alternative controls; no physical experiment is reported.	Eight cities, including Berlin, Stockholm and Reykjavik; seasonal 60-day periods in 2021 at 15-minute resolution.	Greenhouse thermal control, mining heat and auxiliaries; not a measured life-cycle emissions balance.
Rudd et al. (2024) [54]; FT	Models the economics of landfill-gas electricity supplied to mining; this is not measured methane abatement.	North-American cost setting; annual 10 GWh electricity scenario and 2024 equipment assumptions.	Landfill-gas generation and mining economics; no complete measured methane and life-cycle emissions balance.
Guidi et al. (2025) [23]; FT	Estimates electricity-related pollution and population exposure attributable to mining demand; clinical outcomes are not observed.	34 US mines; August 2022–July 2023.	Marginal power-plant emissions and modelled atmospheric transport/exposure, distinct from whole-life hardware effects.
Tranberg et al. (2019) [9]; FT	Estimates consumption-based electricity intensity by tracing generation and cross-border flows.	28 European areas in 2017 at hourly resolution; Danish areas combined for country-level results.	Physical-flow attribution using technology operation factors, including the relevant upstream fuel-chain components; not residual certificate accounting.

Case and access	C1: quantity/design	C2: period/geography	C3: boundary
MARA Finland district-heating pilot (2024) [56]; OR	Operator describes a 2 MW mining installation integrated with district heating; this is not an independent performance measurement.	Satakunta, Finland; operator report dated 20 June 2024.	Mining-facility and district-heating connection; quantified whole-system emissions balance not established.

Table S4a separates measured inputs, operator statements and model outputs. In particular, observed flexible-load records do not make a simulated grid effect an observed emissions outcome. The following table applies the remaining three questions to the same cases in the same order.

Table S4b. Selected-source appraisal: comparisons, assumptions and transfer.

Case and access	C4: comparison	C5: assumptions, validation and uncertainty	C6: supported claim/transfer
Köhler and Pizzol (2019) [20]; PA	Descriptive inventory; an avoided-emissions counterfactual is not required for this claim and was not assessed from the abstract.	Miner geography and equipment efficiency are identified as major drivers; detailed sensitivities remain unassessed here.	Life-cycle boundary is relevant to Europe; numerical results cannot identify a current European facility's footprint or mitigation effect.
Cambridge Centre for Alternative Finance (2025) [38]; IR	Reported curtailment is an operational quantity, without a no-mining emissions counterfactual established by the inspected summary.	Participation, geographic coverage, equipment assumptions and extrapolation affect representativeness.	Useful evidence of reported industrial practice; does not establish Europe-wide uptake or an avoided-emissions coefficient.
Jiang et al. (2021) [37]; FT	Benchmark policy compared with market-access, site-regulation and carbon-tax scenarios.	Mining geography, electricity mix, equipment, network growth, prices and profit feedbacks condition projections.	Scenario logic is informative; projected levels and policy rankings are not European observations or transferable coefficients.
Menati et al. (2023) [50]; FT	System without mining versus mining with no flexibility, price response or command-following control.	Load location and capacity, grid representation, generation profiles, binary switching and price threshold determine outcomes. Observed correlations do not identify whether mandatory demand response or voluntary price response caused load changes.	Counterfactual design and load-response mechanisms transfer; European tariffs, qualification, network constraints and marginal responses require local validation.
Chen and You (2025) [53]; FT	Predictive versus on/off control; gas-heated greenhouse without mining used for financial comparison.	Thermal representation, weather, heat demand, equipment and economic inputs condition results. The simulation uses literature-based parameters; no physical experiment is reported, and prototype validation is identified as future work.	European climates are represented in the model; claimed avoided emissions still need delivered-heat data, the displaced heat source and auxiliary electricity.

Case and access	C4: comparison	C5: assumptions, validation and uncertainty	C6: supported claim/transfer
Rudd et al. (2024) [54]; FT	Existing flaring and other energy uses are discussed; the financial model does not establish a site-specific no-mining gas-treatment baseline.	Gas recovery and conversion, generation costs, mining equipment and revenues, and the existing use of landfill gas condition the claim. Monte Carlo sampling and alternative cost/hashprice scenarios examine financial uncertainty; these results do not establish a measured site-specific methane balance.	European assessment needs the actual gas-treatment baseline, leakage and methane slip, legal obligations and local economics.
Guidi et al. (2025) [23]; FT	Power-plant response attributable to the specified mining demand; model-based marginal comparison.	Estimated mine demand, plant response, pollutant factors, atmospheric model and population distribution affect estimates. The study reports prior InMAP validation and alternative plant-response/uptime analyses; proprietary WattTime inputs limit full independent reproduction.	The causal chain is relevant; European plant dispatch, meteorology and population data are required for regional magnitudes.
Tranberg et al. (2019) [9]; FT	Production versus flow-traced consumption accounting; this is not an intervention-based marginal-emissions counterfactual.	Proportional sharing, geographic aggregation, data availability and technology operation factors condition the account.	Directly relevant European method; 2017 values do not represent 2024–2025, and average-flow attribution cannot establish load-induced dispatch change.
MARA Finland district-heating pilot (2024) [56]; OR	Actual displaced heat and no-project provision must be established before assigning an emissions credit.	Delivered useful heat, temperature, seasonality, auxiliary electricity and operating availability need supporting records.	Documents a European implementation; does not establish measured net greenhouse-gas savings.

Note: A descriptive inventory does not require an avoided-emissions counterfactual to support its descriptive claim. "Not established" or "unassessed" identifies the limit of the inspected evidence; neither means zero environmental effect. FT does not mean independent replication. The MARA case supports the existence of an operator-reported European installation, without establishing measured net greenhouse-gas savings [56].

The worked appraisal supports different conclusions for different claims: source-specific inventories and reported implementation can be retained with their boundaries, while stronger mitigation claims require a suitable comparison and additional observations. No pooled effect size, study-prevalence rate, inter-rater agreement statistic or composite quality score is calculated.

S5. Matched annual inputs and consumption-weight sensitivity

Table S5 supplies the same 24 national domains for 2024 and 2025. The 2024 source is version 1.1 dated 11 August 2025 [18]; the 2025 source is version 1.0 dated 26 May 2026 [19]. Production and residual factors come from Tables 5 and 2, respectively. Total electricity consumption comes from Table 4's total supplier-

mix volume. The paired annual comparison evaluates whether the direction and magnitude of the accounting contrasts recur in the subsequent available year.

The AIB 2024 dataset is identified by the downloaded report's internal version 1.1, although its landing-page link was labelled version 2.0. The 2024 authoritative residual table gives the Netherlands as NA, despite a numerical Dutch residual entry in a separate spreadsheet summary. For 2025, Table 2 footnote 6 expressly identifies corrected Italian values as authoritative: residual factor 420.20 g CO_2/kWh and untracked consumption 60.65%. The older Italian residual entry of 427.78 in the separate CO_2 summary sheet is not used. AIB states that this Italian correction does not affect the other countries [18,19].

Within each year, a country's weight equals its published total-consumption volume divided by the sum across the 24 countries. The weighted mean is the sum of each country's factor multiplied by that weight. Identical within-year weights are applied to production, residual and paired-difference values. Calculations retain the published two-decimal TWh volumes and do not round intermediate products. The ratio of weighted means is calculated after aggregation; it is not the weighted mean of country ratios. The consumption sums are 2,344.24 TWh in 2024 and 2,360.71 TWh in 2025; weights change with the corresponding year's consumption.

Table S5. Matched country factors and annual total-consumption weights.

Country	Year	Production (g CO_2/kWh)	Residual (g CO_2/kWh)	Total consumption (TWh)	Difference (g CO_2/kWh)
Belgium (BE)	2024	104.82	131.73	77.76	26.91
Belgium (BE)	2025	121.86	171.01	77.96	49.15
Bulgaria (BG)	2024	310.74	379.53	33.59	68.79
Bulgaria (BG)	2025	330.95	371.81	34.47	40.86
Cyprus (CY)	2024	586.55	613.08	5.24	26.53
Cyprus (CY)	2025	476.26	503.63	5.64	27.37
Czechia (CZ)	2024	529.13	584.07	60.21	54.94
Czechia (CZ)	2025	510.29	589.81	61.36	79.52
Germany (DE)	2024	311.58	724.56	453.02	412.98
Germany (DE)	2025	304.94	701.47	450.87	396.53
Denmark (DK)	2024	51.18	421.89	38.44	370.71
Denmark (DK)	2025	41.79	448.90	38.52	407.11
Estonia (EE)	2024	364.28	611.96	8.26	247.68
Estonia (EE)	2025	317.30	467.35	8.33	150.05
Spain (ES)	2024	100.66	292.20	247.84	191.54
Spain (ES)	2025	105.99	238.28	255.65	132.29
Finland (FI)	2024	33.20	405.59	82.74	372.39
Finland (FI)	2025	24.19	352.45	84.62	328.26
France (FR)	2024	18.07	23.52	449.20	5.45
France (FR)	2025	13.70	17.11	451.20	3.41
Greece (GR)	2024	231.97	367.07	56.56	135.10
Greece (GR)	2025	225.11	365.20	55.76	140.09
Croatia (HR)	2024	224.38	573.17	16.78	348.79
Croatia (HR)	2025	137.35	432.40	18.87	295.05
Hungary (HU)	2024	177.20	318.64	46.43	141.44
Hungary (HU)	2025	140.86	453.50	46.63	312.64
Italy (IT)	2024	235.24	441.20	310.83	205.96
Italy (IT)	2025	225.04	420.20	309.00	195.16
Lithuania (LT)	2024	118.76	567.91	10.37	449.15

Country	Year	Production (g CO_2/kWh)	Residual (g CO_2/kWh)	Total consumption (TWh)	Difference (g CO_2/kWh)
Lithuania (LT)	2025	135.86	550.26	10.38	414.40
Luxembourg (LU)	2024	46.18	213.07	5.13	166.89
Luxembourg (LU)	2025	44.89	422.28	6.53	377.39
Latvia (LV)	2024	145.65	504.22	6.98	358.57
Latvia (LV)	2025	145.53	371.51	7.20	225.98
Malta (MT)	2024	345.33	398.45	3.10	53.12
Malta (MT)	2025	397.85	427.67	3.21	29.82
Poland (PL)	2024	634.03	808.30	154.20	174.27
Poland (PL)	2025	605.72	726.96	159.51	121.24
Portugal (PT)	2024	43.30	501.76	51.40	458.46
Portugal (PT)	2025	75.19	392.86	54.32	317.67
Romania (RO)	2024	216.47	233.02	50.74	16.55
Romania (RO)	2025	220.41	245.02	50.40	24.61
Sweden (SE)	2024	5.05	85.52	136.29	80.47
Sweden (SE)	2025	4.89	208.56	134.11	203.67
Slovenia (SI)	2024	212.22	429.45	12.80	217.23
Slovenia (SI)	2025	157.83	634.45	12.73	476.62
Slovakia (SK)	2024	99.13	334.33	26.33	235.20
Slovakia (SK)	2025	87.04	350.70	23.44	263.66

Note: The difference is residual minus production. Total supplier-mix volume equals national total electricity consumption within AIB's disclosure boundary; its attribute composition is not a flow-traced physical consumption mix. AIB counts transmission and distribution losses as consumption, so these volumes are not labelled final end-use demand [18,24]. They are not estimates of mining demand. Table 2/Table 4/Table 5 locations are pp. 7–8/18–19/22–23 in the 2024 report and pp. 7–8/17–18/21–22 in the 2025 report.

Equal-country production and residual means are 214.38 and 415.18 g CO_2/kWh in 2024, and 202.12 and 410.97 in 2025. Consumption-weighted means are 193.77 and 388.05 in 2024, and 187.98 and 375.75 in 2025; the corresponding weighted differences are 194.28 and 187.77. Ratios of weighted means are 2.003 and 1.999, whereas weighted means of country ratios are 3.446 and 4.854. These are different estimands. The equal-country median ratios are 1.950 and 2.274; there are 68 and 79 discordant pairs out of 276.

The weighting tests whether greater emphasis on larger electricity markets alters the same country contrast. It does not estimate a physical EU consumption factor or the aggregate residual factor of untracked electricity. The latter requires untracked-volume weights; a production aggregate requires generation volumes. A physical consumption inventory also needs an appropriate treatment of electricity exchanges. National implementation must be checked before applying a harmonized AIB descriptor to a particular facility [9,10,18].

Both vintages use the shifted issuing-based approach, with calendar-year physical production and GO transactions from 1 April of that year to 31 March of the next. National data, Ecoinvent inputs and attribute activity can change between releases. The comparison does not isolate physical generation changes, certificate-market changes or source-factor revisions. Two annual observations per country support a recurrence check, not a long-run trend or a causal policy estimate [18,19].

S6. Complete inputs and outputs for the illustrative scenarios

The two examples answer separate questions. Table S6a varies procurement coverage at fixed annual electricity use. Tables S6b–S6d vary a four-hour load schedule under explicitly assumed prices and marginal factors. None of these

inputs describes an observed European facility. The annual procurement example uses published AIB factors; all hourly prices, marginal factors and loads in the dispatch example are assumed.

Procurement inputs are a 1 MW facility-metered load, 8,784 operating hours in leap year 2024 and electricity use of 8,784 MWh. Hungary's production-context descriptor is 177.20 g CO_2/kWh and its residual descriptor is 318.64 g CO_2/kWh. With eligible covered fraction f and an assumed wind/solar direct factor of zero, conditional market-based attributed direct CO_2 is 8,784 × (1 − f) × 318.64 / 1,000 tonnes. All national factors, physical electricity use and the operating schedule are held fixed [10,18].

Table S6a. Fixed-load procurement assumptions and conditional direct CO_2 attribution.

Arrangement	Coverage (%)	Covered (MWh)	Uncovered (MWh)	Reporting factor (g CO_2/kWh)	Attributed direct CO_2 (t)
No eligible attribute coverage	0	0.00	8,784.00	318.64	2,798.93376
50% eligible wind/solar coverage	50	4,392.00	4,392.00	159.32	1,399.46688
100% eligible unbundled wind/solar GOs	100	8,784.00	0.00	0.00	0.00000
100% PPA with eligible wind/solar attributes retained	100	8,784.00	0.00	0.00	0.00000

Note: Attributes are assumed to meet the applicable market, reporting-period, exclusive-claim and cancellation conditions. A PPA qualifies only when its relevant attributes are retained. Uncovered electricity uses the residual factor only when it is the applicable fallback after qualifying instruments and supplier information [10]. The constant production-context total is 1,556.52480 t CO_2; it is not asserted to be the facility's valid location-based inventory. Physical avoided emissions are not established in any row. Zero attributed direct CO_2 does not mean zero life-cycle impact or demonstrated additional generation.

The dispatch example has four one-hour intervals and a facility limit of 1 MW. The uniform, price-led and emissions-led schedules each consume 2 MWh; the reduced-volume schedule consumes 1 MWh by design. Uniform half-load operation may be interpreted as half of identical modules operating. Equal electricity use is not assumed to imply equal mining rewards or revenue. Table S6b records every interval input.

Table S6b. Assumed hourly prices, marginal factors and facility load schedules.

Hour	Price (EUR/MWh)	Marginal factor (t CO_2/MWh)	Uniform (MW)	Price-led (MW)	Emissions-led (MW)	Reduced volume (MW)
1	20.00	0.80	0.50	1.00	0.00	1.00
2	40.00	0.60	0.50	1.00	0.00	0.00
3	60.00	0.10	0.50	0.00	1.00	0.00
4	80.00	0.30	0.50	0.00	1.00	0.00

For each schedule, electricity use is the sum of hourly load multiplied by the one-hour duration. Cost is the sum of load × price × duration. The first-order emissions approximation is the sum of load × marginal factor × duration. Dividing cost or the emissions approximation by electricity use gives the corresponding load-weighted price or marginal intensity. Table S6c reports these results.

Table S6c. Derived cost, electricity and first-order emissions results.

Schedule	Electricity (MWh)	Cost (EUR)	First-order CO_2 (t)	Load-weighted price (EUR/MWh)	Load-weighted marginal factor (t CO_2/MWh)
Uniform baseline	2.00	100.00	0.90	50.00	0.45

Schedule	Electricity (MWh)	Cost (EUR)	First-order CO_2 (t)	Load-weighted price (EUR/MWh)	Load-weighted marginal factor (t CO_2/MWh)
Price-led	2.00	60.00	1.40	30.00	0.70
Emissions-led	2.00	140.00	0.40	70.00	0.20
Reduced volume	1.00	20.00	0.80	20.00	0.80

The interval-average price is 50 EUR/MWh and the interval-average marginal factor is 0.45 t CO_2/MWh. Population covariance divides the sum of paired deviations from the respective four-interval means by four. Thus, covariance between load and price has units EUR/h, and covariance between load and the marginal factor has units t CO_2/h. Table S6d also reports the volume–intensity decomposition relative to uniform operation, using the ordering in Equation (9) of the manuscript: volume effect = (alternative electricity − baseline electricity) × baseline intensity; intensity effect = alternative electricity × (alternative intensity − baseline intensity).

Table S6d. Population covariances and decomposition relative to uniform operation.

Schedule	Cov(load, price) (EUR/h)	Cov(load, marginal factor) (t CO_2/h)	Volume effect (t)	Intensity effect (t)	Total difference (t)
Uniform baseline	0.00	0.0000	0.00	0.00	0.00
Price-led	-10.00	0.1250	0.00	0.50	0.50
Emissions-led	10.00	-0.1250	0.00	-0.50	-0.50
Reduced volume	-7.50	0.0875	-0.45	0.35	-0.10

Note: Marginal factors are fixed assumptions representing a small-load-change approximation to a common background system. No forecast error, switching delay, minimum operating duration, start-up energy, fixed tariff, tax or grid charge is represented. The example demonstrates a possible lower-cost/higher-emissions schedule and the separation of volume from timing; it does not estimate their prevalence, financial feasibility or size in Europe. For reduced volume, the −0.45 t volume component and +0.35 t intensity component sum to −0.10 t. Less total electricity can lower the emissions approximation even when its load-weighted intensity is higher.

S7. Literature identification and source verification

Evidence identification used targeted scholarly and institutional web searches, exact-title searches and backward citation tracing. The search themes combined Bitcoin or cryptocurrency mining with electricity use, carbon footprints, life-cycle assessment, demand response, ancillary services, waste heat, landfill methane, water, electronic waste and European electricity accounting. Sources were consulted up to 26 October 2026. No common lower publication-year limit was imposed, because foundational protocol and accounting sources remained relevant to the research questions.

Table S7 reports selected exact queries retained for the principal studies and institutional sources used in the review. These queries document source-verification routes; they do not form a complete record of every search, screened item or exclusion. The recorded terms, quotation marks and site restrictions are retained as executed. The presence of a year in a query does not indicate a uniform publication-date filter.

Search results were checked against original publisher platforms, author-institution repositories and official institutional sources. The bibliography cites the final published versions of research studies. Primary institutional reports, technical and accounting guidance, legal texts and identifiable operator disclosures were used for their corresponding evidential roles. Unpublished research

preprints were excluded. Where only an original publisher or author-institution abstract was accessible, methodological interpretation was restricted to information reported in that material; Table S4 identifies the access basis for each detailed appraisal case.

Inclusion required an identifiable cryptocurrency-electricity mechanism, an environmental or operational estimate, an accounting method, a disclosure requirement or a directly relevant implementation. Research on coupled energy and environmental systems was included where it clarified a stated assessment requirement; its numerical results were not transferred to mining without supporting evidence. Unrelated price prediction, general blockchain applications and promotional assertions without an identifiable evidential basis were outside scope. Operator accounts could establish reported implementation but did not independently establish environmental benefit.

The corpus is targeted and non-exhaustive. No prospectively registered protocol, independent duplicate screening, complete screening count or inter-rater statistic is available. The query record does not establish exhaustive coverage or the first-identification route of every source, and it is not used to reconstruct a complete study-selection flow. Observations, estimates, projections, mechanisms and reporting requirements remain separate in the synthesis; findings with incompatible years, geographies or inventory boundaries are not averaged.

Table S7. Selected exact queries used for source verification.

ID	Verification focus	Exact executed query
1	Coupled electricity–water dispatch study	"A progressive polyhedral approximation method for nonlinear PDE-constrained electricity-water nexus dispatch"
2	EU disclosure requirements	site.eur-lex.europa.eu "2025/422" "energy consumption" "estimates"
3	EU disclosure requirements	site.eur-lex.europa.eu "2025/422" "Article 3" "500 000"
4	ESMA implementation concerns	site.esma.europa.eu "sustainability" "miner" "location" crypto-assets
5	EU disclosure requirements	site.eur-lex.europa.eu "2025/422" "estimates" "data"
6	EU disclosure requirements	site.eur-lex.europa.eu/eli/reg_del/2025/422/oj "500"
7	EU disclosure requirements	site.eur-lex.europa.eu/eli/reg_del/2025/422/oj "Article 3"
8	ESMA technical standards	site.esma.europa.eu "sustainability" "second package" "final report" "2024"
9	Market-based disclosure	site.eur-lex.europa.eu/eli/reg_del/2025/422/oj "market-based"
10	Mining flexibility study	"High resolution modeling and analysis of cryptocurrency mining" full text
11	Ancillary-service study	"Optimization of cryptocurrency mining demand for ancillary services" 2024
12	Landfill-gas study	"An integrated landfill gas-to-energy and Bitcoin mining framework" full text
13	Greenhouse heat study	"Energy optimization of bitcoin mining integrated greenhouse with model predictive control"
14	European flow-tracing study	"Real-time carbon accounting method for the European electricity markets" pdf
15	Mining exposure study	"The environmental burden of the United States' bitcoin mining boom" PMC
16	Industry report access	"Cambridge digital mining industry report" filetype:pdf
17	Bitcoin life-cycle study	"Life cycle assessment of Bitcoin mining" full text 2019
18	European balancing rules	site.eur-lex.europa.eu "2017/2195" "aggregation of demand facilities"
19	Cross-border balancing	site.entsoe.eu "PICASSO" "cross-border capacity" "balancing"
20	ESMA technical standards	site.esma.europa.eu "1229" "sustainability indicators"
21	EU disclosure requirements	site.eur-lex.europa.eu/eli/reg_del/2025/422/oj/eng "Article 6" "annual"
22	EU disclosure requirements	site.eur-lex.europa.eu/eli/reg_del/2025/422/oj/eng "renewable" "energy sources"
23	Balancing qualification	site.eur-lex.europa.eu/eli/reg/2017/2195 "18" "prequalification"
24	Finnish reserve participation	site.fingrid.fi reserve markets prequalification consumption aggregation aFRR
25	European provider requirements	site.entsoe.eu electricity balancing guideline demand response qualification provider article 18

ID	Verification focus	Exact executed query
26	AIB years and consumption data	site.aib-net.org European Residual Mixes 2025 2024 2023 download consumption
27	Scope 2 accounting boundaries	site.ghgprotocol.org Scope 2 Guidance residual mix location based national production import exports
28	AIB 2025 release verification	site.aib-net.org "2025" "Residual" "2026" "download"
29	AIB report-table verification	site.aib-net.org "2024" "Residual" "Table 8"

Note: Entries count queries, not studies. Following retrieval, official pages, linked original reports and available full texts were inspected, with title and citation tracing where needed. Sources identified through direct links or bibliography tracing remain cited even when no separate query appears here. The table documents selected retrieval routes and does not establish the completeness of the evidence base.

S8. Calculation workbook and verification

The accompanying Calculation_workbook.xlsx supplies the country factors, consumption volumes and scenario inputs reported in Sections S1, S5 and S6 as machine-readable cells, together with formulas for the published calculations. The Inputs sheet identifies source versions, units, geographic exclusions and the corrected Italian 2025 residual factor. Country calculations and Results reproduce the descriptive statistics, factor ranks, correlations and consumption-weight comparisons. The research-question guide on Results maps the workbook to Sections 3–5 and Table 12 of the manuscript: it provides calculations for RQ2 and the assumed scheduling illustration for RQ3, while RQ1 remains a literature-synthesis question.

Country pairs counts every distinct country pair once in each year. Sensitivity contains the 2024 leave-one-country-out calculations and the separate all-island Ireland variant. Hungary scenarios and Dispatch example reproduce the fixed-load procurement cases and the assumed four-hour schedules. The formulas retain the published input precision and avoid intermediate rounding; display rounding does not change the underlying calculation.