

Certification, procurement and production

Nonlinear VCG and Muir: consolidated calibration

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Abstract

This alternative calibration reconstructs nonlinear Muir and whole-buyer VCG world economies for gold, cobalt, tantalum, tin and tungsten using a shared 2024 evidence bundle. Extraction and processing, disjoint bulk and retail routes, resale, retention, certificate claims and final physical output have separate accounts. Quadratic costs provide a matched supply-exponent-one comparison with the existing empirical extension. All 475 static states in the declared grid solve, and an independent review verifies global cell choices, payments, material balances and the bulk-only compatibility case. Observed production and benchmark prices set scales; unobserved buyer and technological primitives remain assumptions. The resulting comparisons distinguish shared conclusions, mechanism differences and source-dependent uncertainty. They are conditional numerical results, with no identified causal policy-effect confidence intervals or p-values.

1 Question, scope and interpretation

The policy question concerns physical extraction, the institutions that transmit a restriction and the financing of technological and public response. A cleaner certificate register alone does not answer all three. This paper supplies an alternative empirical companion built from the latest consolidated theories, with independent model code and the same observed evidence as the extended existing-method papers. It distinguishes an observed scale from a conditional calibration and from a maintained behavioral assumption.

The five mineral markets are separate. Comparable percentage changes and published fixed-reference-value weights provide a global picture without adding incompatible physical tonnes. Main-text comparisons are accompanied by country appendices, source scenarios and a results register retaining failed cases. The agreement of related constructions is not independent empirical confirmation.

2 The five-mineral evidence base

Gold, cobalt, tantalum, tin and tungsten clear in five separate world markets. The reference year is 2024. Coltan denotes an ore or concentrate; the tantalum model uses contained Ta. Gross concentrates, oxide and contained-metal mass are not interchangeable. Prices remain attached to their stated stage: converting an oxide-equivalent quotation into dollars per tonne of metal does not turn it into a measured minegate receipt. This is particularly important for the 3T minerals. (USGS, 2026; BGS, 2026)

The common archive contains 6,277 BGS country–product–year records for 2005–2024 across the five core minerals and copper, nickel and diamonds. Its global country panel is a separately versioned source scenario, not an average of incompatible USGS and BGS observations. Notes identify export proxies, fiscal years and uncertain content. Gross or niobium-containing tantalum

records with no valid Ta conversion remain unconverted. National scales and world residuals are reconciled in the structural registry; the BGS source panel serves the wider descriptive comparison. All observations retain their provenance.

UN Comtrade extraction covers each year from 2005 to 2024, with 13,125 destination margin records, 14,362 origin margin records and 1,021 records in a six-country 3T route panel. These are the declared query populations, not a complete global bilateral network. Missing and zero observations are distinct. The World partner is an aggregate, not an extra country or territory; origin and destination margins must not be added to each other. HS261590 combines niobium, tantalum and vanadium. Without finer national evidence it remains a mixed trade indicator, never pure tantalum extraction or a direct regulatory-exposure measure. HS2615 is broader still and also includes zirconium. (UN Comtrade, 2026; UN Statistics Division, 2017)

IPIS contributes dated, visited mine-site and institutional observations in DRC and CAR. The DRC raw file contains 7,163 records for 3,423 sites; the admitted historical descriptive subset uses onsite IPIS-source visits through 2024. Administrative qualifications and later visits are not silently pooled with that population. Selection into a visit prevents a simple visited-site fraction from identifying the national candidate share. EITI workbooks for 13 country contexts describe fiscal institutions; their often earlier vintages and aggregate currency accounts do not identify 2024 commodity-specific collection. (IPIS, 2026; EITI, 2026)

Rough diamonds provide a certification comparison through the Kimberley Process. Carats, values and certificate records are kept separate: quality and sorting prevent direct insertion into the homogeneous-metal model. Copper and nickel describe industrial and coproduct contexts. Their prices and output do not enter the five-mineral equilibrium unless an explicitly named joint-revenue experiment provides the physical and revenue accounts. Observed 2025 updates remain separate from the 2024 calibration. (Kimberley Process, 2026)

Table 1: Reference scales and fixed-value weights, 2024

Mineral	Mine content (t)	Reference USD/t	Weight (%)
Gold	3,661.2	76,718,111	93.39
Cobalt	302,000.0	26,103	2.62
Tantalum	2,500.0	203,915	0.17
Tin	294,000.0	30,159	2.95
Tungsten	82,000.0	31,778	0.87

Notes: Weights are $P_{m,2024}Q_{m,2024}/\sum_j P_{j,2024}Q_{j,2024}$. Gold retains the original WGC scale; other core minerals use the admitted USGS vintage. Prices concern different product stages. The resulting index is an accounting comparison, not mine revenue or welfare.

3 A mineral world with two physical routes

Each observed raw-mineral unit enters either bulk procurement or a retail processing cell. The two routes are disjoint. Eligible and candidate origin classes are assumed strata, not an illegal/legal classification of whole countries. Candidate and eligible extraction sum to raw-mineral extraction; processed output is a different physical object. Resale reallocates a previously extracted unit and does not add another unit of extraction.

The reference extraction technology is quadratic, $C(q) = kq^2/2$. It implies the supply exponent $\eta = 1$ used for the explicit comparison with the extended empirical method. National production and reference prices fix scale and normalization. Buyer values, retention technology, processing

capacities, route shares and acquisition charges remain assumptions. They cannot be jointly estimated from country production totals.

The Muir cell has regulated mass 0.005, regulated value 2 and resale probability 0.02. Its inverse unregulated demand is piecewise, and its exact revenue envelope is globally optimized together with genuine retention. With primary delivery m , retained conversion y , final-good price p and acquisition charge parameter τ , the solved problem is

$$\max_{m,y \geq 0} p\{V_\tau(m) + H_\delta(y)\} - \frac{k}{2}(m + y)^2.$$

Every stationary point, kink, endpoint and exit in the polynomial pieces is compared. The retained conversion uses the source's H_δ construction, $\delta = .001$ and $h_0 = .2$. The reference charge is .05. Actual final output comes from the allocation and resale integrals, not from dividing sales receipts by price.

The VCG cell has two whole owners, each with one package and independent uniform $[0, 1]$ raw productivity. Acquisition charges enter the affected owner's net value. The pivot payment removes the entire owner, not an artificial marginal fraction of that owner. Seller retention is genuine, with value phq , $h = .1$ and $k = .2$. Expected payments, retained stock and physical conversion are evaluated by exact polynomial integrals.

The baseline commits all extracted inventory to the specified mechanism. Making a second indivisible package available can change the receipt schedule discontinuously. The solver compares inventory branches and checks attainment. A supremum approached just below a package boundary is not a valid maximizer. Endogenous withholding is a separately named alternative, not an automatic repair to the all-offered model.

4 Origin claims and three simultaneous clearing equations

The bulk contract retains the canonical funded specification: initial late discovery .25, policy discovery .50, deposit .20, forgery curvature 2, diligence curvature .50, early/late rewards .02 and 1, and fee .02. Fraud and diligence are endogenous; total detection combines policy-set late discovery with endogenous diligence within the declared domains. No-silence, supplier participation and origin backing are checked explicitly.

Let Q_v be vulnerable eligible bulk output, π the fraud fraction and d_π the total detection probability. Diverted candidate mass is $D_v = Q_v\pi/(1 - \pi)$; certificate entries are $X = Q_C^{bulk} + D_v$; outside delivery is $Y = Q_D^{bulk} - D_v$. Revoked claims are $d_\pi D_v$ and live candidate claims are $(1 - d_\pi)D_v$. A negative outside-delivery stock cannot be rescued by aggregate price clearing.

Let h be the eligible bulk quote, p_D the candidate bulk quote, p the processed-good quote, f the fee and ℓ the expected buyer loss on a vulnerable entry. With actual processed output Z_R the equations are

$$h\{(1 + f)X + \ell Q_v/(1 - \pi)\} = E_C, \tag{1}$$

$$p_D Y = E_D + \epsilon \frac{Y}{Y + Z_R}, \tag{2}$$

$$p Z_R = E_R + \epsilon \frac{Z_R}{Y + Z_R}. \tag{3}$$

The assumed small coupling is $\epsilon = .001 \min(E_{D0}, E_{R0})$. Reference expenditures fit the baseline at $(h, p_D, p) = (1, .8, 1)$. This exact conditional fit does not identify a demand system. The raw-

mineral world normalizer scales country extraction once; Z_R remains a distinct processed-product unit, not an additional tonne of mineral.

The default static route fraction is .25 for eligible and candidate sources, with .10 and .50 alternatives. The bulk-only compatibility branch removes retail and coupling and separately solves the public-price equations. It is a diagnostic at a different boundary, not an application of the positive-core theorem where its hypotheses no longer hold.

5 Certification, spending and mechanism comparison

The static design solves 475 declared mineral–mechanism–scenario–policy states. It varies unknown candidate shares, retail routing and the explicitly named withholding alternative. Baseline, screening, spending-only contraction, combined policy and outside-spending expansion are retained separately. There is no cross-mineral market-clearing equation.

Each mechanism is anchored to the same observed production and source-stage price scales, but its institutional baseline is its own. A direct comparison between the previous central $\eta = .5$ technology and the nonlinear quadratic technology would mix a supply change into the mechanism contrast. Table 2 therefore uses the independently rerun $\eta = 1$ existing-method comparator.

Table 2: Candidate extraction under stronger discovery: matched curvature

Mineral	Existing method, $\eta = 1$	Nonlinear Muir	Nonlinear VCG
Gold	-0.00888	-0.00666	-0.00666
Cobalt	-0.50559	-0.37916	-0.37915
Tantalum	-0.13541	-0.10155	-0.10155
Tin	-0.13504	-0.10128	-0.10128
Tungsten	-0.13207	-0.09905	-0.09905

Notes: Percentage changes from each model’s own baseline, outside spending fixed. B sends 25% of both source classes to retail; A has the original bulk construction. Unknown country shares are 0.5. These rows match curvature and observed scales, not every institutional primitive.

Table 3: Screening plus a 20% outside-spending contraction

Mineral	Mechanism	Candidate (%)	All mining (%)	Final output (%)
Gold	Muir	-7.908	-3.891	0.001
Gold	VCG	-7.909	-3.891	0.000
Cobalt	Muir	-7.565	-1.636	0.000
Cobalt	VCG	-7.565	-1.636	0.000
Tantalum	Muir	-7.821	-3.989	0.001
Tantalum	VCG	-7.821	-3.990	0.000
Tin	Muir	-7.821	-3.989	0.001
Tin	VCG	-7.822	-3.990	0.000
Tungsten	Muir	-7.823	-3.989	0.001
Tungsten	VCG	-7.824	-3.989	0.000

Notes: The final column uses physical processed-product quantities. It is not added to raw extraction. All changes are relative to the same mechanism’s baseline; they are conditional examples.

The near-equality of Muir and VCG in the displayed screening comparison reflects where that policy acts. It changes the bulk discovery contract while leaving retail acquisition charges and cell primitives fixed. The candidate retail partition responds only through the very small demand coupling. The response is consequently close to 75% of the bulk-only, exponent-one response. This routing effect is not evidence that the two selling mechanisms are generally equivalent. The independently checked zero-retail compatibility branch reproduces the existing-method exponent-one states to approximately 2.7×10^{-15} .

The spending-only and screening-at-changed-spending changes add exactly to the combined change in levels. A shared sign under the two constructions is a conditional mechanism result, not a replicated empirical treatment effect. Their differences arise from different allocation, retention and processing responses and from the degree to which a country supplies each route.

Gold dominates the fixed-reference-value aggregate because its admitted reference value is much larger. Equal-weight sensitivity is therefore supplied alongside the weighted index. Both use extraction quantities and published 2024 weights; neither measures welfare, audited mine receipts or the value of processed goods. Missing admissible mineral pairs cause a complete-core index to be withheld rather than quietly renormalized.

Procurement inference remains limited. The Rwanda evidence supports interlinked payments and distinguishes concentrate grades, deductions and export stages. It does not supply the missing distribution of buyer values or a production elasticity. The questionable tantalum arithmetic is excluded from calibration. The appropriate empirical next step is linked transaction and assay evidence, not interpreting a model-generated price wedge as a measured cost share.

A Executable source crosswalk and independent reconstruction

Both consolidated theoretical parents are frozen beside this edition, with their hashes and equation labels. The static implementation maps the source objects `nw:cellproblem`, `nw:V`, `nw:retention`, `nw:actualfinal`, `nw:vcgcontinuation`, `nw:retailclearing` and `nw:jointclearing` into exact cell and world accounts. Dynamic ownership and government timing follow the specified subclasses of `dg:prize`, `dg:bellman` and `dg:population`. The readable implementation specification records every numerical primitive, domain, fitted moment and additional finite-equilibrium selection.

The independent static review reconstructs 475 saved states, 36 separate Muir global optimizations and direct whole-owner allocation/removal calculations using 1.44 million buyer-value pairs per tested VCG case. It also compares 150 bulk-only states with the original method at $\eta = 1$. Its 13,695 checks pass without modifying the equilibrium engine. Verification of a numerical example does not estimate its buyer primitives or validate an unrestricted theorem beyond its hypotheses.

The Muir reference extraction, final output and profit are approximately 0.2050386143, 0.1527677063 and 0.0984661155. The VCG reference extracts one package, obtains expected receipts .343 and profit .243, produces .667 physical final units and retains .01 expected mineral units. Receipt units and final-product units are visibly distinct even at these reference points.

For a VCG retention-only/one-package global switch the lower positive price root is

$$p = \frac{k}{h^2} \{R_h - \sqrt{R_h^2 - h^2}\},$$

with competing stocks ph/k and 1. A finite mixture checks equality of their global profits and an aggregate fraction in $[0, 1]$. It does not split an individual owner. Other nonconvex branches retain exact global comparisons and explicit nonattainment diagnostics.

Dynamic verification reads saved paths without importing the solver. It reconstructs physical markets, origins, owner leases and deposit/refund prizes, research conditions, country Bellman choices and transitions, inherited liabilities, grants and the permanent service reserve. Static/research admission is 10^{-8} and government admission 10^{-6} , with distinct grid and horizon checks. All excluded cases remain in the coverage denominator.

B Country scales, assumptions and missing calibration

The following registry is shared by the structural exercises. “Range” means the assumed candidate fractions 0.1, 0.5 and 0.9, not measured illegal or artisanal shares. Existing gold and DRC cobalt fractions retain their original transport qualifications. ROW is the source residual with a fixed 0.5 candidate split, no vulnerable certificate origin and no government. Uganda tantalum and DRC/Burundi/Uganda tungsten remain descriptive BGS cases without a named structural scale. Zero production and missing calibration are distinct. The fuller BGS producer tabulation is supplied as a separate CSV source scenario; its country coverage should not be confused with the narrower gold calibration.

Table 4: Admitted structural production registry

Mineral	Country or residual	Tonnes	Candidate share
Gold	Peru	108.15	0.1873 (transported)
Gold	Colombia	56.70	0.5386 (transported)
Gold	Rest of world and source round- ing balance	3,496.35	0.5 (assumed resid- ual)
Cobalt	United States	200.00	Range (assumed)
Cobalt	Australia	4,780.00	Range (assumed)
Cobalt	Canada	3,350.00	Range (assumed)
Cobalt	China	2,000.00	Range (assumed)
Cobalt	Democratic Republic of the Congo	226,000.00	0.1000 (transported)
Cobalt	Cuba	3,450.00	Range (assumed)
Cobalt	Indonesia	35,000.00	Range (assumed)
Cobalt	Madagascar	3,100.00	Range (assumed)
Cobalt	Papua New Guinea	2,630.00	Range (assumed)
Cobalt	Philippines	3,100.00	Range (assumed)
Cobalt	Russia	8,000.00	Range (assumed)
Cobalt	Turkey	2,200.00	Range (assumed)
Cobalt	Rest of world and source round- ing balance	8,190.00	0.5 (assumed resid- ual)
Tantalum	United States	0.00	Zero scale; no experi- ment
Tantalum	Australia	52.00	Range (assumed)
Tantalum	Bolivia	2.00	Range (assumed)
Tantalum	Brazil	210.00	Range (assumed)

Mineral	Country or residual	Tonnes	Candidate share
Tantalum	Burundi	2.00	Range (assumed)
Tantalum	China	76.00	Range (assumed)
Tantalum	Democratic Republic of the Congo	1,270.00	Range (assumed)
Tantalum	Ethiopia	40.00	Range (assumed)
Tantalum	Mozambique	55.00	Range (assumed)
Tantalum	Nigeria	390.00	Range (assumed)
Tantalum	Russia	29.00	Range (assumed)
Tantalum	Rwanda	374.00	Range (assumed)
Tin	United States	0.00	Zero scale; no experiment
Tin	Australia	11,300.00	Range (assumed)
Tin	Bolivia	21,200.00	Range (assumed)
Tin	Brazil	27,600.00	Range (assumed)
Tin	Myanmar	20,000.00	Range (assumed)
Tin	China	71,000.00	Range (assumed)
Tin	Democratic Republic of the Congo	26,000.00	Range (assumed)
Tin	Indonesia	55,000.00	Range (assumed)
Tin	Laos	1,860.00	Range (assumed)
Tin	Malaysia	5,460.00	Range (assumed)
Tin	Nigeria	3,100.00	Range (assumed)
Tin	Peru	32,300.00	Range (assumed)
Tin	Russia	3,260.00	Range (assumed)
Tin	Rwanda	4,100.00	Range (assumed)
Tin	Vietnam	11,000.00	Range (assumed)
Tin	Rest of world and source rounding balance	820.00	0.5 (assumed residual)
Tungsten	United States	0.00	Zero scale; no experiment
Tungsten	Australia	920.00	Range (assumed)
Tungsten	Austria	840.00	Range (assumed)
Tungsten	Bolivia	1,700.00	Range (assumed)
Tungsten	China	67,000.00	Range (assumed)
Tungsten	Kazakhstan	0.00	Zero scale; no experiment
Tungsten	North Korea	1,900.00	Range (assumed)
Tungsten	Portugal	650.00	Range (assumed)
Tungsten	Russia	1,500.00	Range (assumed)
Tungsten	Rwanda	1,300.00	Range (assumed)
Tungsten	Spain	700.00	Range (assumed)
Tungsten	Vietnam	3,400.00	Range (assumed)
Tungsten	Rest of world and source rounding balance	2,090.00	0.5 (assumed residual)

C Country extraction in the central static comparison

These are conditional candidate-stratum changes under the equal-routing static reference. They are not estimates of illegal mining. Countries without an admitted physical scale have no numerical effect. Tonnes and broader sensitivity cases are supplied in the common results archive.

Table 5: Stronger discovery, outside spending fixed: candidate extraction (%)

Mineral	Country	Muir	VCG
Gold	Peru	-0.00666	-0.00666
Gold	Colombia	-0.00666	-0.00666
Cobalt	United States	-0.37916	-0.37915
Cobalt	Australia	-0.37916	-0.37915
Cobalt	Canada	-0.37916	-0.37915
Cobalt	China	-0.37916	-0.37915
Cobalt	Democratic Republic of the Congo	-0.37916	-0.37915
Cobalt	Cuba	-0.37916	-0.37915
Cobalt	Indonesia	-0.37916	-0.37915
Cobalt	Madagascar	-0.37916	-0.37915
Cobalt	Papua New Guinea	-0.37916	-0.37915
Cobalt	Philippines	-0.37916	-0.37915
Cobalt	Russia	-0.37916	-0.37915
Cobalt	Turkey	-0.37916	-0.37915
Tantalum	Australia	-0.10155	-0.10155
Tantalum	Bolivia	-0.10155	-0.10155
Tantalum	Brazil	-0.10155	-0.10155
Tantalum	Burundi	-0.10155	-0.10155
Tantalum	China	-0.10155	-0.10155
Tantalum	Democratic Republic of the Congo	-0.10155	-0.10155
Tantalum	Ethiopia	-0.10155	-0.10155
Tantalum	Mozambique	-0.10155	-0.10155
Tantalum	Nigeria	-0.10155	-0.10155
Tantalum	Russia	-0.10155	-0.10155
Tantalum	Rwanda	-0.10155	-0.10155
Tin	Australia	-0.10128	-0.10128
Tin	Bolivia	-0.10128	-0.10128
Tin	Brazil	-0.10128	-0.10128
Tin	Myanmar	-0.10128	-0.10128
Tin	China	-0.10128	-0.10128
Tin	Democratic Republic of the Congo	-0.10128	-0.10128
Tin	Indonesia	-0.10128	-0.10128
Tin	Laos	-0.10128	-0.10128
Tin	Malaysia	-0.10128	-0.10128
Tin	Nigeria	-0.10128	-0.10128
Tin	Peru	-0.10128	-0.10128
Tin	Russia	-0.10128	-0.10128
Tin	Rwanda	-0.10128	-0.10128

Mineral	Country	Muir	VCG
Tin	Vietnam	-0.10128	-0.10128
Tungsten	Australia	-0.09905	-0.09905
Tungsten	Austria	-0.09905	-0.09905
Tungsten	Bolivia	-0.09905	-0.09905
Tungsten	China	-0.09905	-0.09905
Tungsten	North Korea	-0.09905	-0.09905
Tungsten	Portugal	-0.09905	-0.09905
Tungsten	Russia	-0.09905	-0.09905
Tungsten	Rwanda	-0.09905	-0.09905
Tungsten	Spain	-0.09905	-0.09905
Tungsten	Vietnam	-0.09905	-0.09905

D Measurement and procurement admission

The oxide conversion for tantalum uses the declared Ta fraction 0.81897 in Ta_2O_5 . A quotation of USD 167 per kg oxide-equivalent therefore gives 167000/0.81897 USD per tonne of contained Ta. Tungsten uses the declared 0.793 W fraction in WO_3 : one dry metric tonne unit is 10 kg WO_3 , or 7.93 kg W, giving 252000/7.93 USD/t W for a USD 252/dmtu reference. Cobalt and tin pound quotations use 0.45359237 kg/lb. All these conversions are checked separately from their suitability as procurement prices.

The Rwanda 3T study provides evidence of assays, payment stages and food deductions, but its tantalum table is not admitted as an elasticity moment. The COMIKAGI table reports 1,540 kg concentrate per month at 30% Ta_2O_5 , a USD 130/kg quotation of unclear basis, and USD 37.7/kg concentrate locally. The displayed international total USD 200,200 treats the quotation as per kg concentrate; an oxide-content application instead gives USD 60,060. The table’s combined total USD 514,578 also differs from USD 45,619 plus USD 200,200. The local total USD 58,058 is internally consistent. These alternatives imply radically different ratios, so no tantalum procurement elasticity is inferred. (Rwanda study, 2018)

The cassiterite example is arithmetically coherent: 3,960 kg concentrate, 60% tin and USD 19.20/kg metal imply approximately USD 45,619 internationally; USD 11/kg concentrate implies USD 43,560 locally. The ratio is approximately 0.955. Gifurwe’s tungsten comparison gives approximately 0.686 from USD 8.4/kg concentrate and USD 188.5/dmtu at 65% WO_3 . Both are transaction-stage ratios, not supply elasticities. The independently inspected pages and all arithmetic are retained in the Rwanda procurement audit.

Observed scales, conditional fits and assumptions have distinct records. No new mineral inherits the Colombia or Peru procurement elasticity merely because it is artisanal or traded through the same region. Identifying that elasticity requires matched transaction prices, assay and deduction data, production costs, net margins and a defensible population bridge.

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