

Critical minerals and investment frameworks: Formalizing the bankability framework

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Motivation

Investment is not scaling up, yet neither geology nor capital is scarce

- Projected **30% copper supply shortfall by 2035**; the lithium market may need to roughly quadruple output by 2040 (WEF 2026, Foreword); private investment is not scaling at the required pace
- **Not geology**: known reserves for most transition minerals are sufficient to meet projected demand over several decades
- **Not aggregate capital**: institutional investors hold trillions seeking long-duration, inflation-linked placements
- The constraint is **bankability**: the mismatch between a project's risk profile and the mandates of mainstream private finance
 - Technically viable, commercially rational projects fail to attract debt or equity: the wrong mix of revenue certainty, risk allocation and delivery confidence **at the stage where capital is needed most**

The question: does the WEF bankability framework close the gap? Partly

What it gets right

Bankability failures are **market-specific and stage-specific**: the instrument that unlocks a copper mine in Australia differs from the one that unlocks a graphite refinery in a reforming jurisdiction (WEF 2026)

Where it stops short

It is a **taxonomy** (three parallel classification tables), not an integrated decision rule

A practitioner who applies the tables as directed receives:

- up to **three conflicting instrument signals**, with no guidance on how to sequence them
- **no test** of whether public support is additional or wasteful
- no clarity on which of **four competing policy objectives** a given instrument serves

Can the framework become a decision procedure?

Preview: three additions that turn the taxonomy into a decision procedure

1. **Binding constraint protocol**: the primary friction (the one of maximal gap) is shown to **exist and be generically unique**; treating it is necessary for close, but the sufficient object is the whole sequenced binding set
2. **Crowding-in test**: public support must be gated on a demonstrated market failure, priced at the marginal cost of the risk it transfers, and withdrawn by an **automatic step-down**
3. **Objective hierarchy**: a normative three-tier ordering that makes the **resilience premium** (cost per tonne of diversified supply) explicit
4. **Extensions**: a parallel track for midstream refining, a capacity screen, secondary supply and demand-side levers, credibility of commitments
5. **Corrections** to five items in the framework's case-study evidence base

Illustrative numbers (appendix model, base calibration)

A price floor cuts the investment trigger from 156.35 to 112.00; a guarantee cuts the bankability threshold from 79.40 to 67.64. Floor magnitudes are **illustrative rather than calibrated**; the protocol's predictive validity is untested.

Contribution and related literature

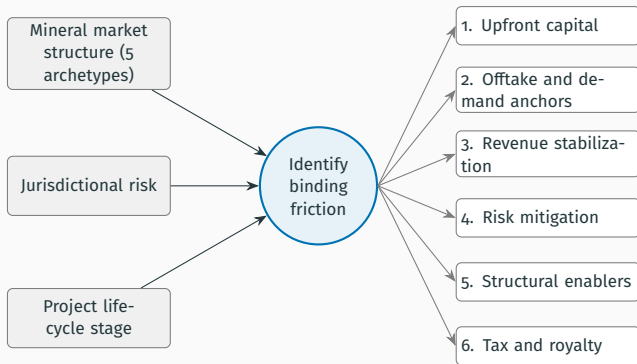
1. **Diagnostics and additionality:** constraint diagnosis at the country level (Hausmann et al. 2008); rules-based royalty design with transparent escalators and buffers (Nwaila et al. 2026)
2. **Objectives of mineral policy:** supply security (Vivoda et al. 2024; Morão 2025; Morão 2026), geopolitical exposure (Depraeter and Goutte 2025; Qin and Zhang 2024), producer-country value addition (Cuevas Verdin et al. 2026); midstream refining (Ucok 2026; Kahraman 2026)
3. **Governance and execution capacity:** costs of coercive downstream policies (Östensson 2019); instrument design that outstrips administrative capability (Maconachie and Hilson 2011; Delgado Jiménez et al. 2024; Wilhelm and Maconachie 2021); tax collection as a durable entry point (Hilson 2020)
4. **Investment under uncertainty:** real options (McDonald and Siegel 1986; Dixit and Pindyck 1994); project finance (Gatti 2013)

Three contributions

(i) Identifies where the framework stops short of being operational. (ii) Formalizes and extends it: protocol with existence and uniqueness, crowding-in test with step-down, objective hierarchy. (iii) Documents corrections to the case-study evidence base.

The framework

The WEF framework matches three dimensions to six instrument categories



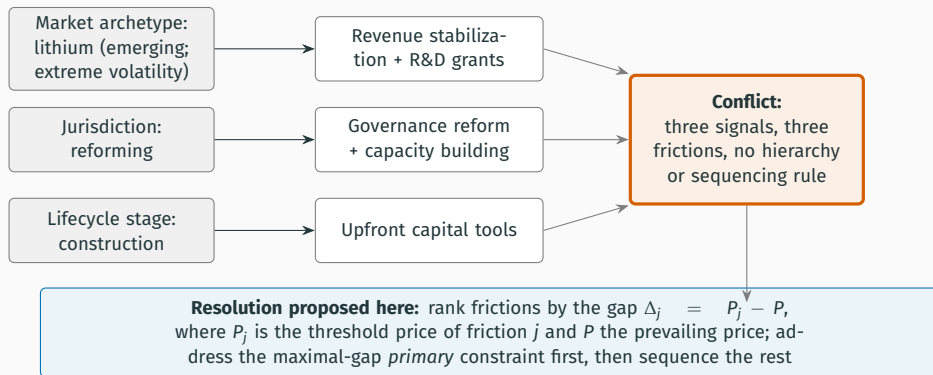
Notes: Schematic after the paper's framework figure.

- Archetypes: **mature, emerging, highly concentrated, opaque, niche**, by liquidity, price discovery and concentration
- **Market failure**: a financing friction that private capital cannot price or resolve on its own
- **Binding constraint**: the friction whose removal is required before a project can reach financial close

Archetypes and instrument categories

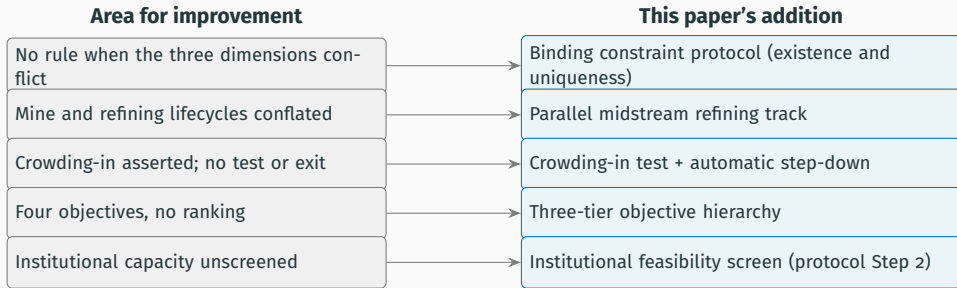
Gaps

When the three dimensions conflict, the framework offers no resolution



Notes: Schematic after the paper's conflict figure. The framework's cross-tabs are separate classifications, not a unified matrix. Addressing a secondary friction while the binding constraint remains does not improve bankability: it **wastes public resources** and may crowd out private instruments.

Five architectural gaps, five additions



Notes: After the paper's contribution figure.

- The four objectives: supply adequacy, geographic diversification, allied-nation processing capacity, producer-country development
- Each addition is meant to be implementable **within the framework's existing architecture**, without replacing it

Midstream refining

Capacity requirements

Model

Two thresholds: bankability (lenders) and investment trigger (sponsor)

Price and project

- P_t : output price, with $dP_t = \mu P_t dt + \sigma P_t dW_t$ (geometric Brownian motion); μ drift, σ volatility, W_t Brownian motion; $P_0 = P$ is the **prevailing price**
- $r > \mu > 0$: discount (required) rate
- q : output rate; c : unit operating cost; I : investment cost; $\ell \in (0, 1]$: leverage
- δ : debt-service coverage ratio lenders require
- $\beta > 1$: positive root of $\frac{1}{2}\sigma^2\beta(\beta - 1) + \mu\beta - r = 0$

Bankability threshold (lenders)

$$P^* = \underbrace{c}_{\text{operating cost}} + \underbrace{\frac{\delta r \ell I}{q}}_{\text{financing wedge}}$$

Investment trigger (option to wait)

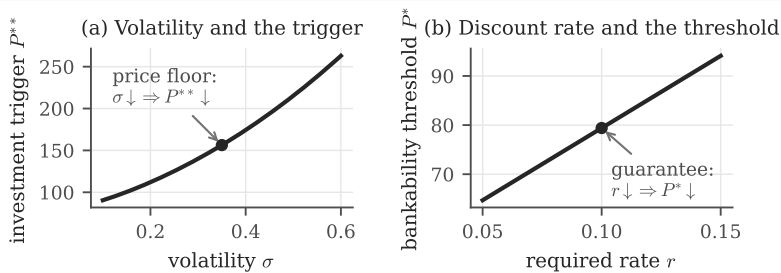
$$P^{**} = \underbrace{\frac{\beta}{\beta - 1}}_{\text{option premium} > 1} \times \underbrace{(r - \mu) \left(\frac{c}{r} + \frac{I}{q} \right)}_{M: \text{break-even price}}$$

Volatility and delay: $\partial P^{**} / \partial \sigma > 0$, so boom-bust cycles delay investment even when long-run NPV is positive (Ozorio et al. 2013). Public instruments work by shifting one or both thresholds.

Close requires clearing the binding threshold: P^{**} when revenue risk binds, not merely P^* .

Setup and derivation

A floor acts on the trigger; a guarantee acts on the bankability threshold



Notes: Paper's figure redrawn at slide size; base calibration in the backup; marked point: base case.

- **Price floor:** truncates the left price tail, lowering effective volatility σ , hence the option premium and P^{**} (panel a)
- **Guarantee:** lowers the required rate r , hence P^* unambiguously, since $\partial P^* / \partial r > 0$ (panel b); it lowers P^{**} only if the discount-rate channel dominates

Full statements

Illustration: a floor lowers the trigger, a guarantee the threshold

Scenario	σ	r	β	$\beta/(\beta - 1)$	P^*	P^{**}
Baseline (no instrument)	0.35	0.10	1.558	2.792	79.40	156.35
Price floor	0.20	0.10	2.000	2.000	79.40	112.00
Guarantee	0.35	0.06	1.277	4.608	67.64	156.66
Floor + guarantee	0.20	0.06	1.500	3.000	67.64	102.00

Notes: Paper's scenario table. Base calibration $\mu = 0.03$, $q = 1$, $c = 50$, $I = 300$, $\ell = 0.7$, $\delta = 1.4$; prevailing price $P = 90$. A floor cuts effective volatility σ ; a guarantee cuts the required rate r .

- At $P = 90$ the baseline project is **debt-serviceable** ($P > P^* = 79.40$) but **below the trigger** ($P < P^{**} = 156.35$)
- The guarantee **barely moves** P^{**} : a lower r raises the option premium enough to offset the lower break-even price
- Floor-effect magnitudes depend on the distributional assumption: **illustrative rather than calibrated**; the signs survive mean reversion

Protocol

Binding constraint: treat the friction of maximal gap first

Definitions

- A project at price $P > 0$ faces a finite set of frictions $J = \{1, \dots, n\}$
- Friction j has a threshold price P_j (its P_j^* or P_j^{**}), below which it alone blocks close; **gap** $\Delta_j = P_j - P$
- j **binds** iff $\Delta_j > 0$; $B = \{j \in J : \Delta_j > 0\}$ is the binding set
- An **intervention** $S \subseteq J$ is the set of frictions addressed; an addressed friction stops binding
- Interventions are **locally orthogonal** (a heuristic simplification): addressing j holds the other P_j fixed

Proposition (binding constraint prioritization)

The primary instrument targets $j^* = \arg \max_j \Delta_j$. Addressing a friction $j \neq j^*$ while j^* is untreated does not enable financial close, whatever Δ_j is.

Sequencing

Structural enablers (which lower P^*) must precede revenue-risk instruments (which lower P^{**} via σ): a lower option premium does not help while P^* still exceeds P .

Identifying the primary constraint is not the same as the deployment order.

The primary friction exists, is generically unique, and is necessary

- **Existence and uniqueness:** if $B \neq \emptyset$, $j^* = \arg \max_j \Delta_j$ exists and lies in B ; it is unique if the gaps are pairwise distinct (two thresholds coincide only on a measure-zero set, so uniqueness is **generic**)
- **Necessity:** every intervention that achieves bankability contains B , in particular j^*
- **Sufficiency is set-valued:** S suffices iff $B \subseteq S$; the minimal sufficient intervention is $S = B$. A single friction suffices only if $B = \{j^*\}$
- **Sequential closure:** addressing binding frictions in decreasing order of gap reaches bankability in exactly $|B|$ steps

Reading the results

Uniqueness of the maximiser does **not** imply $|B| = 1$: several frictions may bind at once. The object sufficient for close is the sequenced set B , not any single friction.

Notes: Machine-checked in Lean 4 against Mathlib (replication package); proofs in the backup.

Proofs

Machine-checked results

The protocol has three steps and returns one primary instrument

Step	Decision	Proceed if yes	If no
1	Which friction is the primary binding constraint (of maximal gap), whose removal is necessary for financial close?	Constraint identified: go to Step 2	Gather project data; iterate across friction categories
2	Can the administering institution execute the recommended instrument?	Capable: go to Step 3	Substitute a simpler instrument or add a capacity precondition
3	Are structural enablers in place before revenue-risk instruments are deployed?	Satisfied: deploy the instrument	Deploy structural enablers first; return to Step 1

Notes: Paper's protocol table. Output: one primary instrument + enabling preconditions + automatic step-down schedule.

- Step 2 example: a tax credit substitutes for a contract for difference where commodity-risk expertise is absent, with a graduation path as capacity develops
- The protocol forces **sequencing, not exclusion**

Stated qualifications

Illustration: revenue risk is primary, but all three frictions bind

Friction j	P_j	$\Delta_j = P_j - P$	Binds?
Revenue risk (P^{**})	156.35	66.35	yes
Permitting	112.00	22.00	yes
Feedstock	95.00	5.00	yes

Notes: Paper's table; base calibration, prevailing price $P = 90$. Permitting and feedstock are *illustrative* structural frictions acting on P^* .

- At $P = 90$ the project is already debt-serviceable ($P > P^* = 79.40$), yet the investment trigger binds: **revenue risk is the primary constraint**
- Binding set
 $B = \{\text{revenue risk, permitting, feedstock}\}$:
closure takes $|B| = 3$ steps
- **Deployment order**: structural enablers (permitting, feedstock) first, since a lower option premium cannot make the project bankable while P^* exceeds P ; the revenue instrument that removes the primary constraint follows

Which friction is primary is not the order of deployment.

Lynas in 2011: the protocol picks offtake, the structure that closed

Step	Question	Application	Outcome
1	Binding constraint?	Highly concentrated archetype; deposit world-class and plant under construction, so neither geology nor upstream capital is primary	Revenue and market-access certainty (highest P^{**} : extreme σ , incumbent behavior)
2	Institution able to execute?	JOGMEC (commodity-security expertise) with trading house Sojitz can execute a long-term offtake (availability) agreement	Screen passes
3	Sequence	March 2011: US\$250 million in loan and equity via the Japan Australia Rare Earth vehicle, plus an availability agreement for at least 8,500 tonnes a year to Japan	Offtake certainty made the debt and equity bankable and financed the plant's expansion

- An undifferentiated menu reading rare earths as a supply gap would default to **upstream capital support**; the protocol names **demand procurement** primary
- Expansion capital was inaccessible on commercial terms without committed offtake, so the support was additional

Notes: An illustration of applicability, not a controlled demonstration of superiority (that needs a matched-sample comparison the data do not yet permit).

Crowding-in test

Crowding-in test: gate on market failure, price at marginal cost, step down

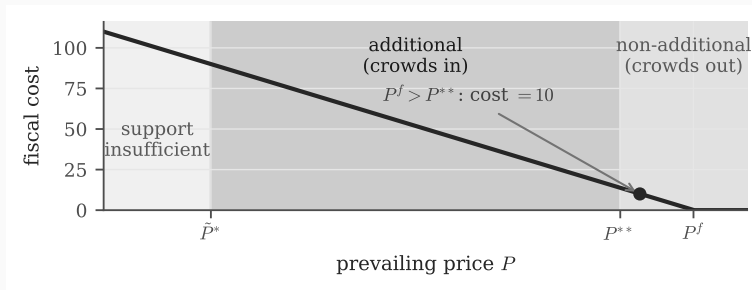
1. **Market failure gate:** is the financing gap due to a defined market failure (missing price benchmark, political risk premium above commercial insurance thresholds, public-good exploration data)? Below-average commercial returns are **not** a market failure: support would displace, not crowd in
2. **Calibration rule:** price the instrument at the marginal cost of the specific risk it transfers. A floor is set at the minimum that brings the project to close, $\max(P^*, P_{\text{post}}^{**})$, where P_{post}^{**} is the post-floor trigger
3. **Automatic step-down:** coverage declines on a predefined schedule tied to observable conditions (benchmark established, investment-grade rating, entry of commercial substitutes)

Why it matters

Overpayment above the bankability threshold subsidizes incumbents and crowds out private offtake and hedging. A floor set only at P^* can leave a project debt-serviceable yet short of the trigger a sponsor requires. Step-downs are tied to refinancing access so the floor stays active for the tenor lenders require.

Caveats and extensions

Support is additional only in a window; above the trigger it displaces



Notes: Paper's figure redrawn at slide size. P : prevailing price; P^f : floor; fiscal cost $q \max(P^f - P, 0)$, q output rate. $\tilde{P}^* = \frac{r}{r-\mu} M$: lowest trigger a full floor can reach ($\approx P^*$ here).

- Additional iff $\tilde{P}^* \leq P < P^{**}$; below $\tilde{P}^*$ a floor alone cannot close the project
- If $P \geq P^{**}$ and $P^f > P^{**}$, the floor is **non-additional**: it displaces private offtake
- Fiscal cost stays positive even when the project is viable: at $P = 160$ it is 10
- Support should **terminate when** $P_t \geq P^{**}$, not when the contract expires

Hierarchy and evidence

An explicit objective hierarchy makes the cost of resilience visible

Tier	Objective	Instrument priority	Trade-off imposed
1 Primary	Supply adequacy: maximize new bankable supply at lowest cost	First-order: instruments serving adequacy and resilience simultaneously	None when the instrument serves several objectives
2 Secondary	Supply resilience: diversify the geographic and supplier base away from concentrated incumbents	Second-order: allied-content requirements; strategic procurement from higher-cost allied sources	Resilience premium: extra cost per tonne of diversified supply relative to least-cost incumbent supply
3 Tertiary	Producer-country development: value addition in host economies	Enabling instruments preferred over trade restrictions	Development benefit minus supply adequacy cost, stated before commitment

Notes: Paper's hierarchy table, condensed. The ordering is *normative*, not derived from the model: a consuming-country perspective that is transparent and contestable (host governments will often invert it). The resilience premium must be stated as a **scenario range** before commitment.

Scope notes

Five corrections to the framework's case-study evidence base

Type	Correction	Instrument consequence
Overclaim	Oyu Tolgoi: layered guarantees said to work without government equity; Mongolia holds a 34% stake	Risk insurance overstated as a standalone bankability solution
Overclaim	Codelco prepayment presented as crowding in private capital; both counterparties are public entities	Offtake additionality evidence overstated
Misdescription	IRA §45X called “a 10% production tax credit”; it is 10% of production costs, not of output value	Cash-flow guidance imprecise for project modeling
Mislocation	Concentration attributed to upstream mining; refining concentration is the primary bottleneck	Instrument mix weighted toward upstream diversification
Mislocation	Rare earths linked to semiconductors; primary use is permanent magnets (EVs, wind, defense)	Table calibrated for the wrong end-use supply chain

Notes: Paper's corrections table, condensed (items refer to the WEF report's boxes, foreword and tables). The critique does not dismiss upstream instruments where geology genuinely constrains diversification (e.g. cobalt in the DRC).

Refining vs mining concentration Details

Conclusion

Caveats stated by the paper and the research agenda

- The protocol's **predictive validity is untested**: no transaction-level dataset compares projects matched under it with those matched by judgment
- It **bounds subjectivity rather than removing it**: analysts can reach differing diagnoses at Step 1; the Step 1 and Step 2 methods are not fully specified
- The resilience premium is a **conceptual benchmark**; no estimate exists for current allied-nation sourcing commitments
- GBM and local orthogonality are simplifications; floor magnitudes are illustrative; the hierarchy is normative
- Out of scope: community opposition (social license) is a legitimacy, not a financing, constraint

Research agenda

1. What is the empirical distribution of binding constraints across archetypes and jurisdictions, and does it shift with price cycles?
2. What is the measured resilience premium of allied sourcing, and when does diversification become fiscally indefensible?
3. Which minimum institutional capability thresholds predict successful execution of each instrument category?

Both data gaps are resolvable with data that DFIs and ECAs hold but have not published in a form suited to systematic analysis.

Conclusion: from a classification of instruments to a decision procedure

- The framework's core insight, that **bankability failures are market- and stage-specific**, is correct and underused in policy discourse
- **Protocol**: identify the primary friction, screen it against institutional capacity, sequence enablers before revenue-risk instruments
- **Crowding-in test**: gate support on demonstrated market failure; price at the marginal cost of the risk; withdraw it by automatic step-down tied to refinancing access
- **Hierarchy**: state the resilience premium as a scenario range before choosing a diversification instrument; state the supply cost of development objectives
- **Evidence**: weight midstream-targeted tools more heavily where refining concentration, not geology, is the market failure; correct the case-study base

Once DFI and ECA transaction-level data are released, the framework can become an evidence-based investment guide.

Thank you! hmorao@phd.iseg.ulisboa.pt

Backup

Archetype logic and the six instrument categories

Market structure drives which friction dominates

- **Copper:** most liquid transition market (benchmark prices, deep futures, about 23 million tonnes a year); the obstacle is jurisdictional risk and permitting cost, not revenue uncertainty
- **Graphite:** priced bilaterally by specification; a production tax credit calibrated to copper does nothing for it, while qualification bridge financing has no analogue in copper
- **Mature:** private finance can hedge price risk; the failures left are political risk and public goods
- **Concentrated:** a credible external demand anchor is needed before entrants can close (Vafeas 2026)
- **Opaque:** missing price benchmarks are a coordination failure

Six categories, each addressing a distinct friction

1. Upfront capital: capex gap before operating cash flow exists
2. Offtake and demand anchors: revenue visibility for long-tenor debt
3. Revenue stabilization (CfDs, price floors): volatility and weak benchmarks
4. Risk mitigation: political and completion tail risks moved to balance sheets that can absorb them
5. Structural enablers: permitting, shared infrastructure, geoscience data
6. Tax and royalty: rules-based changes to the fiscal take

Precedents: DoD–MP Materials rare earth price floor (2025), JOGMEC–Sojitz–Lynas, Queensland Resources Common User Facility, JBIC–Codelco prepayment.

Midstream refining has its own lifecycle and a qualification option



Notes: After the paper's lifecycle figure. The WEF tables place refining as Stage 5 (steady-state) of the mine lifecycle; the instrument that fits is **bridge financing** over the qualification period, not upfront capital or price floors.

T_q : stochastic time from commissioning to qualification; $V_{\text{mine}}(P)$: mine operating value; $\mathbb{E}$: expectation;

$$V(P) = \frac{Pq}{r-\mu} - \frac{cq}{r}.$$

$$V_{\text{refinery}}(P) = \mathbb{E}[e^{-rT_q} V(P_{T_q})] - \mathbb{E}\left[\int_0^{T_q} e^{-rt} cq dt\right] < V_{\text{mine}}(P) \Rightarrow P_{\text{refinery}}^{**} > P_{\text{mine}}^{**}$$

Minimum institutional capability requirements by instrument

Instrument	Capabilities required	Complexity	Feasible substitute
Contract for difference	Daily commodity price monitoring; payment administration on a fixed schedule; dispute resolution without political interference	High	Production tax credit (rules-based)
Strategic stockpile	Procurement logistics; credible release-rule governance; balance-sheet capacity	High	Backstop offtake commitment
Political risk insurance	Actuarial event assessment; claims administration	Medium	First-loss capital tranche
Structured currency hedging	Derivative management; treasury expertise	Very high	Hard-currency denominated contracts
Government offtake agreement	Procurement authority; grade and specification verification	Medium	Government backstop option
Production tax credit	Standard tax administration; eligibility determination	Low	N/A (already the simpler substitute)

Notes: Paper's capability table. Failure when institutions are assigned instruments they cannot administer is documented across mining governance contexts (Maconachie and Hilson 2011; Delgado Jiménez et al. 2024; De Jong and Sauerwein 2021).

Model setup, calibration and the volatility result

- Perpetual operating value $V(P) = \frac{Pq}{r - \mu} - \frac{cq}{r}$: revenue discounted at $r - \mu$, net of constant operating cost discounted at r
- P^* follows from requiring a debt-service coverage ratio $\geq \delta$ (standard project-finance practice (Gatti 2013)); four levers: c, δ, r , capital intensity $\ell l / q$
- δ and r are partially endogenous to the policy environment: lenders revise risk appetite on signals of government support
- Option premium $\beta / (\beta - 1) > 1$ rises with σ ; M is the Marshallian (zero-NPV) entry price (Dixit and Pindyck 1994)
- **Base calibration:** $\mu = 0.03, \sigma = 0.35, r = 0.10, c = 50, l = 300, q = 1, \ell = 0.7, \delta = 1.4; P = 90$. Then $M = 56, P^* = 79.40, P^{**} = 156.35$
- **Why $\partial P^{**} / \partial \sigma > 0$:** M does not depend on σ ; β decreases in σ and $\beta / (\beta - 1)$ decreases in β , so the premium rises with σ

Stated limits of the model

GBM is the standard tractability assumption (McDonald and Siegel 1986; Dixit and Pindyck 1994); commodity prices also show mean reversion and jumps (Schwartz 1997). The sign of the trigger's comparative statics survives mean reversion (Metcalf and Hassett 1995); the precise magnitudes of the floor effect are sensitive to the distribution and illustrative.

Price floor, guarantee and crowding-out: full statements

- **Price floor:** truncates the left price tail, lowers P^{**} by reducing effective volatility and hence the option premium. It lowers P^* not through a volatility term (there is none) but through the risk-adjusted parameters a credible floor improves (δ and r). Additional iff $\tilde{P}^* \leq P < P^{**}$
- **Political risk guarantee:** ρ is a reduced-form proxy for the priceable part of jurisdictional risk, the hurdle-rate markup lenders apply to a reforming jurisdiction; the uninsurable, Knightian part is what the guarantee reallocates to a balance sheet able to bear it. It lowers P^* unambiguously ($\partial P^* / \partial r > 0$); it lowers P^{**} for r bounded away from μ , while near $r = \mu$ the premium channel can offset the level effect
- **Crowding-out:** if $P \geq P^{**}$ and $P^f > P^{**}$, the floor is non-additional and displaces private offtake; support in the window below P^{**} is strictly additional, since the project is debt-serviceable but not yet past the sponsor's trigger. Fiscal cost $q \max(P^f - P_t, 0)$ is positive even when viable. Displacement applies to commercially bankable private alternatives (offtakes backed by investment-grade counterparties)

Notes: The paper states the lower end of the additional window as $\tilde{P}^*$ in the floor proposition and the figure, and as P^* in the crowding-out proposition; the two coincide approximately at the base calibration.

Proofs of the binding-constraint results

- **Lemma** (bankability after an intervention): after addressing S , the project is bankable iff $B \subseteq S$. *Proof.* The still-binding set is $B \setminus S$; bankability requires $B \setminus S = \emptyset$, i.e. $B \subseteq S$.
- **Existence and uniqueness.** *Proof.* J is finite and non-empty, so $\{\Delta_j\}$ attains a maximum $\Delta_{\max}$ and the maximiser set M is non-empty. As $B \neq \emptyset$, $\Delta_{\max} > 0$, so $j^* \in B$. If $j_1 \neq j_2 \in M$ then $\Delta_{j_1} = \Delta_{j_2}$, contradicting pairwise distinctness; hence $|M| = 1$.
- **Necessity.** *Proof.* By the Lemma a closing S satisfies $B \subseteq S$; since $j^* \in B$, $j^* \in S$. Contrapositively, if $j^* \notin S$ then $j^* \in B \setminus S \neq \emptyset$.
- **Sufficiency is set-valued.** *Proof.* Sufficiency $\iff B \subseteq S$ is the Lemma; B lies in every sufficient set and is itself sufficient, hence minimal. Since $j^* \in B$, $B \subseteq \{j^*\}$ iff $B = \{j^*\}$.
- **Sequential closure.** *Proof.* With B_t the binding set after t steps ($B_0 = B$), addressing a binding friction removes one element, so $|B_{t+1}| = |B_t| - 1$; as $|B| < \infty$ the process ends at $B = \emptyset$ in $|B|$ steps.

Notes: Genericity: distinctness fails only if two thresholds coincide, a measure-zero event; where thresholds coincide by design (e.g. a floor set exactly at the bankability threshold) the tie is a deliberate choice.

Machine-checked results (Lean 4 with Mathlib)

- Checked: bankability characterization; existence, uniqueness, necessity, set-valued sufficiency, sequential closure; the root β , $\beta > 1$, option premium and the volatility comparative static
- Floor, guarantee and crowding-out propositions are checked in their **unambiguous form**
- Each theorem uses only the three standard axioms; no sorry, no native_decide; the code ships with the replication package

Result	Lean theorem(s)
Bankability lemma	bankableAfter_iff
Existence and uniqueness	exists_argmax, argmax_unique
Necessity	necessity
Sufficiency	sufficiency, singleton_sufficient_iff
Sequential closure	card_erase_binding
Root β and premium	beta_gt_one, premium_gt_one
Volatility (Prop.)	trigger_strictMono_sigma
Floor, guarantee	floor_lowers_trigger, Pstar_strictMono_r
Crowding-out	fiscalCost_pos

Argued in the text, not formalized

The floor's effect on P^* (through δ and r rather than σ) and the guarantee's effect on P^{**} (only when the discount-rate channel dominates). Numerically, the closed-form trigger matches an independent value-matching and smooth-pasting solution to within 10^{-8} .

Notes: Condensed from the paper's table of machine-checked proofs (toolchain leanprover/lean4:v4.33.0-rc2).

Qualifications the paper places on the protocol

1. The protocol **bounds subjectivity into a logical sequence rather than removing it**: the Step 1 judgment is more focused and contestable than the judgment it replaces, not eliminated
2. The counterfactual analysis in Step 1 and the capability rubric in Step 2 require expert judgment and operational methodologies the paper **does not fully specify**; the capability table is a starting taxonomy and empirical thresholds remain to be established
3. The protocol is designed to be run by the **deploying institution** (DFI, ECA or multilateral), not the host government; the recursive capacity problem applies to the deploying institution, and the three steps can be executed at different levels of analytical depth

Notes: Scope boundary: permitting delays are a structural enabler that institutional reform can resolve; community opposition is a distinct social-license risk that financial instruments cannot address.

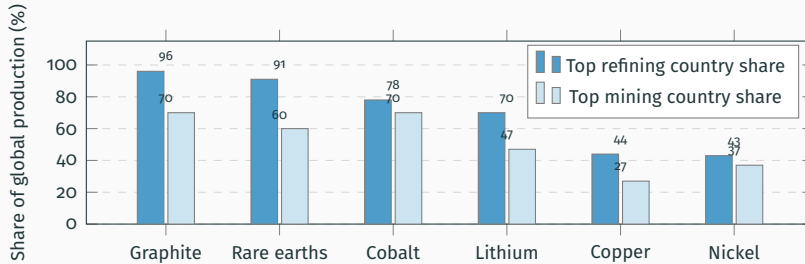
Crowding-in test: caveats and two extensions

- **Carve-out:** in highly concentrated archetypes where state-backed incumbents price below fully allocated cost, below-average returns facing entrants reflect predatory pricing and qualify as a market failure
- **Principal-agent problem:** sponsors hold private information on costs and thresholds and may overstate them. Partial mitigants: open-book cost verification, competitive reverse auctions, reference pricing from sector-wide benchmarks
- **Rules-based pricing is feasible:** an adaptive royalty architecture adjusts the floor with commodity price variance on pre-specified triggers (Nwaila et al. 2026)
- **Secondary supply:** recycled cobalt, lithium and rare earths compete with primary supply in the same benchmarked markets; ignoring this overstates the investment gap and misprices instruments
- **Credibility:** the value of a long-run commitment depends on the probability of honoring it; governments can renegotiate once capital is sunk. Legislation, independent agencies and multilateral backstopping reduce hold-up risk through different mechanisms

Objective hierarchy: scope notes

- The ordering ranks objectives by the **comparative advantage of public financial instruments**, which act most directly on supply adequacy and least directly on producer-country development
- The framework operates within a neoclassical market-failure tradition and does not engage the industrial-policy school; the binding-constraint logic applies in either paradigm
- The resilience-premium analysis is **partial equilibrium**: coordinated subsidization by several allied nations could produce overcapacity and price collapse
- Supply disruption risk is closer to Knightian uncertainty than actuarial risk, so the premium is a deliberative benchmark rather than a precise value
- Evidence on value-addition policies: enabling instruments (skills, infrastructure, technology transfer) serve the objective more reliably than mandatory procurement rules (Cuevas Verdin et al. 2026)

Refining concentration exceeds mining concentration for all six minerals (2024)



Notes: Paper's figure, redrawn. Top refining country is China for all six minerals. Top mining country: China (graphite, rare earths), DRC (cobalt), Australia (lithium), Chile (copper), Indonesia (nickel). Source: author's compilation from WEF (2026).

The security exposure motivating the framework sits at processing and refining (Ucok 2026; Kahraman 2026). Refining concentration is primarily capital-driven and more mobile than geology-bound extraction, though relocating it is neither costless nor immediate.

Corrections in more detail

- **Oyu Tolgoi:** the MIGA guarantee and IFC package came from institutions that took no equity, but host-government equity was present throughout. The case shows multilateral guarantees can unlock a large commercial package in a frontier jurisdiction, as one layer of a structure; it does not show that insurance substitutes for public equity
- **JBIC-Codelco:** the text says Codelco could not easily access capital commercially, yet calls the project “already-bankable”; a project that cannot raise commercial capital is not bankable. A transaction between two public entities with no private co-investors is not crowding in. It is a clean example of consuming-country demand procurement, which validates offtake as a supply-security tool but not additionality
- **Section 45X:** a cost-based credit supports margins independently of output price and offsets cost overruns; an output-value credit delivers more support at high prices. The description would lead a practitioner to overstate the credit’s value in low-price scenarios
- **Rare earth end-use:** rare earths serve mainly NdFeB permanent magnets (EV motors, wind turbines, defense); gallium and germanium are the minerals most relevant to semiconductor fabrication. Geopolitical risk transmits to clean-energy investment through rare earth supply chains (Depraeter and Goutte 2025)

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