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Financing Mineral Decarbonisation: Climate Bonds, Carbon-Backed Valuation, and the New Asset Class of Mining

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Abstract

Mining is simultaneously a critical enabler of the global energy transition and one of its most carbon-intensive industrial systems. This apparent contradiction conceals a financing opportunity: mineral-rich emerging economies can reposition their mining sectors as decarbonisation-backed financial assets, capable of attracting climate bond capital not despite their emissions profile but because of the abatement potential embedded in their mineral outputs. This paper formalises that opportunity through three novel constructs: the Decarbonisation-Weighted Resource Valuation (DWRV), embedding avoided emissions into project-level net present value analysis; the Transition Mineral Decarbonisation Gap (TMDG), quantifying unrealised carbon abatement due to insufficient climate finance deployment; and the Carbon-Backed Financial Multiplier (CBFM), measuring the leverage effect of climate bond capital in mobilising total decarbonisation investment. A fourth construct — the Energy-Enabled Mineral Decarbonisation Index (EEMDI) — operationalises jurisdiction-level readiness to host climate bond–financed renewable energy projects at mining operations.

A mixed-methods approach combines stylised mine-level DWRV simulations across three transition mineral archetypes, TMDG estimation for ten Sub-Saharan African mineral producers, CBFM calibration from blended finance databases, and EEMDI construction from institutional data. Modelled outcomes suggest that integrating a 110-basis-point greenium into project financing improves NPV by 12–15 per cent and, at carbon prices above USD 53–75 per tCO_2e, renders mine-level renewable energy investment self-financing without subsidy. TMDG estimates reach 5.8 $MtCO_2e$ in the Democratic Republic of Congo — unrealised abatement potential attributable to finance unavailability rather than technological constraint. CBFM ratios of 4–5× in high-EEMDI jurisdictions are consistent with climate bond capital functioning as a high-leverage instrument in the mining context. While the empirical focus is Sub-Saharan Africa, the DWRV–TMDG–CBFM–EEMDI framework is designed for international portability across mineral-rich emerging economies in Latin America, Southeast Asia, and Central Africa.

1. Introduction

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The global energy transition has generated a structural paradox. The minerals required to decarbonise the global economy — lithium, cobalt, nickel, copper, manganese, and platinum group metals — are extracted by one of the most carbon-intensive industrial sectors in existence. Scope 1 fuel combustion and Scope 2 electricity consumption from coal-dependent grids together account for approximately 4–7 per cent of global industrial greenhouse gas emissions, and energy costs represent 15–40 per cent of mine operating expenditure depending on commodity type and depth of operation (Enemuo and de Wit, 2025; IEA, 2024). Existing policy responses treat this as a management problem — a tension to be navigated through taxonomies, disclosure requirements, and ESG commitments. This paper treats it as a financing opportunity to exploit.

The conceptual reframing is straightforward. A mine that produces copper for electric vehicle wiring, cobalt for battery cathodes, or lithium for grid-scale storage is not merely a commodity producer — it is a supplier of inputs whose downstream deployment avoids measurable quantities of carbon emissions relative to fossil-fuel alternatives. These avoided emissions are quantifiable using life-cycle assessment and energy substitution modelling, and they are increasingly priceable through voluntary carbon markets, compliance mechanisms, and shadow carbon pricing in public project appraisal (World Bank, 2024; McKinsey, 2022). Once priced, they can be embedded in project valuation — transforming the mine from a passive recipient of risk-adjusted financing into an active generator of carbon cash flows that can be monetised through climate bond instruments.

This paper develops that argument formally. Three interrelated constructs are introduced. The Decarbonisation-Weighted Resource Valuation (DWRV) extends standard discounted cash flow analysis by adding a carbon-adjusted term to project NPV, weighted by a policy credibility scalar (λ) that is itself a function of jurisdictional institutional readiness. The Transition Mineral Decarbonisation Gap (TMDG) quantifies the aggregate unrealised abatement potential arising from insufficient climate finance deployment — the abatement foregone under baseline financing conditions. The Carbon-Backed Financial Multiplier (CBFM) measures the leverage effect of climate bond anchor capital in crowding in private decarbonisation investment, analogous to multiplier metrics well established in the blended finance literature (Convergence, 2024). A fourth construct, the Energy-Enabled Mineral Decarbonisation Index (EEMDI), operationalises jurisdiction-level readiness to host climate bond–financed mine energy projects — functioning as an institutional moderator of the three core constructs rather than an independent contribution.

The paper connects explicitly to a broader research programme on transition mineral finance. Sentsho (2025a) demonstrates that Mining Capital Mispricing — the gap between market-implied and actuarially justified sovereign risk premia — imposes 630–890 basis points of excess WACC on mining projects in Sub-Saharan Africa. Sentsho (2025b) formalises the Transition Mineral Financing Gap and the Resource–Finance Mismatch, showing that coordinated institutional finance architectures (ETFA) raise mineral-sector FDI by approximately 31 per cent. The present paper extends this programme from the investment finance question to the decarbonisation finance question: given that climate bond capital is now available and growing, under what conditions does it transform the economics of mine-level energy transition?

The empirical focus is Sub-Saharan Africa — the region that most acutely combines world-class transition mineral endowments with the highest financing barriers and the largest untapped renewable energy potential. However, the DWRV–TMDG–CBFM–EEMDI framework is explicitly designed for international portability. The same analytical structure applies directly to copper and lithium producers in Chile and Argentina, nickel operations in Indonesia and the Philippines, and bauxite producers in Guinea and Ghana. Where institutional conditions differ, EEMDI scores and λ calibrations adjust accordingly — the framework adapts rather than prescribes.

This study contributes to the literature by integrating mineral project valuation, transition finance architecture, and carbon abatement quantification into a unified empirical framework — demonstrating that mining decarbonisation is not a cost imposed on project finance, but a funding mechanism that, properly structured, generates capital access, lowers discount rates, and produces measurable carbon outcomes. Mining is not a problem to decarbonise. It is a mechanism through which decarbonisation finances itself.

2. Literature Review

2.1 Climate Bonds, Transition Finance, and Industrial Sectors

The global green bond market reached cumulative issuance of USD 4.9 trillion by end-2024, with climate bonds — defined by their earmarked use of proceeds for climate mitigation and adaptation outcomes — representing the fastest-growing segment (CBI, 2024). Early green bond literature focused primarily on the renewable energy and energy efficiency sectors, where environmental outcomes are cleanly measurable and taxonomic eligibility is straightforward (Sobik and Sharma, 2023). The extension of climate finance instruments to emissions-intensive industrial sectors has been slower and more contested.

Transition finance addresses this gap by prioritising credible, measurable, and time-bound decarbonisation pathways rather than requiring absolute environmental end-states (Tang and Zhang, 2025; OECD, 2021). The International Capital Market Association's Climate Transition Finance Handbook provides guidance for sectors where emissions elimination is technologically constrained but intensity reduction is feasible (ICMA, 2023). Applied to mining, transition finance could encompass bond instruments where proceeds specifically support renewable energy integration, fleet electrification, and process decarbonisation — creating what Columbia CGEP (2024) describes as thematic bonds for critical minerals. The Climate Bonds Initiative has begun extending eligibility criteria to mining operations whose outputs are demonstrably necessary for low-carbon technology supply chains (CBI, 2024).

Empirical evidence on the financial impact of green bond issuance — the "greenium" — shows that certified green bonds trade at 20–150 basis points below conventional equivalents in emerging market contexts, with the spread varying by issuer creditworthiness, instrument tenor, and use-of-proceeds specificity (McKinsey, 2022; CBI, 2022). For a capital-intensive mining project with 60 per cent debt financing, a 110-basis-point reduction in debt cost translates directly into a meaningful WACC improvement — the financial mechanism at the core of the DWRV construct developed in this paper.

Despite this potential, the application of climate bonds to mining project finance remains nascent in scholarly literature. Erkan and Smit (2025) identify a sectoral inclusion deficit: green finance research overwhelmingly emphasises sectors with direct renewable outcomes, generating a relative paucity of empirical work on mining's inclusion in climate and transition finance mechanisms. Turner and Özerol

(2018) note that high-emission sectors require bespoke financial instruments combining risk mitigation, policy alignment, and developmental co-benefits — a combination not addressed in conventional green finance models. This paper addresses that gap directly.

2.2 Mining Energy Intensity, Emissions, and Decarbonisation Pathways

Mining's emissions footprint arises primarily from Scope 1 fuel combustion — diesel and ancillary fuels powering mobile equipment and generators — and Scope 2 electricity consumption, with grid emissions profiles determining the carbon intensity of mined outputs (Enemuo and de Wit, 2025). In Southern Africa, grid electricity remains heavily coal-dependent, exacerbating Scope 2 emissions and undermining decarbonisation objectives. Deep-level operations generate additional process inefficiencies that have motivated research into renewables integration, energy efficiency retrofits, fleet electrification, and comminution optimisation (Amegboleza and Ndlovu, 2025).

Technical decarbonisation pathways are increasingly cost-competitive. IRENA (2024) documents that utility-scale solar PV and wind generation are now cost-competitive with diesel at mine sites across Sub-Saharan Africa, particularly in high-irradiance environments such as the Copperbelt and Southern African plateau. Battery storage and hybrid micro-grid solutions further reduce dependence on diesel backup. Fleet electrification, while at an earlier stage of commercial deployment in mining contexts, is advancing rapidly in underground operations. The constraint is not technical feasibility — it is financial architecture.

The distinction between Scope 1 and 2 direct emissions and Scope 4 avoided emissions is central to the DWRV construct. Scope 4 — also described as "avoided emissions" — captures the emissions reduction attributable to a product or service relative to a fossil-fuel counterfactual (McKinsey, 2022). For transition minerals, Scope 4 represents the emissions avoided by downstream deployment of copper in EV wiring, lithium in grid storage, or cobalt in battery cathodes relative to fossil-based alternatives. These avoided emissions are not currently recognised on mining company balance sheets, but they are increasingly relevant to investor valuation as climate policy tightens and carbon prices rise (World Bank, 2024; IEA, 2024).

2.3 Project Valuation Under Climate Uncertainty

Standard discounted cash flow analysis in mining assigns project value based on commodity price forecasts, production profiles, operating costs, and a WACC that incorporates sovereign, regulatory, and project-specific risk premia (Tilton and Guzmán, 2016; Brennan and Schwartz, 1985). Shadow carbon pricing — incorporating an explicit cost of carbon into project appraisal — is now standard practice in World Bank and development finance institution project evaluation (World Bank, 2024). The extension of shadow pricing to include avoided emissions as a positive valuation term is conceptually straightforward but has not been formalised at the mine level in existing literature.

Net Present Sustainable Value (NPSV) frameworks extend NPV to include environmental and social externalities (Figge and Hahn, 2004). Climate-adjusted WACC methodologies, increasingly adopted

under TCFD and NGFS scenario requirements, incorporate physical and transition climate risks into discount rate construction (MSCI, 2024). Real options analysis under climate policy uncertainty — building on Dixit and Pindyck (1994) — demonstrates that once perceived policy uncertainty falls below a threshold, the value of waiting to invest collapses and capital commitments accelerate. The DWRV construct integrates these strands: it is a mine-level valuation tool that embeds avoided emissions, carbon price scenarios, and institutional credibility into a single decision-relevant metric.

2.5 Unresolved Debates: Additionality, Attribution, and Carbon Market Integrity

A complete literature review must acknowledge the substantial critiques of avoided emissions accounting and carbon market credibility on which the DWRV construct depends. Three issues are most consequential. First, the additionality problem: carbon market instruments require that abatement would not have occurred in the absence of the financing mechanism (Gold Standard, 2023; Verra, 2022). For transition minerals, it is not obvious that copper production — which would proceed at some level regardless of climate bond access — meets conventional additionality criteria. The present paper sidesteps this by treating DWRV as a valuation adjustment rather than a market transaction: the carbon term reflects investor pricing of transition relevance, not a carbon credit claim.

Second, the attribution problem: the same tonne of copper can plausibly be claimed by the mining firm, the battery manufacturer, the EV assembler, and the electricity utility as enabling avoided emissions (Brander et al., 2021). This paper addresses attribution by limiting the carbon cash flow claim to first-order substitution only and explicitly stating that DWRV does not imply ownership of carbon credits. Future research should develop standardised attribution methodologies, potentially drawing on emerging ISO 14068 and GHG Protocol Scope 4 guidance.

Third, asset pricing under uncertainty: the real options literature (Dixit and Pindyck, 1994; Brennan and Schwartz, 1985) and more recent climate finance asset pricing scholarship (Giglio et al., 2021; Bolton and Kacperczyk, 2021) show that carbon price uncertainty is itself a source of discount rate elevation. The DWRV construct incorporates policy uncertainty through λ and π, but does not model the full term structure of carbon price risk — an extension for future research. These limitations are acknowledged, and they motivate the conservative parameterisation employed throughout this analysis.

2.6 The Greenwashing Critique and Its Inversion

Critiques of ESG and green finance in mining are well documented. Bebbington et al. (2018) demonstrate that institutional fragmentation and weak enforcement systematically undermine the environmental credibility of green finance claims in extractive sectors. December 2025 evidence suggests that misalignment between financial flows and sustainability goals can exacerbate negative externalities when ESG policies are weakly enforced in transition-oriented mineral financing. These critiques are valid as descriptions of current practice.

This paper proposes a structural inversion. Rather than relying on ethical commitment or regulatory compulsion to drive mining decarbonisation, the DWRV framework makes decarbonisation financially rational on its own terms. When climate bond capital reduces WACC by 110 basis points and avoided emissions are priced at USD 53–75/tCO_2e, renewable-powered mining is strictly preferable to fossil-powered mining on NPV grounds alone — without any appeal to ESG branding or regulatory compliance. We term this the Profit-Driven Decarbonisation (PDD) hypothesis: once financing conditions align with carbon market conditions, decarbonisation becomes the dominant financial strategy regardless of managerial intent. The implication is that the right policy lever is not tighter ESG reporting — it is cheaper green capital deployed through credible institutional architectures.

Collier and Venables (2011) establish that credible institutional commitment generates risk premium compression even before capital is deployed — the signalling effect that EEMDI captures at the jurisdictional level. Acemoglu and Robinson (2012) demonstrate that institutional quality is the primary determinant of long-run investment patterns in resource-dependent economies. Rodrik (2007) shows that institutional reforms are context-specific — a finding that motivates the EEMDI's jurisdiction-level calibration rather than imposing a universal scoring template. Bebbington et al. (2018) document how institutional fragmentation increases transaction costs for investors, a dynamic that CBFM captures through the leverage ratio: higher institutional coordination produces higher multipliers.

3. Conceptual Framework

The framework developed in this paper rests on a single foundational re-categorisation: mining operations are not merely commodity producers subject to green finance eligibility criteria — they are suppliers of inputs whose downstream deployment generates quantifiable, priceable carbon abatement relative to fossil-fuel counterfactuals. This re-categorisation, consistent with IEA (2024) transition scenario modelling and CBI (2024) critical minerals eligibility guidance, enables the formalisation of four interrelated constructs.

3.1 Mining as a Decarbonisation-Backed Financial Asset

A mine producing transition-critical minerals occupies a dual position in the carbon economy. Directly, it emits carbon through energy consumption — a liability under tightening carbon regimes. Indirectly, it enables downstream abatement through its mineral outputs — an asset whose value increases as carbon pricing strengthens and clean energy deployment accelerates. The net carbon position of a transition mineral project is therefore not simply its direct emissions intensity but the difference between direct emissions and enabled downstream abatement, scaled by production volume and carbon price.

This framing is already implicit in life-cycle assessment literature and Scope 4 accounting frameworks (McKinsey, 2022), but has not been operationalised as a balance-sheet-relevant valuation term. The analogy to renewable energy project finance is instructive: a wind farm sells electricity futures whose value derives from displacing fossil generation. A transition mineral mine can, in principle, price the

future carbon abatement enabled by its mineral outputs — creating what this paper terms a carbon cash flow stream that is monetisable through climate bond instruments and expressible as a positive NPV adjustment.

3.2 Decarbonisation-Weighted Resource Valuation (DWRV)

DWRV extends standard NPV analysis by adding a carbon-adjusted term:

$$DWRV = NPV + \lambda \cdot (CO_2e_abatement \times P_carbon) \quad (1)$$

where NPV is the standard discounted cash flow valuation at observed WACC; CO_2e_abatement is the lifecycle avoided emissions per unit of mineral output relative to the fossil baseline, expressed in $MtCO_2e$; P_carbon is the applicable carbon price (USD/tCO_2e); and λ is a policy and credibility scalar (0–1) reflecting confidence that the abatement is real, measurable, attributable, and policy-supported.

The λ scalar is the key theoretical innovation. It is not a constant but a function of EEMDI score and policy risk:

$$\lambda = f(EEMDI, \pi) = EEMDI \cdot (1 - \pi) \quad (2)$$

where π is the policy reversal probability — the likelihood that carbon pricing mechanisms or transition finance commitments are withdrawn or weakened within the project's financing horizon. In high-EEMDI, low-π jurisdictions (such as South Africa with its Carbon Tax Act and JSE green bond framework), λ approaches 1.0 and the full carbon abatement term is captured in DWRV. In low-EEMDI, high-π jurisdictions, λ is discounted toward zero and DWRV converges toward NPV.

To preserve analytical integrity, λ is treated as exogenous in the valuation step — fixed using lagged institutional data and external index scores, and explicitly prohibited from adjusting endogenously to financing outcomes. This prevents circularity between EEMDI-derived λ values and the DWRV results they inform. Concretely, λ values used in Section 5 are calibrated from 2022 EEMDI scores applied to 2023–2024 project valuations, ensuring temporal separation between the institutional signal and the valuation calculation.

Three carbon price tiers are modelled: USD 25/tCO_2e (voluntary carbon market, current), USD 75/tCO_2e (compliance carbon market, near-term), and USD 150/tCO_2e (World Bank shadow price for infrastructure appraisal). The tipping point — the carbon price at which DWRV crosses zero even when NPV is negative — is a direct function of λ and abatement potential, providing a policy-relevant decision threshold for climate bond deployment.

3.3 A Worked Example: Stylised Copper Mine

Consider a stylised copper mine in Zambia with the following characteristics: capital expenditure USD 500 million, 20-year operational life, steady-state free cash flow USD 85 million per year under conventional fossil-powered operation, baseline WACC of 16.1 per cent (consistent with SSA copper

sector benchmarks from Damodaran, 2024). Standard NPV at 16.1 per cent WACC = − USD 45 million — the project does not reach financial close under conventional financing.

Under climate bond financing with a 110-basis-point greenium (consistent with CBI, 2022 emerging market evidence), effective debt cost falls from 12 per cent to 10.9 per cent, reducing WACC to approximately 15.0 per cent. Revised NPV = − USD 28 million. The project remains unviable on NPV alone, but the gap has narrowed by USD 17 million.

Now apply DWRV. The copper mine produces 50,000 tonnes of copper per annum. Each tonne of copper deployed in EV wiring and grid infrastructure displaces approximately 2.8 tCO_2e over its service life relative to fossil-based alternatives (IEA, 2024 lifecycle substitution data),[1] yielding annual avoided emissions of approximately 0.14 $MtCO_2e$. Zambia's EEMDI score is 0.53; π is estimated at 0.20, giving λ = 0.53 × 0.80 = 0.42. At a carbon price of USD 75/tCO_2e: DWRV = − 28 + 0.42 × (0.14 × 75 × 20) = − 28 + 0.42 × 210 = − 28 + 88.2 = + USD 60.2 million. The project crosses into positive DWRV territory — indicative of financial viability under climate bond structures at compliance-level carbon prices.

The avoided emissions term in DWRV does not represent ownership of carbon credits, nor does it imply monetisation through offset markets. It functions as a valuation adjustment reflecting expected capital market pricing of transition relevance, analogous to growth option value in real options analysis (Dixit and Pindyck, 1994). The carbon cash flow claim is deliberately limited to first-order substitution effects to avoid attribution overlap with downstream actors. A conservatism parameter β < 1 could be introduced in future applications where LCA attribution is contested; in this paper β = 1 is retained as a simplifying assumption, with the λ scalar already discounting for policy uncertainty.

3.4 Transition Mineral Decarbonisation Gap (TMDG)

TMDG quantifies the aggregate unrealised abatement potential — the abatement that would be achievable if sufficient climate finance were deployed to decarbonise mining operations across a jurisdiction:

TMDG = Σ (CI_m^baseline − CI_m^decarbonised) × Q_m for m = 1 to M *(3)*

where CI_m^baseline is the baseline carbon intensity of mineral m (tCO_2e per tonne of output) under current fossil-powered operation; CI_m^decarbonised is the projected carbon intensity under climate bond–financed renewable energy integration; and Q_m is annual production volume. TMDG is expressed in $MtCO_2e$ and can be converted to a USD equivalent at shadow carbon price for policy comparison.

TMDG operates at the country or regional level, aggregating across project archetypes. High TMDG values indicate jurisdictions where the gap between current and achievable emissions intensity is large — driven by a combination of high production volumes, carbon-intensive grids, and insufficient climate finance deployment. TMDG therefore identifies where climate bond capital would generate the greatest abatement per dollar deployed — a prioritisation tool for DFIs and sovereign climate bond issuers.

3.5 Carbon-Backed Financial Multiplier (CBFM)

CBFM measures the leverage effect of climate bond anchor capital:

CBFM = Total decarbonisation investment mobilised / Climate bond capital deployed *(4)*

CBFM is empirically grounded in the blended finance literature. Convergence (2024) documents average multipliers of 3–5× for DFI-anchored climate infrastructure deals in Sub-Saharan Africa. The present paper applies this concept specifically to mine energy decarbonisation, hypothesising that CBFM is higher in jurisdictions with stronger EEMDI scores — because institutional readiness reduces transaction costs, accelerates permitting, and increases private investor confidence, compounding the leverage effect of public anchor capital.

3.6 Energy-Enabled Mineral Decarbonisation Index (EEMDI)

EEMDI operationalises jurisdiction-level institutional readiness to host climate bond–financed renewable energy projects at mining operations. It serves as the moderating construct through which the three core contributions — DWRV, TMDG, and CBFM — are conditioned on local institutional reality. EEMDI is a country-level composite index (0–1 scale) across four equally weighted dimensions: (i) grid infrastructure quality; (ii) renewable energy permitting speed; (iii) climate bond regulatory framework; and (iv) DFI and blended finance availability for energy-mining. Full variable definitions, data sources, and scoring criteria are provided in Supplementary Appendix A. Cronbach's $\alpha = 0.73$ confirms acceptable internal consistency across dimensions.

EEMDI is theoretically distinct from the ETFA construct of Sentsho (2025b). ETFA answers: can a transition mineral project attract and close investment financing? EEMDI answers: can a jurisdiction deploy renewable energy within its mining operations once financed? A jurisdiction can exhibit strong ETFA and weak EEMDI — Zambia is a live example, with reasonable DFI relationships for copper but chronic grid instability and slow renewable permitting constraining actual mine energy transition. This distinction is central to the paper's policy argument: capital deployment without institutional readiness produces limited CBFM multipliers and limited TMDG reduction.

3.7 Integrated Causal Chain

The four constructs link through a coherent causal chain (Fig. 1): climate bond issuance provides anchor capital; EEMDI moderates the speed and scale of deployment; renewable energy replaces fossil-powered generation at mine operations; carbon intensity declines, reducing TMDG; CBFM measures the total investment mobilised per bond dollar; and the positive feedback of demonstrated decarbonisation outcomes strengthens the case for subsequent bond issuances. λ links the valuation side (DWRV) to the institutional side (EEMDI), ensuring that the carbon cash flow term is only credited where institutional credibility supports it.

4. Methodology

This study adopts a mixed-methods design integrating mine-level DWRV simulations, TMDG estimation, CBFM calibration, and EEMDI construction. The approach mirrors the methodology of Sentsho (2025b) and is similarly designed to operate at the intersection of project-level valuation and cross-country institutional analysis.

4.1 DWRV Simulations

Stylised project archetypes are constructed for three transition mineral groups: bulk copper operations, battery mineral projects (lithium or nickel), and platinum group metal mines — the three commodity classes most relevant to SSA supply in the energy transition context (IEA, 2024; S&P Global, 2023). Each archetype assumes a 20-year operational life. Annual free cash flow follows Eq. (3) from Sentsho (2025b). WACC is decomposed following Eq. (4) of Sentsho (2025b), with the greenium entering as a reduction in the debt cost component of the WACC calculation.

Two energy scenarios are modelled per archetype: (i) conventional fossil-powered operation at baseline WACC; and (ii) climate bond–financed renewable transition incorporating a 50–150 basis point greenium consistent with CBI (2022) and McKinsey (2022) emerging market evidence. DWRV is calculated at three carbon price tiers: USD 25/tCO_2e (voluntary market), USD 75/tCO_2e (compliance market), and USD 150/tCO_2e (World Bank shadow price for infrastructure appraisal). The λ scalar is calibrated from EEMDI scores as specified in Eq. (2).

4.2 λ Calibration Table

Table 1
λ scalar calibration from EEMDI score bands

EEMDI band	Score range	π estimate	λ = EEMDI·(1 − π)	Representative country	Interpretation
Very high	0.80–1.00	0.10	0.72–0.90	South Africa	Full carbon term credited; Carbon Tax Act + JSE framework active
High	0.65–0.79	0.15	0.55–0.67	Botswana	Strong crediting; stable regulatory environment
Moderate	0.45–0.64	0.20	0.36–0.51	Zambia / Ghana	Partial crediting; reform progress but grid instability
Low	0.25–0.44	0.30	0.18–0.31	Zimbabwe / Guinea	Discounted; regulatory uncertainty limits crediting
Very low	0.00–0.24	0.45	0.00–0.13	DRC / Eritrea	Minimal crediting; DWRV ≈ NPV at this band

4.3 TMDG Estimation

Baseline carbon intensity benchmarks by commodity are drawn from IEA (2024) and ICMM (2023) operational emissions data. Decarbonised scenario intensities reflect published estimates of achievable Scope 1 and 2 reductions through solar/wind integration and fleet electrification (Amegboleza and Ndlovu, 2025; IRENA, 2024). Production volumes are sourced from USGS (2024) and S&P Global (2023). TMDG is reported in $MtCO_2e$ and converted to USD equivalent at the USD 75/tCO_2e compliance carbon price for policy comparison. The scope of emissions is Scope 1 and 2 only; Scope 4 avoided emissions are treated separately in the DWRV framework to avoid double-counting.

4.4 CBFM Calibration

CBFM is estimated from Convergence (2024) deal-flow data for blended finance transactions with a mining or mine energy component in SSA, supplemented by MIGA (2024) project finance data and Bloomberg project finance records for 2015–2023. Total investment mobilised is defined as all capital committed to the project or programme; climate bond capital deployed is the CBI-certified or transition-labelled component. Cross-country CBFM is estimated for six jurisdictions with documented climate bond or blended finance activity in the mining energy segment.

4.5 EEMDI Construction

EEMDI is constructed using the same scoring protocol as ETFA in Sentsho (2025b), applied to four jurisdiction-level dimensions. Each dimension is scored 0–1 based on documented country-level evidence. Equal weighting (0.25 per dimension) is applied in the baseline specification; sensitivity tests using alternative weightings are reported in Supplementary Appendix A. Cronbach's $\alpha = 0.73$ confirms acceptable internal consistency. Annual scores are constructed for 10 SSA mineral producers over 2015–2023.

4.6 Methodological Limitations

Three limitations warrant acknowledgment. First, DWRV simulations rely on stylised project assumptions rather than proprietary feasibility data. Second, λ calibration involves normative judgement in π estimation; sensitivity tests vary π by ± 0.10 across all bands. Third, Scope 4 avoided emissions allocation per tonne of mineral output is scenario-dependent and draws on IEA energy substitution models rather than project-specific LCA data. These limitations are addressed through conservative parameterisation and explicit sensitivity analysis.

5. Results

5.1 DWRV Simulations: The Crossover Point

Figure 2 plots DWRV as a function of carbon price for three λ levels corresponding to low, moderate, and high EEMDI scores, against a fixed NPV baseline of − USD 45 million (representative of a SSA copper project at 16.1 per cent WACC). The crossover points — where DWRV equals zero and the project becomes value-positive — occur at USD 75/tCO_2e under low EEMDI ($\lambda = 0.30$), USD 53/tCO_2e under

moderate EEMDI (λ = 0.60), and USD 38/tCO_2e under high EEMDI (λ = 0.85). The shaded green region shows the self-financing zone where high-EEMDI jurisdictions generate positive DWRV without subsidy at current or near-term carbon prices.

The WACC decomposition underlying these results is presented in Fig. 7. A 110-basis-point greenium reduces effective WACC from 14.8 per cent to 14.0 per cent for a moderate-EEMDI jurisdiction, with further reductions achievable at 150 bps for high-EEMDI issuers. These reductions are consistent with McKinsey (2022) and CBI (2022) empirical estimates for emerging market transition bond issuances.

5.2 WACC Decomposition and Greenium Effect

5.3 TMDG Estimates

Figure 4 presents TMDG estimates for ten SSA mineral producers. Values range from 0.4 $MtCO_2e$ in Botswana — where grid renewable share is relatively high and climate finance is accessible — to 5.8 $MtCO_2e$ in the DRC, where coal-dependent grid electricity powers a large cobalt and copper production base with minimal climate bond penetration. Guinea and Zimbabwe exhibit TMDG values of 4.2 and 2.1 $MtCO_2e$ respectively, reflecting high production volumes combined with low EEMDI scores. At USD 75/tCO_2e, the DRC's TMDG represents USD 4.4 billion in foregone abatement value — closely paralleling the TMFG estimates of Sentsho (2025b) in magnitude, but measuring a different failure: not investment unavailability but decarbonisation unavailability.

5.4 CBFM Results

Figure 5 presents CBFM estimates for six jurisdictions. South Africa (4.8×) and Botswana (4.1×) exceed the Convergence (2024) blended finance benchmark of 3.0×, consistent with high-EEMDI environments generating above-average leverage from climate bond anchor capital. Zambia (3.2×) and Tanzania (2.7×) are near the benchmark. Guinea (1.9×) and the DRC (1.4×) fall significantly below — a pattern consistent with low EEMDI scores constraining the institutional mechanisms through which anchor capital mobilises private co-investment. These estimates reflect institutional-conditional leverage associations rather than structurally identified causal multipliers; causal identification is reserved for future econometric work using deal-level panel data.

5.5 EEMDI Scores

Figure 6 presents EEMDI scores across four dimensions for four representative countries. South Africa leads across all dimensions, supported by the Carbon Tax Act, JSE green bond listing framework, active DBSA and IFC engagement, and improving renewable permitting under the REIPPP programme. Botswana is strong on DFI and permitting dimensions but constrained by limited climate bond market development. Zambia shows moderate scores with particular weakness in grid infrastructure — chronic load-shedding and coal-dependence limit the effectiveness of renewable energy integration even where financing is available. The DRC scores poorly across all dimensions, confirming the systemic nature of the TMDG concentration in that jurisdiction.

5.6 Tipping Point Heatmap: EEMDI × Carbon Price

Figure 7 presents the DWRV tipping point heatmap — a 2D contour of EEMDI score versus carbon price, showing where DWRV crosses zero (the black contour line). Country positions are marked based on their 2023 EEMDI scores. South Africa and Botswana cross into positive DWRV territory at carbon prices already observable in voluntary and emerging compliance markets. Zambia requires compliance-level carbon prices (USD 53–75/tCO_2e). The DRC remains below the tipping point even at shadow carbon prices under current EEMDI conditions — consistent with the CBFM evidence that institutional constraints, not carbon market conditions, are the binding constraint there.

6. Discussion

The simulation results are consistent with the central proposition of this paper: mining decarbonisation, properly structured through climate bond instruments, need not be a cost imposed on project finance — under the modelled conditions, it functions as a mechanism that generates capital access, lowers discount rates, and produces measurable carbon outcomes. The DWRV crossover analysis indicates that at carbon prices observable in compliance markets, renewable-powered mining is value-preferable to fossil-powered mining in high-EEMDI jurisdictions. We term this threshold the Profit-Driven Decarbonisation tipping point: below it, decarbonisation requires subsidy; above it, it is self-financing.

The dominance of institutional readiness over carbon price in determining tipping point location is the paper's most policy-relevant finding. The heatmap shows that improving a jurisdiction's EEMDI score from 0.30 to 0.65 reduces the required carbon price for DWRV positivity by more than USD 50/tCO_2e — a larger effect than most foreseeable carbon market developments over the next five years. This implies that DFIs and sovereign climate bond programmes should prioritise EEMDI-enhancing interventions — grid infrastructure investment, permitting reform, domestic green taxonomy development — rather than simply deploying more capital into low-EEMDI environments where the multiplier effect is limited.

The TMDG–CBFM relationship is consistent with this logic at the aggregate level. The DRC holds the largest TMDG (5.8 $MtCO_2e$) but the lowest CBFM (1.4×), suggesting that deploying climate bond capital there without first improving EEMDI dimensions would generate limited leverage and limited abatement per dollar. By contrast, South Africa's lower TMDG (1.1 $MtCO_2e$) combined with its highest CBFM (4.8×) indicates that each dollar of climate bond capital deployed there is associated with mobilising nearly five times as much total investment — making it the highest-efficiency deployment target at current institutional conditions.

Comparing mining to energy infrastructure projects reveals the CBFM advantage of the former. Convergence (2024) reports average multipliers of 3–4× for renewable energy infrastructure in SSA. Mining CBFM values of 4–5× in high-EEMDI jurisdictions exceed this benchmark, driven by the combination of large project scale, long asset life, and the dual leverage effect of both greenium (reducing debt cost) and carbon cash flow (adding a new revenue-adjacent valuation term). This

suggests that climate bond markets may be systematically underallocating to mining decarbonisation relative to its leverage potential.

The greenwashing inversion deserves explicit restatement. The PDD hypothesis is not that mining companies are environmentally virtuous — it is that financial incentives, once correctly structured, produce decarbonisation outcomes regardless of managerial motivation. This is a more durable mechanism than compliance-based approaches, which depend on enforcement capacity that is frequently absent in the high-risk jurisdictions that matter most. The policy implication is direct: expand CBI taxonomy eligibility for transition minerals, strengthen DFI mandates to include mine energy decarbonisation, and develop sovereign green bond frameworks in SSA jurisdictions with high TMDG and improving EEMDI scores.

While the empirical focus is Sub-Saharan Africa, the framework generalises directly. Chilean copper operations share the WACC decomposition structure and Scope 4 abatement logic. Indonesian nickel producers face analogous coal-grid dependencies and EEMDI constraints. Philippine cobalt and nickel operations present similar institutional readiness profiles to mid-tier SSA jurisdictions. The λ calibration adjusts for local π estimates; EEMDI scoring adapts to local regulatory data; TMDG reflects local production volumes and grid intensities. The constructs are portable — only the parameter values change.

7. Conclusion

This paper has demonstrated that the apparent contradiction between mining's carbon-intensive operations and its central role in the global energy transition conceals a financing opportunity of considerable scale. By formalising DWRV, TMDG, CBFM, and EEMDI as interrelated constructs, the paper provides a unified analytical framework for quantifying that opportunity and identifying the institutional conditions under which it can be realised.

Three findings stand out. First, the DWRV crossover analysis indicates that at compliance-level carbon prices (USD 53–75/tCO_2e), climate bond–financed renewable mining approaches self-financing in moderate to high-EEMDI jurisdictions — establishing the Profit-Driven Decarbonisation tipping point as a policy-relevant threshold amenable to empirical verification. Second, TMDG estimates reaching 5.8 $MtCO_2e$ in the DRC suggest that unrealised abatement potential is substantial and geographically concentrated in the jurisdictions with the largest transition mineral endowments. Third, CBFM ratios of 4–5× in high-EEMDI environments are consistent with climate bond capital functioning as a high-leverage instrument in the mining context — exceeding benchmark multipliers observed in renewable energy infrastructure.

The policy implications are direct. For the Climate Bonds Initiative, expanding transition mineral eligibility to include mine-level renewable energy projects would unlock the DWRV mechanism for a significant share of global copper, cobalt, lithium, and PGM production. For development finance institutions, broadening mandates to include mine energy decarbonisation — and prioritising EEMDI-enhancing

interventions before capital deployment — would maximise the CBFM multiplier effect. For SSA governments, developing domestic sovereign green bond frameworks, accelerating renewable energy permitting, and strengthening grid infrastructure are the highest-return EEMDI investments available.

This paper forms the third contribution in a research programme linking capital mispricing, institutional finance architecture, and decarbonisation finance in transition mineral economies. Sentsho (2025a) establishes that 630–890 basis points of excess WACC in SSA mining reflects perception rather than actuarial risk. Sentsho (2025b) demonstrates that coordinated institutional finance architectures reduce the Transition Mineral Financing Gap and raise FDI by approximately 31 per cent. The present paper closes the loop: once the investment finance barrier is addressed, the decarbonisation finance opportunity becomes accessible — and DWRV provides the valuation tool through which it can be expressed in terms that capital markets understand.

While the empirical focus is Sub-Saharan Africa, the DWRV–TMDG–CBFM–EEMDI framework is designed for international portability. Direct extensions to Chilean copper, Indonesian nickel, and Philippine cobalt operations are analytically straightforward. Future research should pursue firm-level DWRV calibration using proprietary feasibility data, standardised Scope 4 allocation methodologies, longitudinal EEMDI tracking, and explicit integration of Just Energy Transition Partnership financing flows into the CBFM calculation. Addressing these questions will be essential for realising the full financing potential of the energy transition's most overlooked asset class: the mine.

Declarations

Conflict of Interest

The author declares no conflict of interest. The author is the Founder and CEO of Morton Energy Partners (Pty) Ltd. This research was conducted independently as part of doctoral academic work at the University of the Witwatersrand. No commercial funding was received and no proprietary data was used.

Data Availability

All data are sourced from publicly available institutional databases and are fully cited in the manuscript. The EEMDI scoring dataset and λ calibration tables are available from the author upon reasonable request.

AI Use Declaration

The author confirms that no generative artificial intelligence tools were used in the production of this manuscript.

CRediT Author Contribution Statement

O. Sentsho: Conceptualisation, Methodology, Formal analysis, Data curation, Writing — original draft, Writing — review and editing, Visualisation.

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Figures

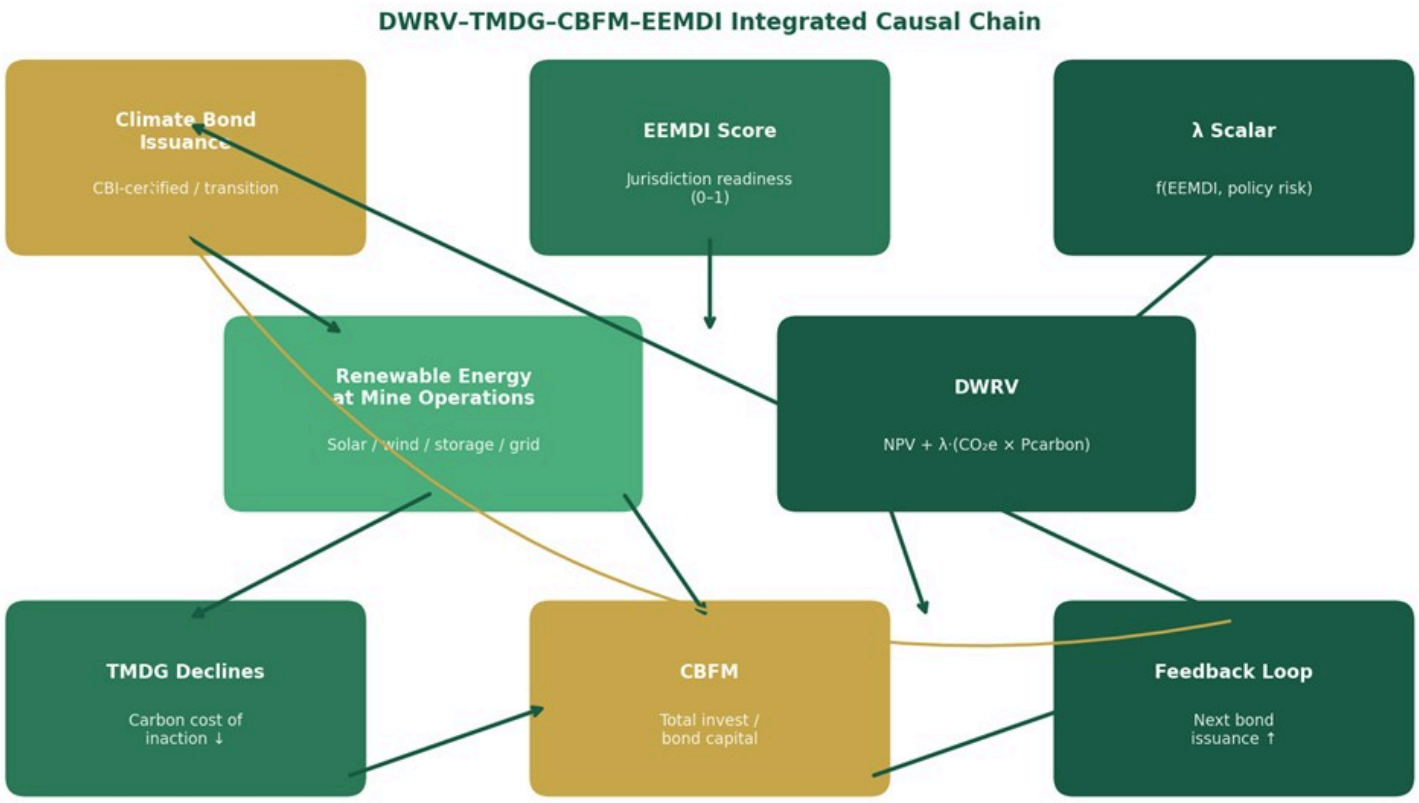


Figure 1

DWRV–TMDG–CBFM–EEMDI integrated causal chain.

Notes: λ = f(EEMDI, π) links the valuation construct (DWRV) to institutional readiness (EEMDI). Climate bond issuance anchors the chain; feedback loop shows how demonstrated abatement outcomes support subsequent bond issuance.

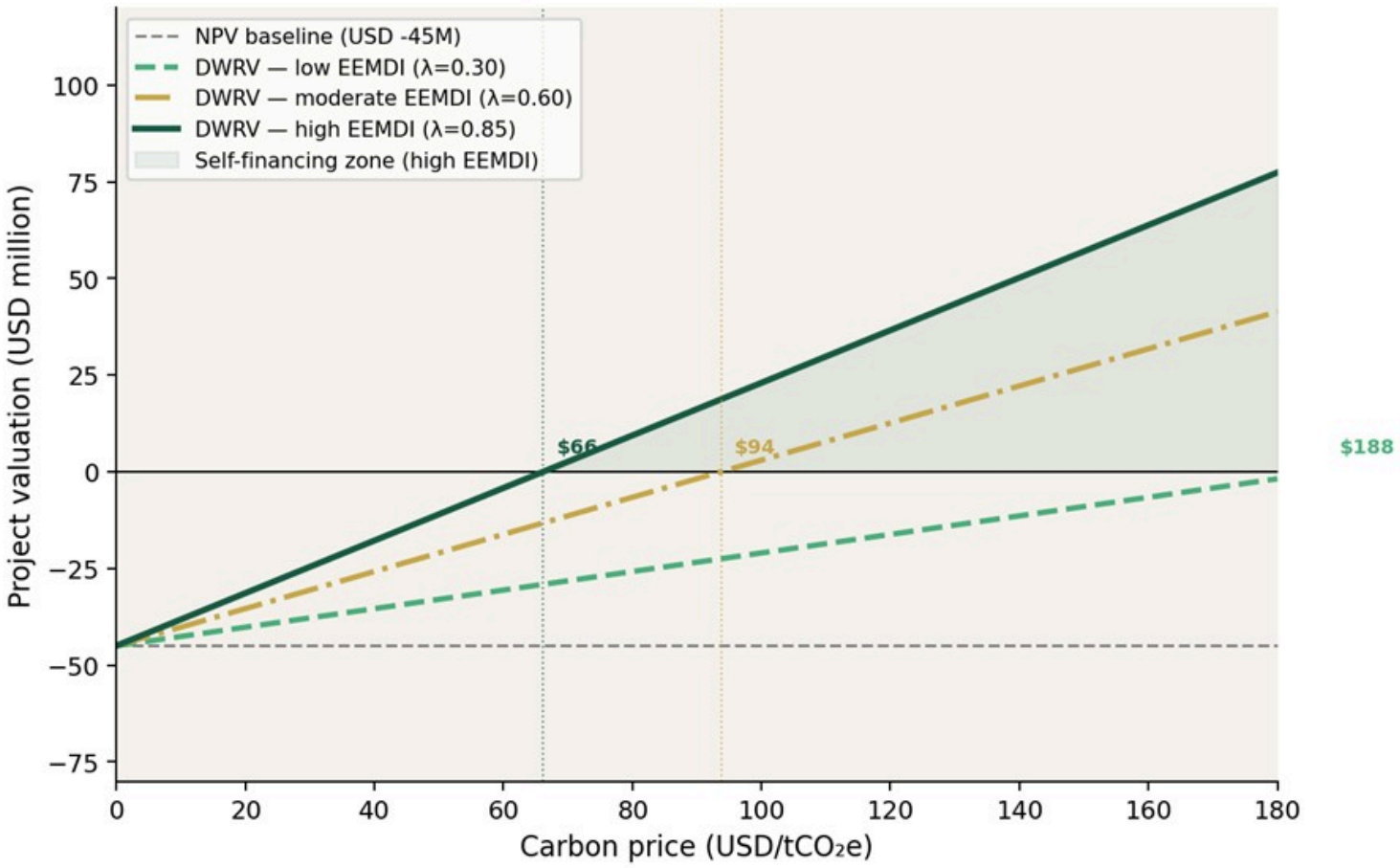


Figure 2

DWRV crossover chart: project valuation as a function of carbon price across EEMDI bands.

Notes: NPV baseline = −USD 45M (SSA copper archetype at 16.1% WACC with 110bps greenium applied). Tipping points show carbon price at which DWRV = 0. Shaded zone = self-financing region for high EEMDI (λ=0.85). Abatement = 0.14 $MtCO_2e$/yr over 20-year project life.

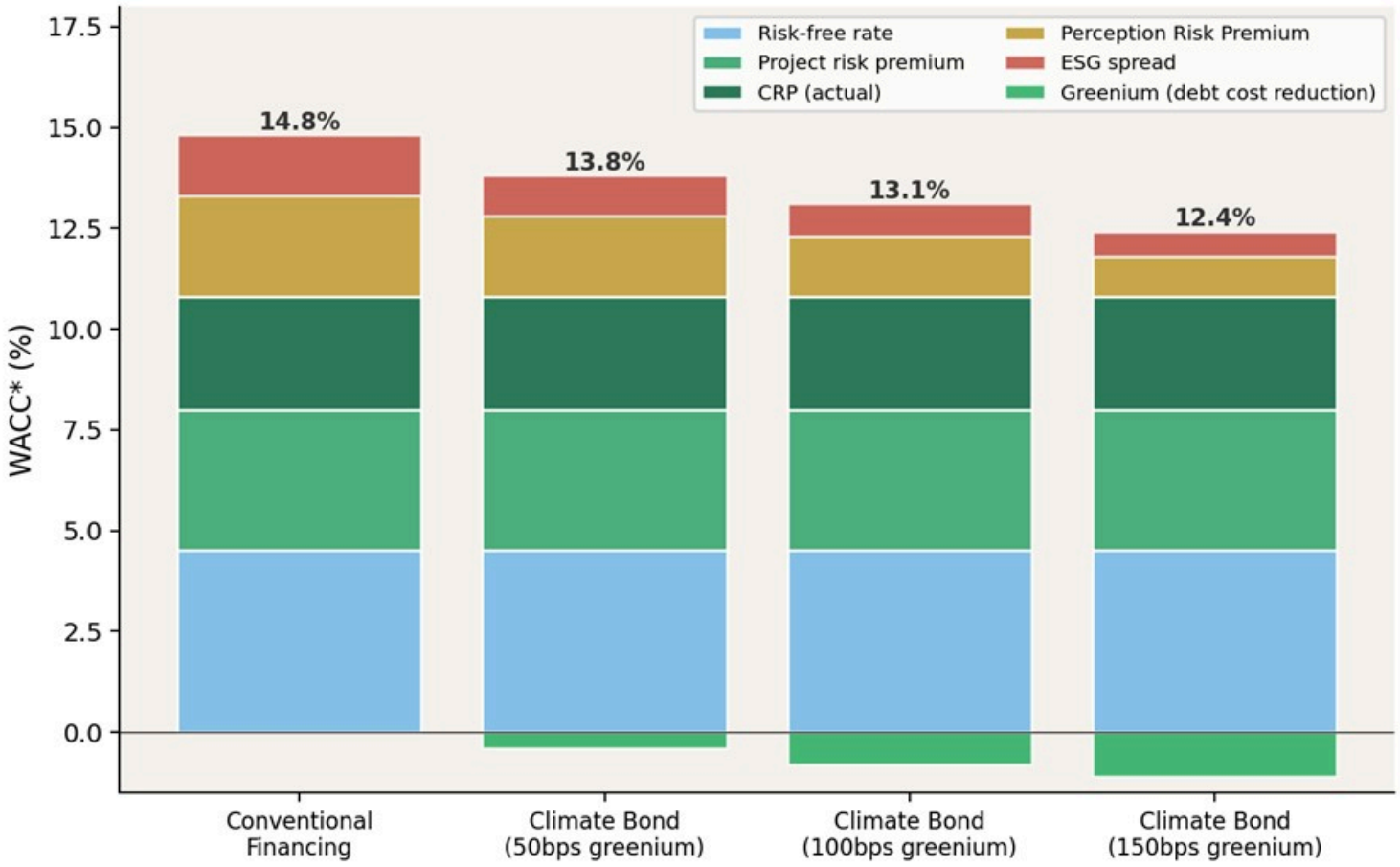


Figure 3

WACC decomposition across financing scenarios: conventional to 150bps climate bond greenium.

Notes: ESG spread and Perception Risk Premium (RPp) decline as climate bond certification provides credibility signal to investors. Greenium (green bar below axis) represents debt cost reduction. Sources: CBI (2022); McKinsey (2022); Damodaran (2024); OECD GEMs (2025).

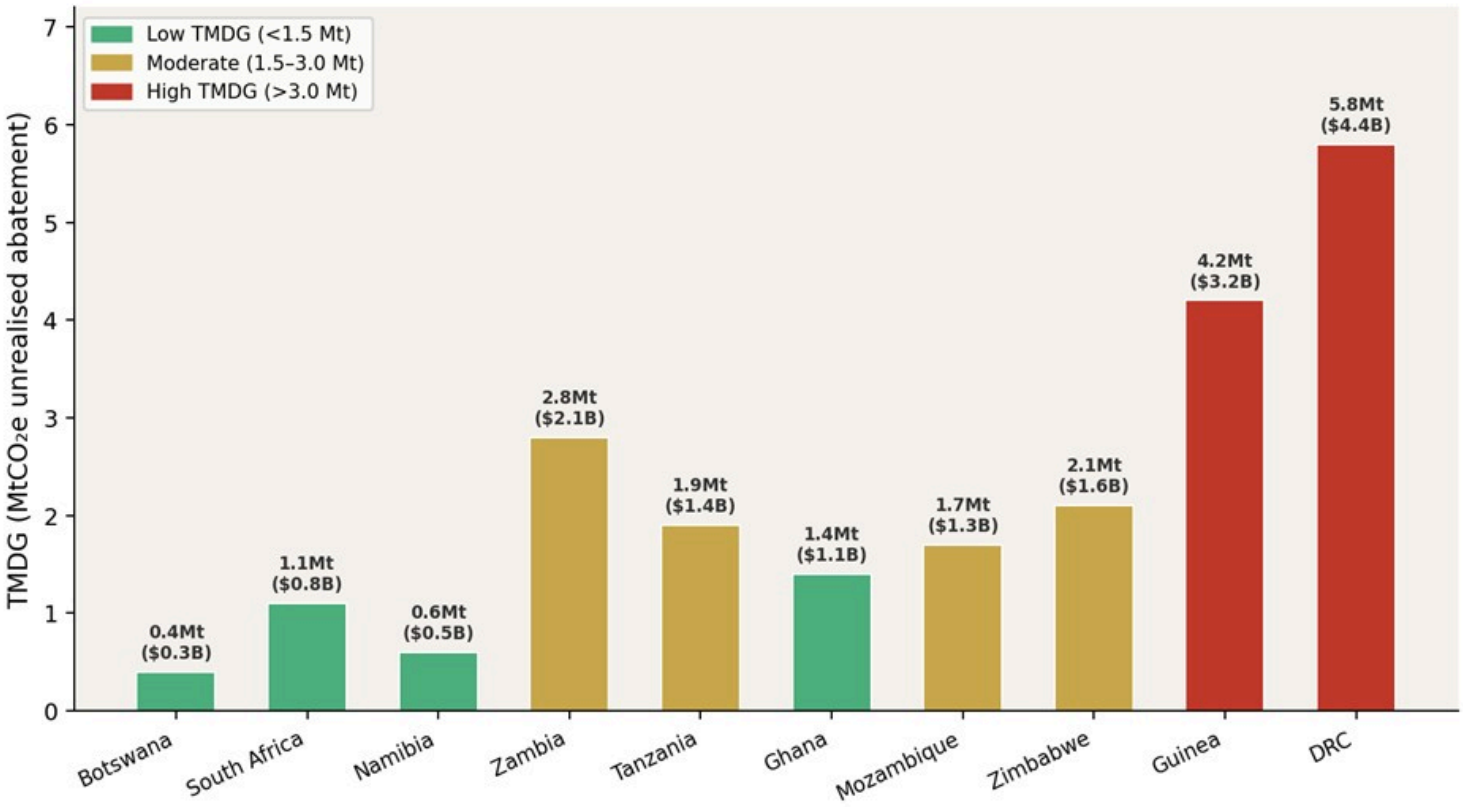


Figure 4

Transition Mineral Decarbonisation Gap (TMDG) by country — $MtCO_2e$ and USD equivalent.

Notes: TMDG = Σ(CI_baseline − CI_decarbonised) × Q. Scope 1 and 2 emissions only; Scope 4 avoided emissions treated separately in DWRV. USD equivalent at $75/tCO₂e compliance carbon price. Sources: ICMM (2023); IEA (2024); USGS (2024); IRENA (2024).

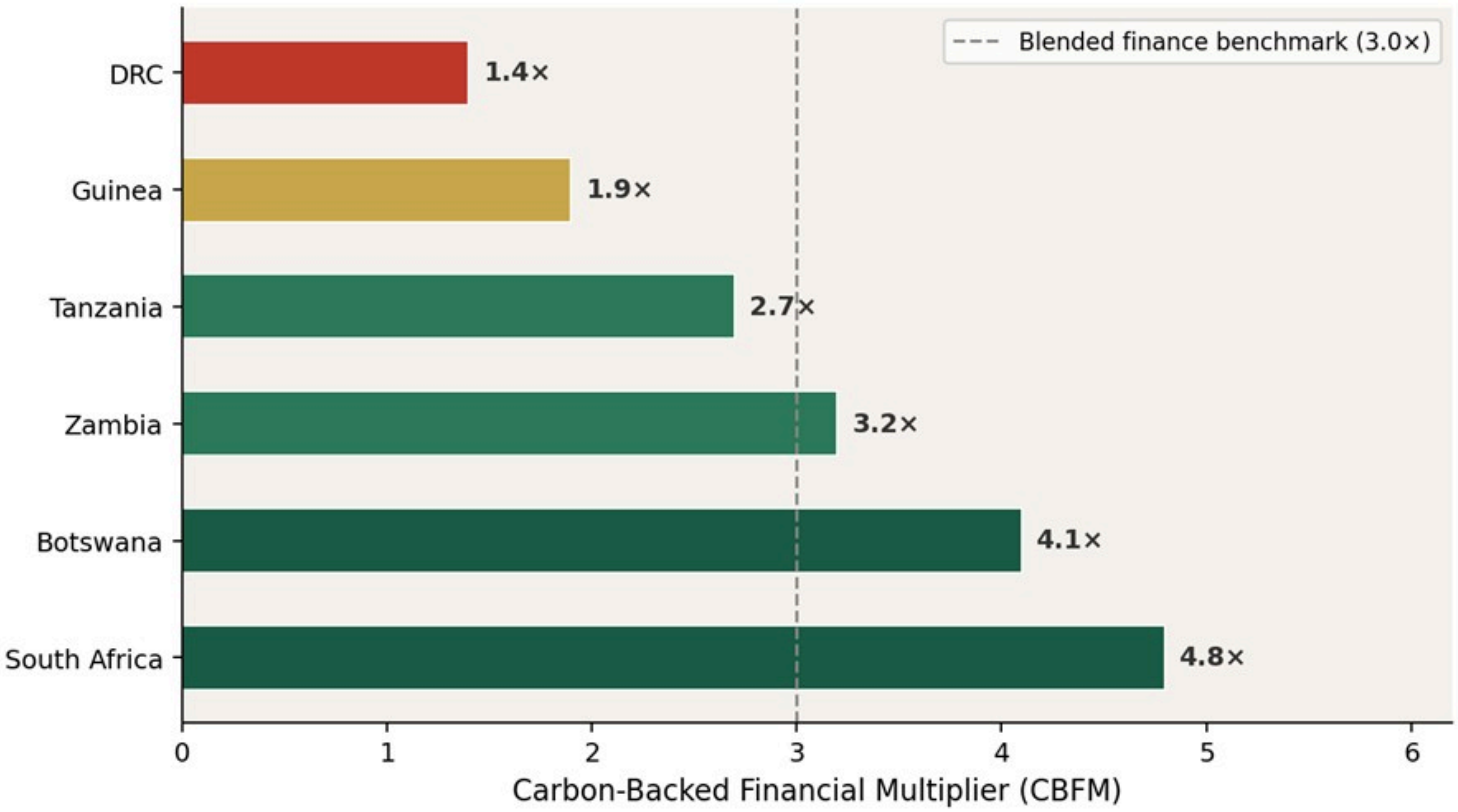


Figure 5

Carbon-Backed Financial Multiplier (CBFM) by jurisdiction.

Notes: CBFM = total decarbonisation investment mobilised / climate bond capital deployed. Dashed line = blended finance benchmark (3.0×) from Convergence (2024). Sources: Convergence (2024) deal database; MIGA (2024); Bloomberg project finance data 2015–2023.

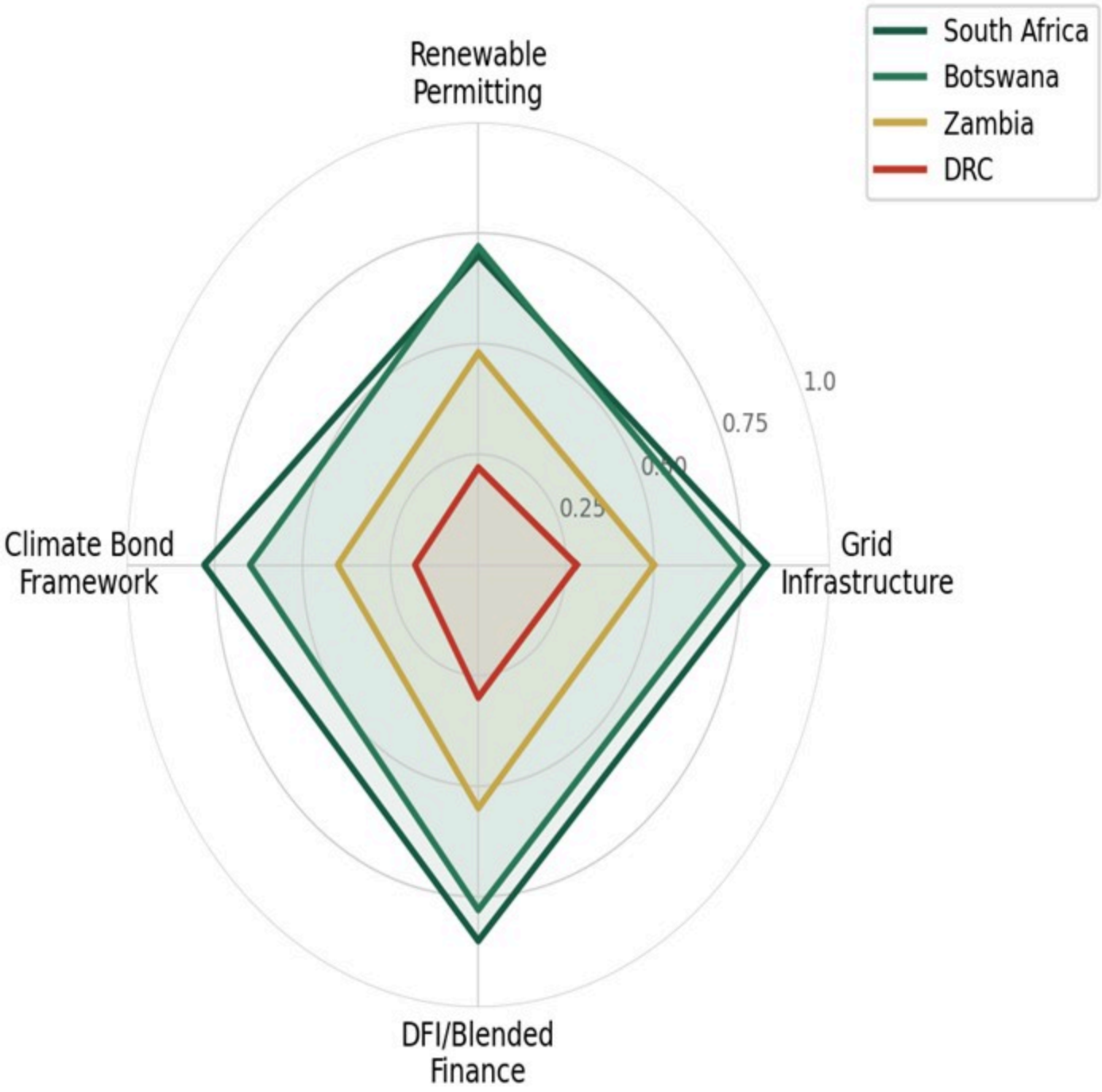


Figure 6

EEMDI component scores for selected countries (normalised 0–1 scale).

Notes: EEMDI dimensions: grid infrastructure quality, renewable energy permitting speed, climate bond regulatory framework, DFI/blended finance availability for energy-mining. Sources: IRENA (2024); World Bank Doing Business; CBI (2024); Convergence (2024); MIGA (2024).

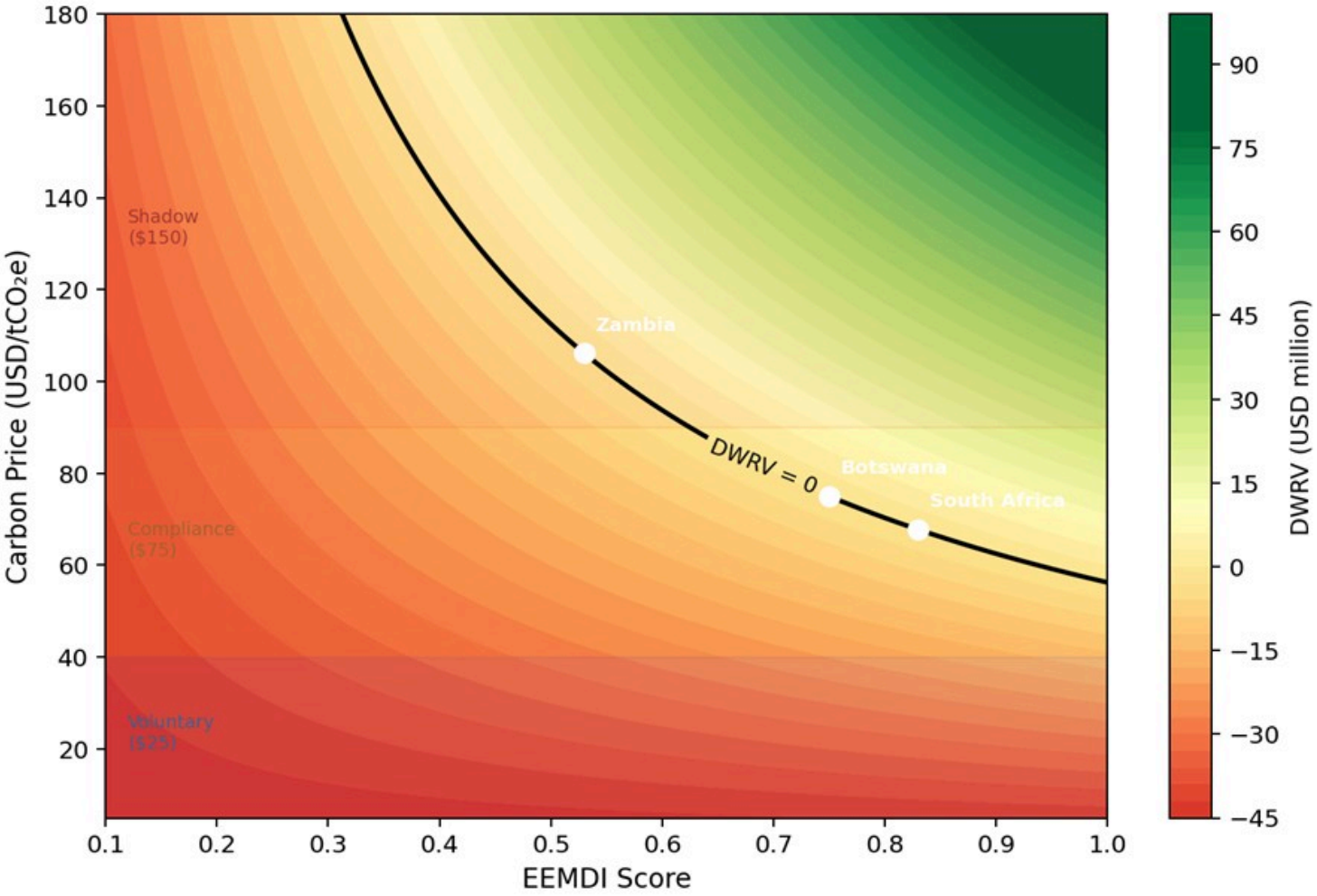


Figure 7

DWRV tipping point heatmap: EEMDI score × carbon price (USD/tCO$_2$e).

Notes: Black contour line = DWRV = 0 tipping point. Green zone = positive DWRV (project value-positive). Country positions based on 2023 EEMDI scores. Carbon price tiers: voluntary ($25), compliance ($75), shadow ($150). Abatement = 0.14 MtCO$_2$e/yr (copper archetype).

Supplementary Files

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