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Can Landfill Mining Be a Sustainable Alternative for Strategic-Metal Recovery? A Price-Indexed Contained-Value Screening Model for Closed Landfills and Mine-Waste Deposits in Portugal

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Abstract

Background

Closed landfills and abandoned mine-waste deposits are increasingly read as anthropogenic reservoirs of strategic metals, yet the value of Portugal's deposits has never been quantified in economic terms, even as the European Critical Raw Materials Act intensifies the search for secondary sources.

Methods

A first-order screening model separates gross in-place contained value, computed from published assays and mid-2026 market prices, from recoverable value obtained through published recovery efficiencies; it adds an explicit avoided-liability credit and derives a break-even frontier, applied to deposit archetypes anchored on Iberian Pyrite Belt data.

Results

Polymetallic sulphide hotspots carry more than US$200 per tonne in gross contained metal, of which roughly 62 to 77 percent is recoverable, and stay profitable across realistic processing costs, whereas bulk material does not.

Conclusions

Landfill mining can be sustainable where grade, recovery, and avoided liability coincide, rather than as an undifferentiated strategy.

Introduction

Landfill mining, understood here as the controlled excavation, processing, and valorization of materials previously consigned to landfills, tailings impoundments, and uncontrolled dumpsites, has travelled over four decades from a niche remediation tactic toward a candidate instrument of resource policy [1]. The early projects were modest in ambition. They recovered cover soil, reclaimed disposal volume, and treated localized pollution, while the recovery of marketable materials remained almost incidental [1]. The interest that has gathered around the practice more recently is different in kind. It is driven less by the scarcity of disposal capacity than by the scarcity, and the geopolitical exposure, of the metals on which electrification, digital infrastructure, and defense supply chains have come to depend. Europe occupies an uncomfortable position in this respect, importing the large majority of the base and critical metals it consumes while hosting, within its own borders, an inventory of several hundred thousand legacy landfills together with an extensive legacy of abandoned mining sites [2]. The question that motivates the present study is therefore not whether buried waste can be excavated, which is settled, but

whether the metal it contains is worth recovering once prices, recoverable fractions, and avoided liabilities are weighed together.

Portugal is an unusually instructive setting for that question, because its territory combines a long industrial mining history with a still-incomplete transition to modern waste management. The Iberian Pyrite Belt, one of the largest metallogenic provinces in the world, was exploited for more than a century and left behind impoundments and dump-fields whose residual contents are far from negligible. Recent characterization of waste from abandoned copper and manganese mines in the belt has shown copper, manganese, and rare earth elements at concentrations well above their crustal abundance, with chalcopyrite, pyrolusite, and rhodochrosite among the recovered phases and cobalt, lithium, and tungsten identified as accessory targets [3]. Complementary drilling at the São Domingos complex has framed the same material through the explicit language of remining, estimating the economic potential of accumulated sediments and pointing to silver and scandium as candidate by-products of a rehabilitation strategy built on circular-economy premises [4]. These findings matter because the circular economy, for all the breadth of its interpretations, is ultimately tested by whether secondary materials can re-enter supply chains on economic terms rather than rhetorical ones [5]. Landfill mining sits squarely within that test, since it promises to convert environmental liabilities into assets while contributing to climate objectives through the recovery of materials, nutrients, and energy [6].

The deeper rationale for revisiting these deposits is the divergence between two trends in the supply of strategic metals. On one side, the grades of primary ore are falling and the geopolitical concentration of supply is rising, so that the marginal cost and the marginal risk of fresh extraction both climb. On the other, the stock of metal already mobilized into anthropogenic deposits is large, surficial, and partly characterized, which lowers the exploration cost that dominates greenfield projects. Portugal embodies the contrast with particular sharpness, because its richest legacy deposits sit at the surface in unconsolidated form, sometimes within a few hundred metres of population, and because the metals they contain include precisely those that European industry now treats as critical. The Panasqueira complex, one of the largest tungsten mines in the world, has accumulated very large volumes of waste-rock whose potential reuse has been examined for exactly this reason [7], and reprocessing studies at the associated Cabeço do Pião impoundment have shown that zinc, tungsten, and copper can be concentrated from tailings as a combined remediation-and-revenue operation [8]. The screening question, then, is whether the economics that these scattered studies hint at survive a consistent, price-indexed accounting, and that is the question the present model is built to answer.

The optimism of that promise has to be reconciled with a sober record. Systematic reviews of ex ante economic and environmental assessments have repeatedly found that most landfill-mining projects forecast non-profitability, and that the economic logic underpinning them is frequently left as a black box [9]. Where enhanced landfill mining has been modelled in detail, the thermal treatment of the combustible fraction tends to dominate both cost and environmental burden, so that profitability hinges on parameters far removed from the metal content itself [10]. Efforts to bring discipline to the field have borrowed the resource-and-reserve grammar of primary geology, applying the United Nations Framework

Classification to ask whether landfilled material constitutes a resource or a reserve, and concluding that the answer turns on technology and price rather than on tonnage alone [11]. Parallel work in Austria has laid out the technical, economic, and regulatory foundations for an integrated assessment, while stressing that the relevant system boundaries must be set project by project [12]. What is missing, for Portugal specifically, is the economic screening layer that would translate the qualitative claim that its deposits are rich into figures a decision-maker could act on. Portuguese life-cycle research has compared municipal-waste management alternatives with considerable rigor [13], yet no comparable analysis exists for the recovery of strategic metals from the country's closed landfills and mine-waste deposits.

This study addresses that gap with a deliberately first-order, price-indexed contained-value screening model. The model performs three operations that, taken together, distinguish it from generic enhanced-landfill-mining frameworks calibrated on northern-European municipal waste. First, it separates the gross in-place contained value of a deposit from the value that is actually recoverable, by passing the former through published recovery efficiencies rather than assuming complete extraction. Second, it introduces an explicit avoided-liability credit, so that hazardous constituents such as arsenic enter the calculation as a remediation benefit rather than as a notional revenue, which keeps the economics honest about what the market will and will not pay for. Third, it derives a transparent break-even frontier that exposes the conditions under which recovery becomes rational. Applied to deposit archetypes anchored on hard Iberian Pyrite Belt data, the model converts the rhetoric of abundance into defensible per-tonne estimates and identifies, rather than asserts, where landfill mining in Portugal is worth pursuing. The contribution is conceptual rather than experimental, and it is offered as the screening instrument that the national debate currently lacks.

Methodology

Analytical framework and scope

The model treats one tonne of in-situ deposited material as the unit of analysis and asks a single screening question of it: does the value that can be recovered, once netted against the cost of recovery and credited with any liability avoided, exceed zero. This framing is deliberately conservative and transparent, because the purpose is not to substitute for a full feasibility study but to filter a large and heterogeneous population of deposits down to those that merit one. The approach follows the resource-and-reserve logic that has proven useful for anthropogenic deposits, in which material is classified by reference to the prospect of economic extraction rather than by its mere presence [11], and it adopts the principle, established for integrated landfill-mining assessment, that economic, environmental, and technical factors are mutually conditioning and must be evaluated together [12]. Three deposit archetypes structure the analysis. The first is the polymetallic sulphide mine-waste typical of the Iberian Pyrite Belt, for which hard assay data exist. The second is the acid-mine-drainage-affected dump, exemplified by São Domingos, where copper and silver dominate the recoverable basket. The third is the residue monofill, represented by municipal-waste incineration residues, where metal grades are lower but

other value streams may apply. The quantitative core of the study is developed for the first archetype, because it offers the most defensible grades, and the remaining archetypes are treated comparatively. The overall logic of the screen, from deposit characterization through valuation to the break-even decision, is summarized in Fig. 1.

Several assumptions follow from the screening purpose and are stated plainly so that the model can be challenged on its own terms. The analysis is static, taking a single price snapshot rather than a forward curve, because the aim is to locate the present margin and its sensitivity rather than to forecast it; the volatility of the markets is then addressed through the break-even frontier rather than through speculative price paths. Capital recovery, discounting, and the time value of money are deliberately omitted at this stage, since they belong to the project-level feasibility study that screening is meant to precede, and their inclusion would impose a spurious precision on inputs that are themselves indicative. Only metals for which both a published grade and a liquid reference price exist are admitted to the valuation, which excludes scandium and the rare earth elements that the source studies flag qualitatively but do not quantify at these sites. The deposit is treated as a homogeneous tonne for the purpose of the screen, even though heterogeneity is its defining feature, precisely so that the consequences of grade variation can be examined explicitly rather than buried in an average. These choices make the model transparent and conservative, and they keep its outputs interpretable as a filter rather than a forecast.

Data sources for deposit grades and recovery efficiencies

All concentrations entering the model are drawn from published field studies rather than from new sampling, which both grounds the analysis in observed reality and respects the screening purpose. The anchor dataset is the geochemical survey of the Aljustrel mining area, in which principal-component analysis of soil and tailings identified severe contamination with copper reaching 5,414 mg/kg, lead and zinc each reaching 20,000 mg/kg, arsenic reaching 3,936 mg/kg, antimony reaching 980.6 mg/kg, and cadmium reaching 22 mg/kg in the most enriched zones [14]. Comparable enrichment is documented at the Caveira abandoned mine, where copper, lead, zinc, arsenic, cadmium, and mercury accumulate in soils near the tailings [15], and at São Domingos, whose dump-fields show an irregular spatial distribution of potentially toxic elements that frequently exceed national and European limits [16]. The mineralogical context, which conditions both mobility and recoverability, is provided by studies showing that trace elements concentrate in the clay-size fraction of mining soils [17] and that iron- and arsenic-rich nanoprecipitates associate with clay minerals in sulphide-rich dumps [18]. For the residue-monofill archetype, a first-generation incinerator-residue landfill furnishes representative ranges, with copper up to 5,498 mg/kg, lead up to 9,806 mg/kg, and zinc up to 11,453 mg/kg [19], while an Iberian survey of incineration bottom ash confirms that ferrous and non-ferrous metals are already recovered at the few percent level in Portugal [20]. The acid-mine-drainage archetype is grounded in the same belt, where effluent from the inactive São Domingos mine has been measured at copper concentrations of roughly 5.3 grams per litre, a liquid feedstock from which selective extraction is demonstrably effective [21]; this confirms that the recoverable basket for that archetype is copper-led, with silver as the documented by-

product of its remining [4]. A contrasting case underlines how strongly speciation varies between sites, since at the abandoned Pinhal do Souto uranium mine the metals and metalloids are retained preferentially in iron-oxyhydroxide precipitates and organic-rich phases, with uranium and arsenic concentrated in soils above the regional background [22]; the lesson carried into the model is that grade alone is an incomplete guide to recoverability, and that the binding phase must temper any optimism drawn from total concentrations. The full set of compiled grades, with their crustal references and enrichment factors, is presented in Table 1.

Table 1
Strategic-metal concentrations in representative Portuguese deposits, with upper-continental-crust reference values and enrichment factors for the Aljustrel anchor dataset.

Element	Aljustrel, max (mg/kg)	MSWI residue (mg/kg)	Upper crust (mg/kg)	Enrichment factor
Cu	5,414	5,498	28	193
Pb	20,000	9,806	17	1,176
Zn	20,000	11,453	67	299
As	3,936	—	4.8	820
Sb	980.6	—	0.4	2,452
Cd	22	—	0.09	244

Note. Aljustrel values are maxima in the most enriched zones [14]; *municipal solid waste incineration (MSWI) residue ranges are from* [19]; *upper-continental-crust values are standard geochemical baselines; the enrichment factor is the Aljustrel maximum divided by crustal abundance. A dash denotes a value not reported for that matrix.*

The recoverable fraction of this endowment is bounded by the efficiencies that candidate technologies have actually demonstrated, again taken from the literature rather than assumed. Electrodialytic treatment of Panasqueira mine tailings has recovered 22 percent of the tungsten and 63 percent of the arsenic present, with hydrogen co-production offering partial energy offset [23], and a reactor-design study of the same residues reported simultaneous extraction of copper, tin, and tungsten alongside 63 percent of the arsenic [24]. Solvent extraction applied to extreme acid mine drainage from São Domingos achieved selective copper recovery of approximately 96 percent in successive stages, with the organic phase recyclable over multiple cycles [21]. Electrocoagulation has removed lead at more than 99 percent and zinc at 72 percent from sanitary-landfill leachate using recyclable steel-swarf electrodes [25], consistent with earlier work in which electrocoagulation removed more than 99 percent of several metals from soil leachates [26]. Tailings-reprocessing studies at Cabeço do Pião have demonstrated the staged concentration of zinc, tungsten, and copper as a route to both remediation and revenue [8], within a sustainability framework that allocates metal recovery, commodity prices, and life-cycle considerations to a single decision model [27]. The demonstrated efficiencies adopted as inputs to the valuation are summarized in Table 2.

Table 2
Demonstrated recovery efficiencies for target metals from Portuguese mine-waste, acid-mine-drainage, and leachate matrices.

Metal(s)	Recovery (%)	Process	Matrix	Source
Cu	≈ 96	Solvent extraction	São Domingos acid mine drainage	[21]
Pb	> 99	Electrocoagulation	Sanitary-landfill leachate	[25]
Zn	72	Electrocoagulation	Sanitary-landfill leachate	[25]
W	22	Electrodialytic treatment	Panasqueira tailings	[23]
As	63	Electrodialytic treatment	Panasqueira tailings	[23]
Cu, Sn, W	simultaneous	Electrodialytic reactor	Panasqueira residues	[24]
Multiple	> 99	Electrocoagulation	Soil leachate	[26]

Note. Arsenic removal is credited as remediation rather than revenue. "Simultaneous" denotes co-extraction reported without a separate efficiency for each metal.

Valuation model and break-even formulation

The valuation proceeds in three stages. The gross in-place contained value of a deposit aggregates, across the metals it contains, the product of grade and price, and is written as $V = \Sigma\, g_i p_i$, the sum across the metals of the product of grade and price. The recoverable contained value applies to each term the demonstrated recovery efficiency, giving $R = \Sigma\, g_i p_i r_i$. With grades expressed in grams per tonne, which is numerically identical to milligrams per kilogram, and prices expressed in US dollars per kilogram of metal, a factor of 10^{-3} converts both quantities to US dollars per tonne of deposit. The reference prices were taken at mid-June 2026 from exchange and market assessments, and they capture an unusually eventful moment in several of the relevant markets, as compiled in Table 3. Copper stood near US$13,700 per tonne, zinc near US$3,600 per tonne, and lead near US$2,000 per tonne, while antimony, after a historic spike, was assessed at roughly US$26,500 per tonne in the European market, and silver traded near US$66 per troy ounce. The arsenic contained in the deposits is excluded from V and R because it commands no positive price; it enters the model only through the liability it represents.

Table 3
Reference metal prices used in the valuation, mid-June 2026.

Metal	Price	Unit	Market basis
Cu	≈ 13,700	US$/t	LME spot
Zn	≈ 3,600	US$/t	LME spot
Pb	≈ 2,000	US$/t	LME spot
Sb	≈ 26,500	US$/t	European market assessment
Ag	≈ 66	US$/troy oz	Spot (≈ US$2,122/kg)
As	no positive price	—	Liability; excluded from valuation

Note. Values are indicative snapshots for mid-June 2026 used for first-order screening. LME = London Metal Exchange.

The net valorization margin then subtracts the unit cost of recovery and adds any liability avoided, giving the net margin $M = R + A_D - C$. The cost term C bundles excavation, mechanical separation, and metallurgical recovery into a single indicative band, informed by Portuguese cost evidence. A large-scale construction-and-demolition-waste recycling plant in the Lisbon area was found to recover its investment in about two years while collecting €21.8 million per year in gate fees against roughly €11.9 million per year in running costs at a throughput of 350 tonnes per hour [28], and the accompanying sensitivity analysis showed that the investment-return period generally remained below eight years under parameter variations of plus or minus 30 percent [29]. Selective-demolition economics confirm that labour costs, tipping fees, and recovered-material prices vary strongly by region and bind the outcome [30]. On this basis the analysis adopts a cost band of US$40 to US$120 per tonne, broadly equivalent in euro at prevailing exchange rates, and treats it as indicative rather than definitive. The avoided-liability credit A_D captures the remediation and aftercare expenditure that recovery renders unnecessary, together with the value of reclaimed land and disposal volume; it is bounded between zero and US$30 per tonne, the lower bound applying where no remediation was otherwise mandated. Avoided disposal also carries a policy dimension, since the diversion of waste from landfill interacts with gate fees and with the pay-as-you-throw tariffs that Portugal has begun to consolidate [31] and to pilot at municipal scale [32]. The environmental side of the ledger, which the present screening reports qualitatively, rests on the life-cycle evidence assembled for Portuguese waste systems [13]. Finally, the break-even grade for any single metal, the grade at which its recoverable value just covers the unit cost, follows as $g^*_i = C \cdot 10^3 / (p_i r_i)$, and provides a compact test of whether a deposit clears the threshold on one metal alone.

Two further conventions govern how marginal value streams are handled, both chosen to err toward caution. Co-products that the source studies report only as recovery percentages without a corresponding grade, notably the tungsten and tin extracted from Panasqueira residues [24], are acknowledged in the narrative but are not added to the quantitative basket, since a percentage of an

unstated grade cannot be priced without invention. Where a metal appears in the in-place value but lacks any demonstrated recovery route in the cited corpus, as is the case for antimony, it is carried as latent value and reported separately rather than folded into the recoverable total, so that the optimistic case is never contaminated by undemonstrated extraction. The avoided-disposal component of the credit also has a rising trajectory that the static snapshot understates, because the European landfill-diversion framework and the national tariffs aligned with it push the cost of disposal upward over time, which would, if anything, strengthen the margins reported here. By keeping every such adjustment on the conservative side, the model is designed so that a positive screening result is robust and a negative one is genuinely discouraging.

Results

Strategic-metal endowment of Portuguese deposits

The first result is simply the scale of enrichment, and it is substantial. Plotted against typical upper-continental-crust values, the Aljustrel grades are elevated by two to three orders of magnitude for every element measured, as shown in Fig. 2. Copper is enriched roughly 190-fold and zinc roughly 300-fold, while lead, arsenic, and cadmium reach enrichment factors of about 1,180, 820, and 240 respectively, and antimony is the most enriched of all at more than 2,400 times its crustal abundance. These are not trace anomalies but ore-grade or near-ore-grade concentrations sitting at the surface in unconsolidated form. The pattern is corroborated beyond Aljustrel. Caveira soils carry comparable burdens of copper, lead, zinc, arsenic, cadmium, and mercury near the tailings [15], the São Domingos dump-fields exceed regulatory limits across a similar suite [16], and the broader characterization of Iberian Pyrite Belt waste confirms copper, manganese, and rare earth elements above crustal abundance together with cobalt, lithium, and tungsten [3]. Incinerator-residue monofills present a different but still meaningful profile, with copper, lead, and zinc reaching several thousand milligrams per kilogram [19] and ferrous and non-ferrous metals already recovered, if modestly, from Iberian bottom ash [20]. The endowment, in short, is real and geographically distributed, although its concentration within sites is highly uneven, a point that proves decisive for the economics.

The unevenness is not incidental but structural, and it shapes everything that follows. At Aljustrel the highest pollution-load indices are confined to the Algares tailing deposits and a handful of adjacent dams, where metal concentrations exceed typical background by as much as two orders of magnitude, while the surrounding ground is far less enriched [14]. The same patchiness characterizes São Domingos and Caveira, where contamination follows the tailings and dump-fields in irregular plumes rather than spreading uniformly [16]. For a recovery programme this concentration is double-edged. It means that the attractive grades are real but spatially restricted, so that the tonnage available at hotspot grade is a fraction of the total deposit, and it means that careful delineation is a prerequisite rather than a refinement. The mineralogical partitioning compounds the effect, because the enrichment of trace elements in the clay-size fraction [17] implies that a simple size-based pre-concentration step could raise the feed grade to a metallurgical circuit, turning a marginal bulk material into a viable concentrate. The

endowment is therefore best read not as a uniform blanket of value but as a set of discrete targets whose boundaries must be mapped before any of the figures that follow can be applied to a specific site.

Gross in-place versus recoverable contained value

Translating these grades into value through the model produces the central quantitative finding. For the Aljustrel-anchored polymetallic archetype, the gross in-place contained value of the four priced metals sums to approximately US$212 per tonne of deposit, distributed as US$74 from copper, US$72 from zinc, US$40 from lead, and US$26 from antimony. This figure alone reframes the deposits, since US$212 per tonne is comparable to the contained value of many primary ores and far exceeds what intuition would attach to mine waste. The recoverable value, however, is the quantity that matters for a recovery decision, and it is necessarily lower. Applying the demonstrated efficiencies of approximately 96 percent for copper by solvent extraction [21], more than 99 percent for lead and 72 percent for zinc by electrocoagulation [25], the recoverable value of the copper, lead, and zinc basket reaches about US$163 per tonne under an optimistic recovery scenario, equivalent to 77 percent of the gross value of those three metals. A conservative scenario, assuming 70 percent copper, 90 percent lead, and 60 percent zinc recovery, still yields about US$131 per tonne. The decomposition is displayed in Fig. 3. Antimony is treated separately, because although it contributes nearly US$26 per tonne to the in-place value, no recovery process for it is demonstrated in the cited Portuguese corpus; it is therefore reported as latent value, recoverable in principle should a process mature, but excluded from the conservative recoverable total. The full set of computed values is given in Table 4.

Table 4
Gross in-place and recoverable contained value for the Aljustrel-anchored polymetallic archetype (US$ per tonne of deposit).

Metal	Grade (mg/kg)	Price (US$/kg)	In-place value (US$/t)	Recovery (%)	Recoverable value (US$/t)
Cu	5,414	13.70	74.17	96	71.20
Pb	20,000	2.00	40.00	> 99	39.60
Zn	20,000	3.60	72.00	72	51.84
Sb	980.6	26.50	25.99	latent	—
Cu + Pb + Zn subtotal	**—**	**—**	**186.17**	**—**	**162.64**
Total (incl. Sb)	**—**	**—**	**212.16**	**—**	**—**

Note. Optimistic recovery is shown; the conservative scenario (70% Cu, 90% Pb, 60% Zn) yields ≈ US$131/t. Antimony is reported as latent value, having no demonstrated recovery route in the cited corpus. The net margin is M = R + A_D − C, with an indicative cost C = US$40–120/t and an avoided-liability credit A_D = US$0–30/t; under optimistic recovery the basket clears break-even costs up to ≈ US$178/t.

Two recoverable streams sit just outside this basket and would, if priced, widen the margin rather than narrow it. The tungsten and tin that electrodialytic and reactor-based treatment extract from Panasqueira residues are reported as recovery percentages without a corresponding site grade [24], so they cannot be valued here without invention, yet tungsten is among the metals whose supply Europe treats as most exposed, and any realized grade would add directly to the recoverable total. Silver occupies a similar position in the acid-mine-drainage archetype, where it is documented as a by-product of São Domingos remining [4] and where, at a mid-2026 price near US$66 per troy ounce, even gram-per-tonne grades would contribute materially to the copper-led basket. The conservative convention adopted here, which admits only metals possessing both a published grade and a demonstrated recovery route, therefore biases the recoverable estimate downward, so that the true basket at a fully characterized site is likely to exceed the figures reported for copper, lead, and zinc alone. This asymmetry reinforces the screening logic, since a deposit that already clears the threshold on its priced metals carries unpriced upside rather than hidden downside.

Net valorization margin and the viability envelope

The decisive result emerges when costs and credits are applied. Across the indicative processing-cost band of US$40 to US$120 per tonne, the high-grade polymetallic archetype remains profitable under both recovery scenarios, as the net-margin curves in Fig. 4 make clear. Under optimistic recovery with a modest avoided-liability credit, the margin stays positive until the unit cost approaches US$178 per tonne; under conservative recovery with no credit, the break-even cost is about US$131 per tonne. Both thresholds lie at or above the upper edge of the indicative cost band, which means that, for hotspot grades of the kind documented at Aljustrel, recovery is economically rational across the full range of plausible costs. The picture inverts for bulk material. When grades are reduced to a quarter of the hotspot values, a deliberately cautious proxy for the more typical concentrations encountered away from the most enriched zones, the recoverable value falls to roughly US$33 per tonne and the margin turns negative once the unit cost exceeds about US$33 per tonne, that is, across essentially the whole of the realistic cost band. The viability of landfill mining for strategic metals in Portugal is therefore not a property of the deposits as a class but of the hotspots within them. The same logic illuminates the treatment of hazardous constituents. The arsenic that disqualifies these deposits as benign also confers value when recovery removes it, since electrodialytic and electrocoagulation routes have eliminated 63 and 59 percent of arsenic respectively in the cited work [18], and analogous reclamation projects elsewhere have reduced arsenic and chromium by more than 98 percent while saving over a third of the cost through local relocation [33]. Comparable engineering-geological investigations of uncontrolled dumpsites have shown that contaminant containment and recovery can be designed together [34], and the avoided-liability term captures precisely this co-benefit, modest in magnitude but real, and most valuable where remediation would otherwise have been compulsory [22].

The envelope is best understood through its sensitivity to the two terms that the screening isolates. Holding recovery at the optimistic setting, raising the avoided-liability credit from zero to its upper bound

of US$30 per tonne shifts the break-even cost upward by the same amount, from about US$148 to about US$178 per tonne, so that the credit alone can move a deposit from marginal to comfortably viable where remediation was otherwise mandatory. Price movement acts in the same direction but with greater leverage, because copper, zinc, and lead together dominate the recoverable basket. A uniform 30 percent fall in their prices, of the order the sensitivity evidence treats as plausible [29], lowers the recoverable value from about US$163 to about US$114 per tonne and pulls the no-credit break-even down to roughly the same figure, still at the upper edge of the indicative cost band, whereas a symmetric rise lifts the threshold well clear of any plausible cost. The viability of a hotspot is therefore robust to ordinary market swings but not unconditional, and the regional variation in labour, tipping, and recovered-material prices that selective-demolition economics document [30] means that the cost term must ultimately be localized before any single deposit is committed to.

Discussion

Why polymetallic basket economics outperform single-metal recovery

The results turn on a mechanism that deserves to be made explicit, because it is the analytical heart of the case. A single metal rarely justifies recovery from these deposits on its own. The break-even formulation shows that, at a unit cost of US$80 per tonne and optimistic copper recovery, a deposit would need a copper grade of about 6,080 mg/kg to clear the threshold on copper alone, which even the enriched Aljustrel copper grade of 5,414 mg/kg fails to reach. The economics become favourable only because the metals stack. When copper, lead, and zinc are recovered together, their combined recoverable value of roughly US$163 per tonne clears unit costs up to nearly US$178 per tonne, an envelope that no single metal could open. This is why the polymetallic character of Iberian Pyrite Belt waste, often discussed as a complication for remediation, is in fact its economic salvation, and why the resource-and-reserve classification that hinges on price and technology rather than tonnage is the correct lens [11]. It also explains why enhanced-landfill-mining models dominated by the thermal treatment of municipal waste reach systematically gloomier conclusions [10], since they are valuing a fundamentally different and far less metalliferous feedstock.

The quantitative anatomy of the basket makes the point sharper still. Of the roughly US$163 per tonne of recoverable value under the optimistic scenario, copper supplies about US$71, zinc about US$52, and lead about US$40, so that the three contributions are of the same order and none dominates. Copper alone, as the break-even grade shows, cannot clear a unit cost in the middle of the indicative band, and it is the addition of zinc and lead that lifts the basket decisively above the cost range and widens the margin far beyond what any single metal could provide. This additivity is the reason the break-even frontier for the polymetallic case lies so far above the single-metal thresholds, and it is also why delineation that preserves the co-occurrence of the three metals matters more than maximizing the grade of any one of them. A pre-concentration step that enriched copper while discarding the lead- and

zinc-bearing fractions could, paradoxically, destroy more value than it created, a consideration that the resource-and-reserve framing captures by tying reserve status to the recoverable assemblage rather than to a headline metal [11].

Mineralogical and process constraints on recovery

Recoverability is not a fixed property of a grade but a function of how metals are bound, and the Portuguese mineralogical record cautions against optimism that ignores speciation. Trace elements in these systems concentrate in the clay-size fraction [17], and iron- and arsenic-rich nanoprecipitates associate intimately with clay minerals such as illite, halloysite, and beidellite, with jarosite and goethite as accessory phases [18]. Clayey materials retain heavy metals strongly, a property exploited deliberately in landfill liner design, where the abundance of clay minerals, carbonate content, and specific surface area govern sorption capacity [35]. Such binding reduces leaching risk, which is environmentally welcome, but it complicates extraction, since metals locked in secondary phases resist the hydrometallurgical routes that perform well on more labile fractions. Mobility, moreover, is controlled more by speciation and by the physico-chemical state of the deposit than by total content, with acidic and young conditions favouring solubility and alkaline, methanogenic conditions suppressing it [36], and with redox state, organic matter, and moisture further modulating release [37]. These observations explain why the recovery efficiencies adopted here are bounded well below unity and why a conservative scenario is reported alongside the optimistic one. They also flag energy as a recurring constraint, since the electrodialytic routes that recover tungsten and arsenic are sensitive to the choice of energy source, even as their hydrogen co-production offers a partial offset [23], and since the selectivity of solvent extraction and electrocoagulation, though high, is achieved at a cost in reagents and current [21].

Avoided liability, valorization pathways, and the circular-economy frame

The honest accounting of hazardous constituents is one of the model's more consequential features, and it connects the economic case to a wider set of pathways. Treating arsenic as a liability to be discharged rather than a product to be sold avoids the inflation of value that has weakened earlier optimistic assessments, yet it still credits recovery with the remediation it accomplishes, as the international reclamation record makes vivid [33]. Beyond the metals themselves, the residues of recovery carry their own value streams. Inert fractions can substitute for virgin aggregate in cementitious products, an avenue that Portuguese research has pursued through the incorporation of metallurgical and manufacturing wastes into precast concrete [38] and through the systematic mapping of recycling routes for industrial residues [39]. The ashes that landfill mining would mobilize are themselves candidates for secondary-raw-material recovery rather than disposal, as work on incineration-residue management has shown across multiple recovery routes [40]. Even the organic and soil-like fractions of older deposits have been valorized as compost or cover material in dumpsite-mining practice [41]. Set within the circular economy, these pathways move landfill mining from a single-product extraction toward an integrated valorization that recovers materials, nutrients, and energy in combination [6], an integration that recent work frames as essential to aligning waste management with carbon

neutrality [42] and to unlocking synergies between resource recovery and climate mitigation through leachate-based nutrient, energy, and material recovery [43]. The same circular logic underlies comparative analyses of European landfilling practice, which advocate region-specific strategies and the integration of advanced treatment to reduce landfill dependence [44], and it is consistent with the broader, and appropriately critical, scholarship on the circular economy that warns against techno-managerial readings detached from systemic implications [5]. The Portuguese context adds urgency through its legacy of diffuse contamination, documented for microplastics [45], for the persistence of dioxin-like compounds in coastal biota [46], and for the country's standing as a net importer of waste whose valorization could yield widespread benefit [47].

Policy implications and international benchmarking

The policy reading of these results is that incentive design, not geological potential, is the binding constraint in Portugal. The European Critical Raw Materials Act supplies the strategic rationale and the demand signal, and the recent characterization of Iberian mining waste explicitly aligns recovery with its objectives [3], yet national policy still lacks landfill-mining-specific incentives and is oriented toward meeting European recycling and landfill-diversion targets, which themselves demand sorted-collection rates of 75 to 90 percent that Portugal is at risk of missing [48]. International experience offers both encouragement and caution. Reviews of closed-landfill reclamation stress that effective recovery is an adaptive process requiring sustained institutional responsibility rather than a one-off intervention [49], and comparative analyses of dumpsite rehabilitation in other jurisdictions weigh landfill mining against alternatives such as microbial methane oxidation through explicit decision matrices [50]. The reclamation of contaminated sites elsewhere has combined hazard reduction with economic efficiency, achieving large contaminant reductions and cost savings through local material relocation [33] and through engineering-geological investigation that designs containment and recovery in concert [34]. The integrated ecological and economic assessment pioneered in Austria [12] and the resource-or-reserve classification applied to a Belgian case [11] together provide the methodological scaffolding that a Portuguese programme would need, while the enhanced-landfill-mining evidence base supplies a benchmark against which metalliferous mine-waste, valued here at far higher contained grades, compares favourably [10]. The volatility of the relevant markets reinforces the case for screening rather than commitment, since tungsten and antimony prices have moved dramatically in recent years, and the reuse of tungsten mining waste-rock has been explored precisely because Panasqueira generates large volumes of such material [7]. Tariff and gate-fee policy provides a further lever, as the consolidation [31] and piloting [32] of pay-as-you-throw schemes alter the avoided-disposal term that the model isolates. Decisions taken on this basis should be informed by life-cycle evidence, which for Portuguese waste systems consistently favours recovery and recycling over direct landfilling [13], whether for waste-to-energy [51], end-of-life vehicles [52], packaging [53], or spent batteries [54]. The convergence of all these strands points to the same conclusion the numbers reach independently, namely that a targeted, hotspot-led programme is both economically defensible and strategically timely.

Conclusions

This study set out to test, with figures rather than rhetoric, whether landfill mining can be a sustainable route to strategic-metal recovery in Portugal, and it answers in a qualified affirmative. By separating the gross in-place value of a deposit from the value that published technologies can actually recover, by crediting recovery with the liability it removes rather than with revenue the market will not pay, and by exposing a break-even frontier, the proposed screening model converts the longstanding claim that Portuguese deposits are rich into defensible per-tonne estimates. For polymetallic sulphide hotspots of the kind documented in the Iberian Pyrite Belt, the gross contained metal exceeds US$200 per tonne, of which roughly two-thirds to three-quarters is recoverable, and the resulting margin stays positive across the full range of realistic processing costs. The mechanism behind this result is the stacking of several metals into a basket that no single metal could fill, which makes the polymetallic character of the waste its economic strength rather than merely a remediation burden. The same analysis is candid about the limits of the case. Away from the hotspots, where grades fall to a fraction of their peak, the margin turns negative across essentially the whole plausible cost range, so that viability is grade-selective and hotspot-led rather than a property of the deposits as a class. Recoverability is further constrained by mineralogy, since metals bound in clay and secondary phases resist extraction, and by the energy intensity of the candidate processes. The practical implication is therefore precise. Portugal should not pursue landfill mining indiscriminately, nor dismiss it, but should target characterization and pilot-scale demonstration at the high-grade, polymetallic deposits where the model predicts a positive margin, while designing the national incentives and tariff structures that the avoided-liability and avoided-disposal terms show to be decisive. On those terms, and only on those terms, landfill mining is a credible and timely contribution to Europe's search for secondary sources of strategic metals.

Declarations

Author Contribution

As the sole author, all the work concerning the article was conducted by L.N.

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Figures

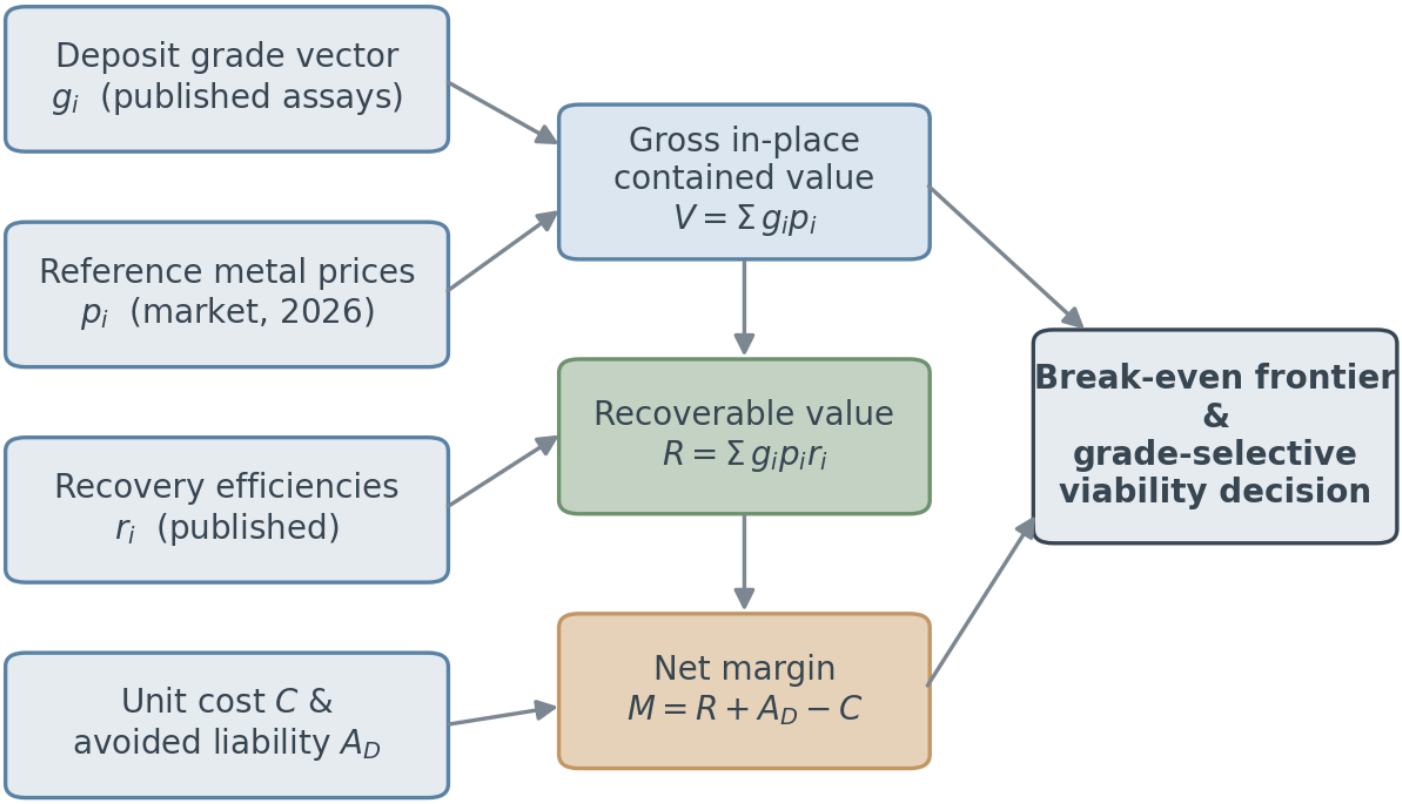

Figure 1

Conceptual workflow of the price-indexed contained-value screening model, proceeding from deposit characterization and assay compilation, through gross in-place and recoverable value, to the net-margin and break-even decision.

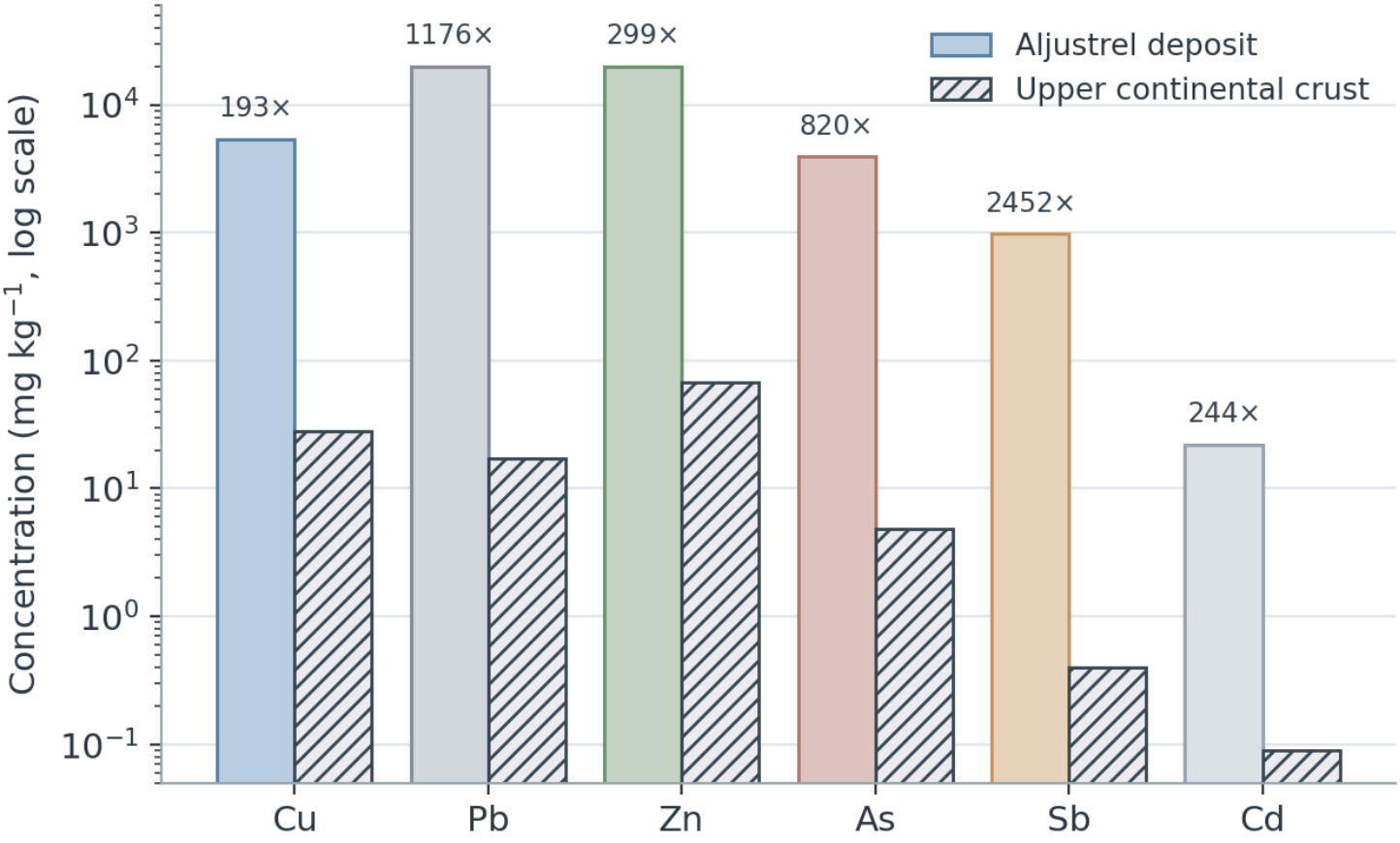

Figure 2

Strategic-metal concentrations at the Aljustrel mining area compared with upper-continental-crust abundance on a logarithmic scale; annotated values are enrichment factors relative to crustal background.

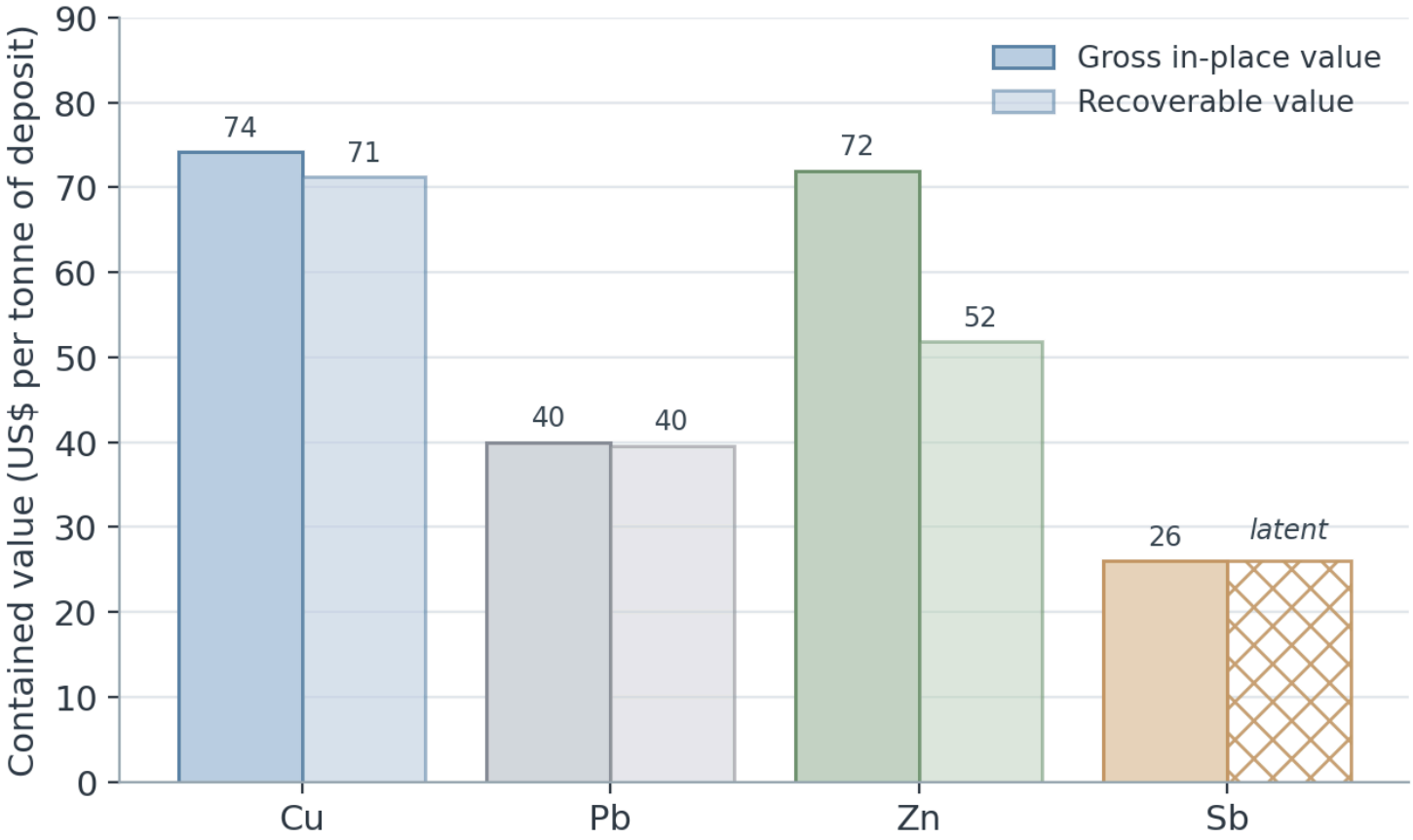

Figure 3

Gross in-place versus recoverable contained value by metal for the Aljustrel-anchored polymetallic archetype (US$ per tonne of deposit). Antimony is shown as latent value, lacking a demonstrated recovery route in the cited corpus.

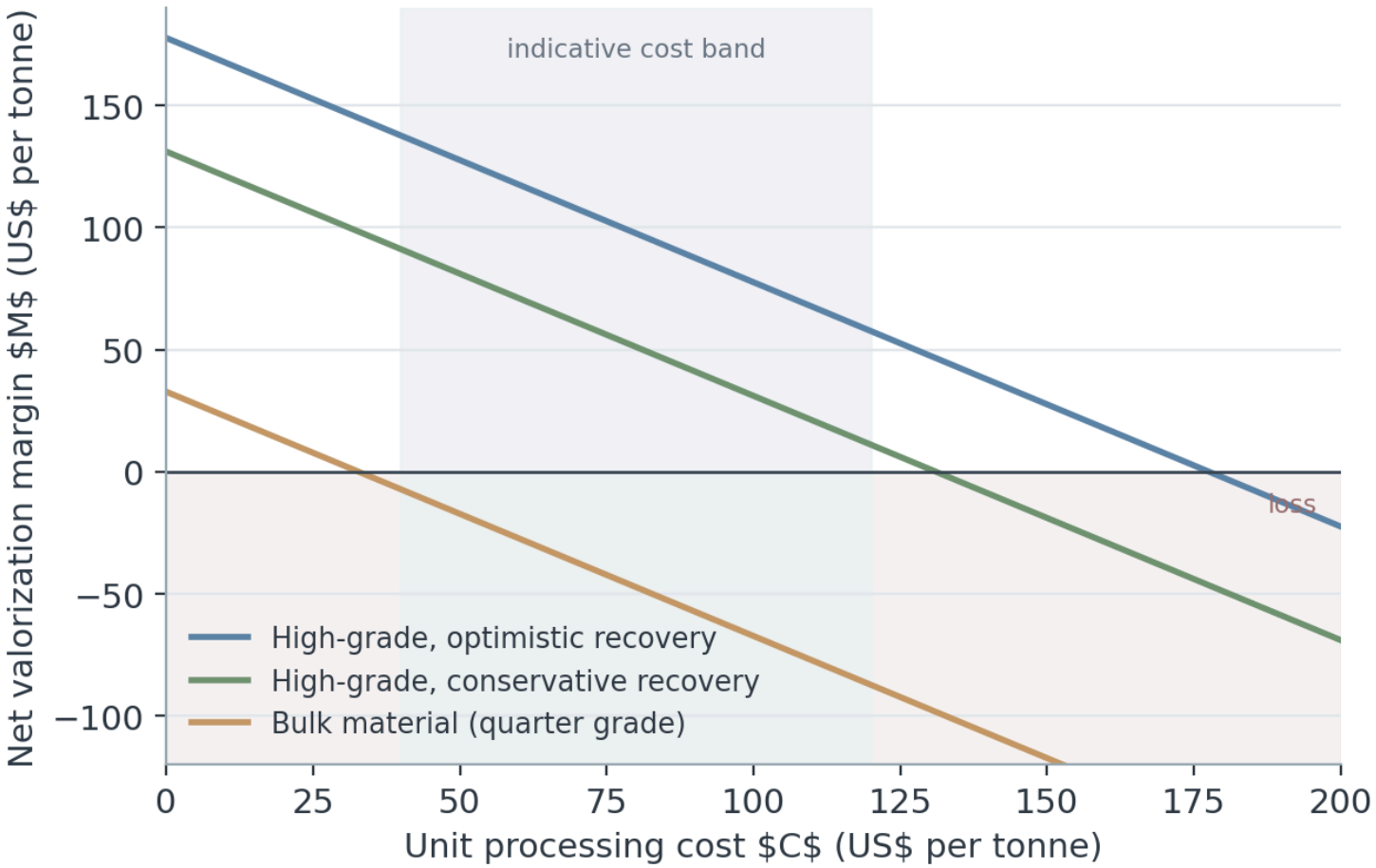

Figure 4

Net valorization margin as a function of unit processing cost for the high-grade polymetallic archetype under optimistic and conservative recovery, and for bulk quarter-grade material; the shaded band marks the indicative US$40 to US$120 per tonne cost range, and markers indicate break-even crossings.