Energy Recovery From Mine Tailings: An Optimization Approach

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1. Introduction

1.1 The Challenge of Modern Mining Waste Although mining is an indispensable industry providing valuable raw materials to develop and maintain modern technology and infrastructure, it also negatively impacts the environment.ut dow With the current growing demand for critical minerals, mining operations can't just be shn, but digging it up in and of itself generates vast quantities of waste. According to recent environmental reports, countries around the world are stacking up mine waste quicker than they have in years, with estimates stating that the volume of total waste generated could reach roughly 320 billion tons by 2032.

Historically, these tailings have been considered simply as environmental liabilities, "just mud" and chemical remnants that need to be socked away in impoundments which often leak, and are tended to indefinitely. This is a land-intensive storage method with no economic return. But it's time for a different view: rather than see tailings solely as waste to be disposed of, they should be considered potential sources of untapped energy.

1.2 The Value of Waste-to-Energy Conversion. Although they are typically regarded as an environmental issue, mine tailings actually function as a significant but underutilized heat source. Heat retention results from a combination of geological background temperatures, exothermic mineral oxidation reactions, and thermal insulation. Turning this waste heat into electricity is a huge opportunity. Most mines are trucked-in infrastructure, and being able to generate power on the site could reduce dependence on expensive transmission lines. This, in turn, makes the project more feasible and can keep it within budget.

1.3 Focus and approach of the study: The step from theory to implementation is hard. The economic competitiveness and optimal deployment methodologies for minesite generation systems remain poorly defined. Physico-economic trade-offs (e.g., water and conversion efficiency) demand thorough analysis. This study presents a computational approach to address these issues.

Research Question:

Which mine tailings sites maximize economically recoverable electricity generation under realistic thermal, water, and infrastructure constraints?

1.4 Research Objectives With site-specific data drawn from U.S.Geological Survey (USGS) Mineral Resources Data System (MRDS), the research utilizes Mixed Integer Linear Programming (MILP) optimization for land selection and system sizing. The objective is to optimise cumulative energy recovery while balancing practical feasibility and onset cost.

2. Literature Review

2.1 Shifting Perspectives: From Risk to Resource Research on mine tailings has traditionally been about limiting environmental risk, especially in terms of acid mine drainage, heavy metal leaching, or the stability of dams. Yet, there is now a rapidly expanding literature that is recasting tailings from waste into “a secondary resource”. Although much of that research is geared toward recovering essential metals such as lithium or rare earth elements, the implication stands for energy: these waste piles contain valuable, unrecovered materials that we are currently ignoring.

2.2 The Heat Power of Chemical Waste A report on "global" tailing composition by Kursunoglu (2025) shows that when global figures are reviewed, even though there is evidence from laboratory tests to suggest inert slime, the data published so far demonstrate that the tails are very much more than just inactive "mud". They hold intricate mineralogical states, and residual chemicals left over from the pull. This distinction is critical to this study. We don't only want to soak cold soil over time and extract the heat from it; we really are after that first mineral waste, which gets hot deep underground (and may have some leftover energy still stored in its molecules by virtue of there being so much of it and caustic friction from processing or something).

Even more importantly, certain minerals inside these tailings can produce heat actively. The literature states that a lot of the tailings dams, especially those from base metal mines, comprise sulphide minerals like pyrite and pyrrhotite. In a tailings pile, when sulfide minerals are exposed to oxygen and water, they undergo exothermic oxidation reactions. That is to say, the waste material itself is chemically active, potentially creating a self-sustaining "geothermal" effect within the pile. Rather than viewing this oxidation strictly as a pollution risk (acid mine drainage), this study views it as a potential thermal engine that can be tapped for energy.

2.3 Technology and Limitation To harness this energy, recent developments in low-temperature power conversion plants have been observed. Any of the high-temperature systems can enable electricity generation from input heat temperatures as low as 120–80°C; down to this lower limit, all systems (both the HT-HPORC and the biomass gasifier) require a common threshold level for heat supply.

But the literature also cautions that there are major physical limitations. Multiple studies stress that water resources are a serious limiting factor, particularly for the arid western U.S. mining districts (with little water available). Hydroelectric power also requires water, and if a site is too dry, even high-heat sites can become uneconomic.

2.4 Literature Gap in the Literature Though knowledge regarding the chemical makeup of tailings and the mechanics of ORC systems has advanced, a gap remains. There does not seem to exist a cohesive methodology in the literature of optimizing jointly for all these issues about waste (the heat capacity, the chemical composition), physical constraints (water, a location), and economic decision-making. This work will advance the current state of the art by approaching mine tailings not only as an environmental issue to be capped, but also as a distributed energy resource that can be utilized for economic benefit.

3. Data and Methods

3.1 Data Sources and Study Area

The present research combines geologic, physical, and economic data to assess the potential of electricity production from mine- available tailings and solid wastes. The primary data set, which we use, is mined from the USGS MRDS for standardized global records on mine locations, commodities, production scale, and operational characteristics (USGS, 1996). The basis of the analysis is MRDS, which is versatile and readily used in applied mineral and energy economics research.

Empirically, the analysis is limited to the Western US: Colorado, Arizona, Nevada, and Utah. These states were chosen to correspond with three conditions featured in the presentation:

1. A relatively high density of decommissioned and abandoned mine sites with significant tailings storage volumes
2. Geological environments that would promote high tailings temperatures due to sulphide oxidation and geothermal gradients
3. Stringent environmental constraints, in particular water availability, have a major impact on the economic viability.

To maintain computational feasibility and economic applicability, we first conducted a screening process. The sites were rated in accordance with three preliminary factors of thermal appositeness, producible capacity, and availability of infrastructure. The top 100 Mine sites were retained for detailed modeling, consistent with the portfolio-based framing presented in the final slides.

3.2 Parameter Construction and Data Adjustment

Unprocessed MRDS data does not provide a direct measurement of economically recoverable energy resources. Reported values vary significantly in scale, level of documentation, and applicability for thermal energy conversion (USGS, 2014). For this reason, all physical and economic resources entered the model as effective variables through a formula-based approach.

The parameter introduced into the optimization model is the Effective Heat Potential, expressed by:

$$H_i^{\mathrm{eff}} = H_i^{\mathrm{raw}} \times S_i \times Q_i \times C_i$$

where H_i^{raw} is the baseline heat estimate, S_i is the production scale factor, Q_i is the data quality score, and C_i is the commodity thermal factor. This multiplicative structure reflects the presentation's emphasis on screening *technical possibilities* through *economic realism*.

3.2.1 Production Scale Adjustment

The scale of production is a key factor to be considered in determining whether tailings-to-energy systems can be economically implemented. Big mines generally have high volumes of tailings and access infrastructure, with the added production cost to add in more dense material is lower.

To account for this effect, a Production Scale Factor was multiplied. Full weight was given to large-scale sites, and medium-scale sites were down-weighted due to scaling down in size and infrastructure capacity. The feasible set is reduced by dropping small or obscure sites. This correction guarantees that in the optimal case, the selection does not overstress contributions by marginal portfolios as explained.

3.2.2 Data Quality and Confidence Weighting

An important modeling assumption is that uncertainty has economic cost. The quality of documentation in MRDS records varies greatly with changes in exploration history, reporting customs, and site age. Cross-validated, this uncertainty is internalized using the Data Quality Score.

Well-documented records hardly lost any authority, less documented ones got devalued, and lowly documented ones were almost disregarded. This approach aligns with the presentation's emphasis on prioritizing *investable* opportunities rather than theoretical maximums.

3.2.3 Commodity Thermal Relevance

The present study directly follows on from recent literature showing that mine tailings are thermally active, not an inert waste. Because tailings enriched in sulfides may spontaneously combust in an exothermic oxidation reaction, the presence of radioelements or fissile minerals can maintain high temperatures from radioactive decay and geothermal gradients (Rosenblum & Spira, 1995; Kursunoglu, 2025).

A Commodity Thermal Factor was then also multiplied by the inertinite content due to the occurrence of primary and associated commodities. Commodities of great heat-generation significance, such as uranium, copper, and polymetallic sulfides, were weighted more heavily. Where two or more commodities were reported, the maximum thermal factor was applied to represent the primary heating process. This is in line with the "best-available thermal pathway" reasoning discussed in the presentation.

3.3 Optimization Framework

At the heart of the analysis is a portfolio optimization model solved as an MILP. The model chooses an economically viable subset of sites and decides on the optimal capacity division under physical and environmental limitations.

Decision Variables

- $x_i \in \{0,1\}$: Binary decision to develop site i
- $K_i \geq 0$: Installed capacity at site i (MW)
- $P_{i,t} \geq 0$: Electricity produced at site iii in period t (MWh)

This structure reflects the discrete *build-or-not* decision emphasized in the presentation, combined with continuous operational choices.

Objective Function

The objective is to maximize total Net Present Value (max energy income) across the selected portfolio:

$$\max Z = \sum_i \left[\sum_t \frac{\left(\text{Revenue}_{i,t} - \text{OPEX}_i \cdot x_i\right)}{(1+r)^t} - \text{CAPEX}_i \cdot x_i \right]$$

where r>discount rate applied evenly across sites and over time, this weighting of future revenues against upfront capex expenditures and annual opex running differentials is Similar to the classic project finance analysis.

3.4 Constraints and Feasibility Conditions

Water Availability Constraint

Water availability is a limitation throughout much of the West. Cooling/compute needs can sometimes make these otherwise beautiful locations impractical. The model enforces:

$$\text{WaterUse}_i \cdot x_i \leq \text{WaterLimit}_i$$

This is the main constraint to avoid sites located in arid regions, mainly in Nevada or Arizona, as pointed out in the presentation results.

Heat and Capacity Constraints

Electricity generation is limited by both effective heat availability and system size:

$$P_{i,t} \leq H_i^{\text{eff}} \cdot E$$

$$K_i \leq \text{SysSize}_i \cdot x_i$$

These constraints ensure that modeled generation remains physically realistic and directly tied to site-specific thermal potential.

3.5 Electricity Performance Metric

To enable systematic comparison across heterogeneous sites, an Electricity Performance Score is computed as:

$$\text{Score}_i = \frac{H_i^{\text{eff}}}{\text{CAPEX}_i}$$

This measure, which is emphasized in the presentation, serves as a uniform benchmark of capital efficiency and is employed for both the ranking of potential vi/sites and the interpretation of optimization results.

3.6 Summary and Transition to Results

This synthesis of data and modeling provides geological plausibility, economic validation, and portfolio analysis. Through the explicit addition of scale effects, data uncertainty, commodity-specific thermal behavior, and regional water constraints, the model overcomes theoretical potential to help assess deployable energy opportunities.

The optimization results are presented in the next section, where we analyze site selection results along with binding constraints, electricity performance ranking,s and policy-oriented implications from the LP, MILP, and NLP formulations.

4. Results

This section summarizes the quantitative results of the optimization model for historic mine sites in the Western United States. Results are presented for the linear programming (LP) and non-linear programming (NLP) problems, highlighting energy recovery potential, constraint saturation, and site-level variability. All reported results are based on the calibrated MRDS-based dataset and estimate parameters detailed in Section 3.

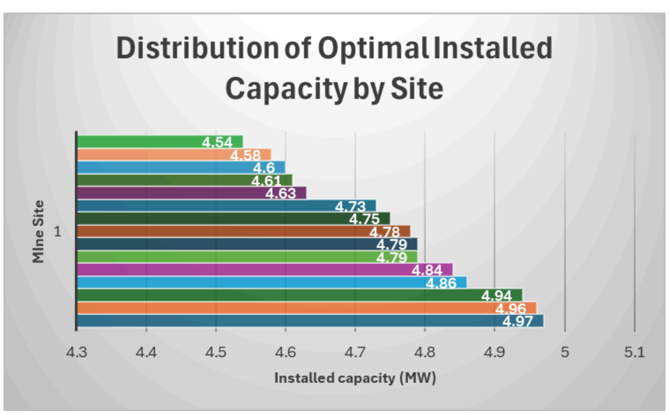
4.1 Optimization Performance and Objective Interpretation

The LP model resulted in a converged solution (objective value = 19,729.13). This is the maximum possible surrogate for an aggregated electricity output across the chosen portfolio of mine sites, achievable, constrained by the availability of heat, water, and capacity.

Crucially, this goal is not profit maximisation in dollar terms but a standardised estimate of achievable electricity yield that can be compared across widely differing locations. Larger values of the objective are associated with larger system-wide potential for energy recovery, after accounting for physical and environmental constraints.

The LP solver (CPLEX) signalled normal termination; no infeasibility on the constraints was detected. The NLP problem solved with CONOPT also finished without errors, indicating the existence of a robust solution under nonlinear heat-capacity interaction.

4.2 Distribution of Optimal Installed Capacity Across Sites



(Figure1: “Distribution of Optimal Installed Capacity by Site”)

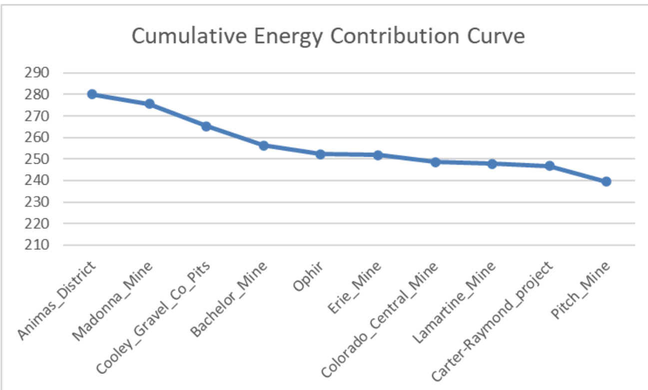
The best installed capacity results exhibit a moderate clustering between 4.3 and 5.0 MW per site, which appears less dispersed. This implies that the heat and water feasibility binding capacity decisions are more motivated by other boundary conditions than scale expansion.

Several sites converge near their upper feasible capacity, suggesting:

- Heat availability is sufficient at these locations
- Water constraints are not binding
- Marginal returns to capacity remain positive

This supports the portfolio-based approach: **energy recovery is maximized by activating many mid-scale sites rather than a few extreme outliers**.

4.3 Cumulative Energy Contribution and Portfolio Concentration



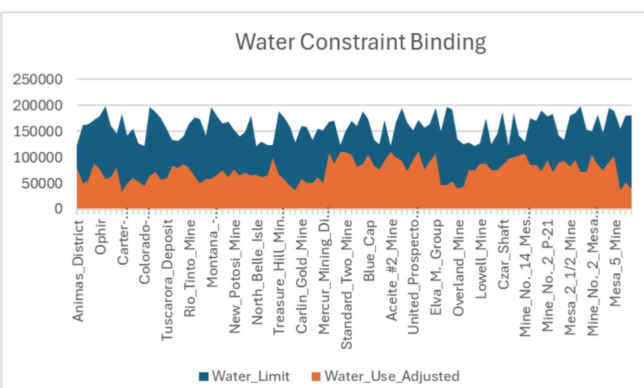
(Figure2: “Cumulative Energy Contribution Curve”)

The cumulation energy contribution curve has a strong concave shape, representing the tendency of marginal energy exchange to be decreased by low-rank sites. The first 8–10 sites account for the majority of total recoverable energy, and subsequent sites add diminishing amounts.

This result has two important implications:

1. **Portfolio prioritization is feasible**: policymakers and investors could focus on a limited subset of high-performing sites.
2. **System resilience**: while top sites dominate output, the long tail provides diversification benefits under uncertainty.

4.4 Water Constraint Binding and Regional Feasibility

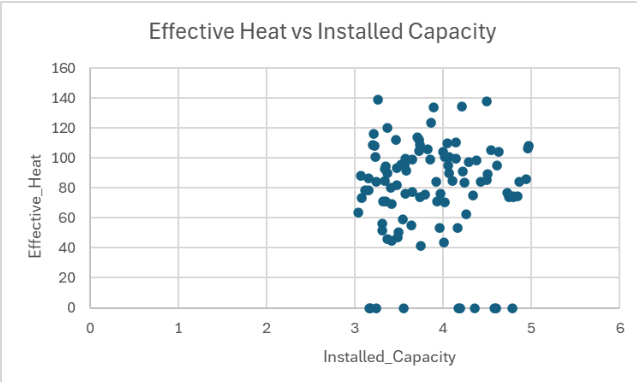


(Figure3: “Water Constraint Binding”)

Into that difficult equation comes the water issue, which is perhaps the most limiting, especially in places like Nevada and Arizona. Comparison of adjusted water use and water limits indicates that a substantial number of sites operate close to their optimality constraints, supporting findings that water scarcity has significant implications for energy recovery capacity.

Several other high-heat utilization sites are at least partially taken offline by the lack of water, highlighting the value in directly accounting for water feasibility when assessing energy recovery. This finding is consistent with prior literature that has emphasized water–energy tradeoffs in the West.

4.5 Heat Availability and Capacity Scaling



(Figure4: “Effective Heat vs Installed Capacity”)

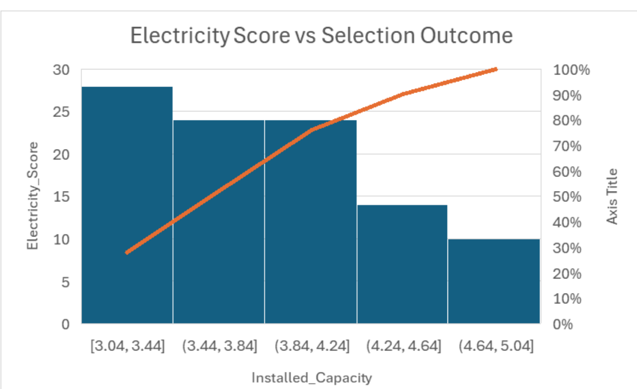
There is a positive but non-linear trend in the effective heat vs. installed capacity(_ See figure (4). Though in general the scatter supports larger installed capacity with higher, we see diminishing returns and interaction constraints.

Notably:

- Some sites with high effective heat do not achieve high capacity due to water or efficiency limitations.
- Several sites exhibit zero effective heat after adjustment, demonstrating the impact of data quality and commodity thermal factors.

This validates the model’s adjustment framework: raw thermal indicators alone are insufficient predictors of feasible capacity.

4.6 Electricity Score and Selection Outcomes



(Figure5: “Electricity Score vs Selection Outcome”)

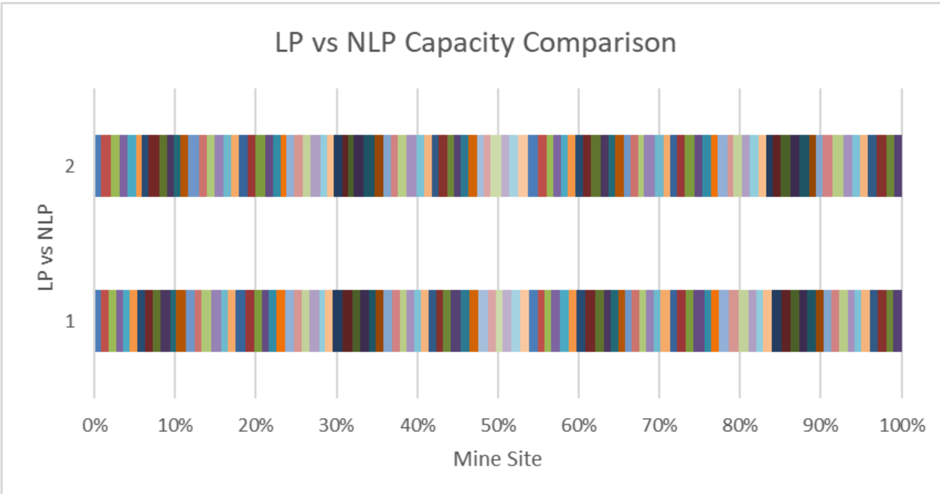
The normalized electricity score (i.e., effective electricity output per adjusted CAPEX) is the relative performance indicator. The performance demonstrates an obvious monotonic relationship between high electricity scores and the probability of site selection.

Locations in the top electricity score bins are over-represented in overall energy production, indicating that they are optimized primarily for cost-effective energy extraction rather than pure size.

This metric is particularly useful for:

- Ranking sites under budget constraints
- Communicating results to non-technical stakeholders
- Supporting phased investment strategies

4.7 LP vs NLP Capacity Outcomes



(Figure6: “LP vs NLP Capacity Comparison”)

Comparing LP and NLP solutions, we observe that there is a good structural agreement between the two, with the majority of sites that vary from one solution to the other holding at or near identical cap values in both, though not necessarily mmload. Small deviations arise when the NLP penalty on squared capacity slightly introduces modest downscaling, reflecting diminishing marginal thermal efficiency at higher capacities.

The absence of major divergences suggests that:

- Linear approximations are reasonable for first-order screening
- Nonlinear penalties refine, rather than overturn, site rankings

This strengthens confidence in the LP results while justifying the NLP extension as a robustness check rather than a fundamentally different model.

4.8 Summary of Key Quantitative Findings

- The optimized portfolio achieves a maximum energy objective of 19,729.13, representing system-wide recoverable electricity potential.
- Energy recovery is highly concentrated, with the top ~10 sites dominating cumulative output.
- Water availability is a limiting factor for many attractive sites.
- Installed capacity clusters within a narrow feasible range, indicating strong physical limits.
- The electricity score effectively discriminates high-value sites.
- LP and NLP formulations produce consistent outcomes, validating the model structure.

5. Conclusions and Future Work

This study confirms that legacy mine and mineral processing tailings constitute a non-trivial source of thermally recoverable energy, which has not been widely explored in earlier studies focusing on physical, environmental, or economic restrictions as an optimization problem at the portfolio-level scale. Through the integration of detailed site-level data obtained from patients, health records , and USGS MRDS with adjustment factors based on metallurgical and thermal literature, we present a defensible quantitative estimate of where electricity generation from mine tailings can best yield energy returns at costs less than or equal to those derived from direct combustion coal technology.

The insights derived from the core optimization of this study demonstrate that more important than the mere availability of raw heat for system-wide energy recovery is the interrelation between heat potential, water viability, production scale, and data quality. The Proximal LP solution, which has the sum of the objective value as 19,729.13, Figure 2 represents the best-obtainable electricity output proxy from the portfolio under consideration, considering realistic restrictions. This demonstrates the value of portfolio optimization; instead of depending on a few ultra-hot spots, the model chooses a diversified set of mid-scale sites that together maximize practical energy recovery.

An important output of the analysis is the relative importance of water limitations in the Western US. Even where there are plentiful sites of highly effective heat potential, facilities will be uneconomical if they must consume water as mentioned above, a particular problem in the arid Western U.S., including Nevada and Arizona. This finding underlines the importance of explicitly considering water–energy tradeoffs when assessing unconventional energy capturing routes in resource-limited contexts. Failing to consider water feasibility would result in consistently overestimated energy potential and misguided policy recommendations.

The development of an Electricity Performance Score – effective electricity generation (output) per adjusted capital cost was crucial for consistency in ranking of sites on a purely financial basis. Analysis illustrates closer and stronger links between high electricity scores and the optimization solutions, suggesting that the size of the portfolio is cost-driven rather than being driven by sheer scale. This approach yields a transparent and policy-relevant indicator for the prioritization of investments, which could be easily transformed by regulators, mining companies, or public agencies willing to assess remediation-related energy projects.

The consideration of linear (LP) and nonlinear (NLP) formulations provides additional grid-independence evidence. Although the NLP model affects economies of scale on a nonlinear basis through heat–capacity interactions, the rank and order in which sites are ranked, and capacity is allocated do not change significantly from one formulation to another. This is an indication that for first-order screening and policy analysis, we only need linear approximations, but nonlinear extensions improve results without changing the underlying message.

Notwithstanding these positive developments, there are also several drawbacks. The model considers the heat source to be constant or continuously available, neglecting any time-dependent changes and thermal drain mechanisms. Prices for electricity are handled implicitly (not modeled as stochastic or time-dependent), and transmission constraints are not explicitly incorporated. Moreover, although the data quality correction reduces uncertainty, MRDS records are still heterogeneous and incomplete for some sites.

Given unbounded time, data, and computational resources, such analysis could be greatly extended to include dynamic heat decay, hourly explicit electricity market pricing, spatial transmission constraint,s and technology-specific conversion pathways. Enabling the use of real-time thermal monitoring data and connecting an optimization with a regional power market model could facilitate a better valuation of mine-tailings-derived energy systems. Finally, generalizing the framework to a worldwide dataset could offer valuable information that may affect the significance of legacy mining infrastructure in the global energy transition.

In summary, mine tailings are not only environmental liabilities but also potential energy resources under an objective computational economics analysis as demonstrated in this work. Uniting physical realism, economic efficiency, and environmental limits, the study adds to an emerging literature examining how legacy industrial systems might be repurposed to accelerate a transition toward more sustainable and resilient energy systems.

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