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Integrated assessment of geothermal projects with critical mineral recovery

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The paper proposes an integrated framework for evaluating geothermal projects in which thermal energy production is combined with recovery of critical raw materials (CRM) from geothermal and formation brines. The approach links geological and hydrogeochemical data, temperature depth conditions, brine flow rate, target element concentration, recovery efficiency, project maturity, technology selection, and economic indicators within a single decision sequence. The methodology is illustrated using scenarios for Transcarpathian brines, with lithium considered as the principal target component and Mg, Sr, Ge and I as additional potentially valuable constituents. For the Solotvyno basin, the analysed dataset includes Li concentrations from 3.2 to 80 mg/L, temperatures beetween 55, 90 and 115 °C and assumed recovery rates of 70-90%. The proposed assessment distinguishes resource potential from technically recoverable and economically viable production and incorporates uncertainty through minimum, average and maximum scenarios.

Keywords: geothermal brines; critical raw materials; lithium; direct lithium extraction; project evaluation

Introduction

Geothermal projects are increasingly considered not only as sources of heat and electricity but also as potential integrated subsurface resource projects. Geothermal fluids may contain dissolved lithium and other elements that can become recoverable co-products or by-products when suitable concentrations, flow rates and separation technologies are available. This approach is especially relevant for high-salinity brines and sedimentary basins, where the same well infrastructure can potentially support both energy production and mineral recovery. Recent European and U.S. programmes explicitly connect geothermal development with CRM supply, while the United Nations Framework Classification for Resources UNFC provides a common project based framework for evaluating geothermal resources (*Balaram, V.*, 2026; *European Commission*, 2026; *United Nations Economic Commission for Europe*, 2022; *U.S. Department of Energy*. 2026).

For Ukraine, integrated geothermal CRM evaluation is relevant because geothermal prospects in the Transcarpathian region coincide with highly mineralized formation waters and a long history of deep drilling (*Virshylo, I.,* 2026). The key methodological challenge is that a high concentration of a target element alone does not define a viable project. Project value is controlled by the combined influence of geological knowledge, temperature, sustainable fluid production, chemistry of the brine, selectivity and recovery of the extraction process, infrastructure, environmental constraints, product specifications and market conditions.

Objective and methodology

The objective of this study is to develop a practical integrated assessment sequence for geothermal projects with associated CRM recovery and to demonstrate its application to lithium-bearing brines in Transcarpathia. The proposed workflow consists of six linked blocks: (1) geological and geothermal resource characterization; (2) hydrogeochemical screening; (3) estimation of recoverable mineral output; (4) technology selection; (5) economic and environmental assessment; and (6) project-maturity and uncertainty classification.

Hydrogeochemical screening uses threshold concentrations as an initial filter rather than as a direct economic cut-off. The working dataset applies indicative screening values of 10 mg/L for Li, 500 mg/L for Mg, 300 mg/L for Sr, 0.1 mg/L for Ge and 10 mg/L for I. These values identify samples or areas that require more detailed technological and economic evaluation. For lithium, recoverable production is estimated from concentration, brine flow, operating time and recovery efficiency. Minimum, average and maximum scenarios are retained throughout the calculation to prevent a single deterministic estimate from masking geological and technological uncertainty.

The proposed workflow is implemented in the Critical HydroMinerals Calculator (CHydroMC), a software product developed for screening and scenario based evaluation of critical raw materials in geothermal, formation and oilfield brines. CHydroMC integrates source-water chemistry, well depth, temperature, flow rate, project stage, operating life and technology-specific recovery assumptions to estimate potentially recoverable mineral output and to compare alternative development scenarios. The calculator is designed to bridge the gap between an initial hydrogeochemical indication and a project-oriented assessment by converting concentration data into production and economic metrics under explicitly stated assumptions. In the present study, the Solotvyno and other Transcarpathian scenarios are used to demonstrate this logic. CHydroMC is therefore considered not as a substitute for laboratory or feasibility studies, but as a decision-support tool for early-stage screening, identification of key data gaps and prioritization of wells or areas for further testing.

Table 1. Integrated framework for geothermal projects with CRM recovery

Assessment block	Key parameters	Main uncertainty	Decision output
Geological / thermal	Depth, temperature, reservoir geometry, permeability, sustainable flow	Spatial continuity and production response	Energy-resource scenario
Hydrogeochemical	Li, Mg, Sr, Ge, I; salinity; interfering ions	Sampling representativeness and temporal variability	CRM screening and target selection
Technology	Pre-treatment, DLE/selective recovery, reinjection compatibility	Selectivity, recovery, scaling, sorbent/reagent performance	Process route and recovery factor
Economic	CAPEX, OPEX, product price, project life, discount rate	Price and scale sensitivity	NPV, payback, cost and capacity class
Project maturity	Data quality, studies, permits, environmental/social conditions	Maturity of evidence and approvals	UNFC consistent project status

Results and discussion

The Transcarpathian scenarios demonstrate why geothermal and mineral components should be assessed together. For the Solotvyno basin, the available dataset gives Li concentrations of 3.2–80 mg/L. The corresponding temperature scenarios are approximately 55 °C at 1 km, 90 °C at 2 km and 115 °C. For the Rakhiv-Komarivska area, Li values range from 25 to 250 mg/L, while modelled temperatures increase from about 65 °C at 1 km to 120 °C at 3 km. The Zaluzhanska scenario uses an average Li concentration of 25 mg/L and temperatures of about 70, 105 and 125 °C at 1, 2 and 3 km, respectively. These ranges indicate that a deeper and hotter target does not automatically produce the strongest mineral case; concentration, fluid productivity and recovery must be evaluated simultaneously.

For technology screening, the source model considers recovery efficiencies of 70, 80 and 90%. Direct lithium extraction (DLE) is particularly relevant for geothermal brines because it can be integrated into a circulating-fluid system and can reduce the surface footprint compared with conventional evaporation-based lithium production. However, DLE performance is brine-specific. High salinity, Mg/Li ratio, silica, iron and other dissolved components may control pre-treatment requirements, selectivity, reagent consumption, scaling behaviour and reinjection conditions. Therefore, laboratory and pilot testing on representative brine is required before assigning a feasibility level recovery factor.

The economic model evaluates a Solotvyno case with a nominal brine capacity from 300 to 900 m^3/day, a depth from 1,000 to 2,000 m and a 20-year operating life. The model uses a lithium product price of USD 10,094.4/t, a 15% discount rate and reports a payback period of about 4.5 years for the base case. These results are useful as a screening-level illustration rather than a bankable estimate, because the economic outputs depend strongly on unit conventions, flow

sustainability, actual DLE performance, product specification, infrastructure sharing with the geothermal plant and the allocation of common CAPEX and OPEX between energy and mineral products.

A central feature of the proposed approach is the treatment of mineral recovery as an additional project product rather than an isolated deposit. In an integrated project, the geothermal system supplies the fluid and may provide heat and electricity for the mineral-processing circuit, while CRM recovery can create an additional revenue stream and improve resource efficiency. Conversely, mineral extraction can introduce new technical risks, including brine pre-treatment, handling of residual streams and changes to fluid chemistry before reinjection. The optimum project configuration is therefore defined by the combined value of energy and mineral products, not by maximum recovery of a single element.

The integrated assessment should distinguish between a geochemical occurrence, a recoverable mineral resource and a project-defined product stream. Concentration alone is insufficient: recoverable output also depends on sustainable brine flow, operating time, recovery efficiency and product specification. This distinction is important at early stages, when historical chemical analyses may suggest mineral potential but do not yet demonstrate continuity, long-term productivity or process performance. Accordingly, CHydroMC treats concentration as one input in a broader scenario rather than as a stand-alone economic cut-off.

Technology selection must be based on brine-specific characteristics. DLE routes may use adsorption, ion exchange, membranes or other selective separation approaches, but their performance depends on salinity, Mg/Li ratio, silica, iron and competing ions. The appropriate recovery factor should therefore evolve from an assumed screening value to a laboratory-tested and then pilot-validated parameter. For integrated geothermal schemes, the process must also remain compatible with heat extraction and reinjection requirements.

Potential co-products should be assessed by the same logic. The source data identify Mg, Sr, Ge and I as additional components of interest. Their presence may increase project value, but only where concentration, recoverability, product quality and market scale justify an additional separation stage. Multi-component brines therefore require a product hierarchy: a principal revenue product, technically realistic co-products and non-economic dissolved constituents. This hierarchy can be tested in CHydroMC through alternative recovery and product scenarios.

Economic evaluation should separate common geothermal infrastructure from mineral-specific facilities. Wells, pumps, gathering systems and reinjection may serve both energy and mineral recovery, whereas pre-treatment, DLE units, polishing and product conversion are mineral-specific. This allocation is essential because co-production may improve project economics through shared infrastructure, while additional processing may increase CAPEX, OPEX and technical risk. Sensitivity analysis should therefore focus on brine flow, recovery, product price, operating life and the allocation of shared costs.

Uncertainty should be tracked separately for geology, hydrogeology, chemistry, technology and economics. Minimum-average-maximum scenarios are useful for screening, but later stages require measured flow, repeated chemical sampling, process testwork and updated cost data. The largest value of scenario tools such as CHydroMC is not a single forecast, but identification of the variables that most strongly control recoverable output and economic performance.

An integrated UNFC representation prevents geological confidence from being mistaken for commercial readiness. A project may have well-defined brine chemistry but still remain immature because recovery technology, permits, infrastructure or commercial conditions are unresolved. Linking CHydroMC scenarios to the E-F-G logic therefore provides a transparent path from initial screening to prefeasibility and feasibility, with assumptions progressively replaced by verified project data.

The novelty of the approach is the combination of geothermal resource assessment and CRM recovery in one project evaluation chain with common uncertainty scenarios. Instead of treating brine chemistry as a secondary descriptive characteristic, the method connects chemical composition directly to recoverable product, technology choice, project economics and maturity. This provides a practical screening tool for ranking wells and areas, identifying the data that most

strongly affect project value, and defining the next-stage work programme. The practical implementation of this methodology in CHydroMC adds a reproducible digital layer to the assessment, allowing geological, technological and economic assumptions to be tested consistently across alternative brine and project scenarios.

Conclusions

Integrated geothermal CRM projects require simultaneous assessment of heat, fluid and dissolved mineral resources. A robust evaluation should include temperature/depth conditions and sustainable flow; representative brine chemistry; target element concentration and interfering components; technology specific recovery; energy and mineral product scenarios; CAPEX and OPEX allocation; environmental and reinjection constraints; and project maturity. The Transcarpathian case study shows that lithium-bearing brines can be screened using minimum–average–maximum scenarios, but commercial conclusions should only be made after validation of flow, chemistry and extraction performance. The proposed framework can be used as a basis for prefeasibility studies and for UNFC consistent classification of integrated geothermal projects with critical mineral recovery. CHydroMC can support this workflow at the screening and prefeasibility stages by structuring input data, testing minimum-average-maximum cases and identifying the parameters that most strongly control recoverable output and project economics.

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