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Risk assessment of geothermal projects: approaches to uncertainty identification and management

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Geothermal projects are characterized by a combination of geological, technological, regulatory, financial and environmental uncertainties that evolve significantly during the project life cycle. The paper presents a structured approach to risk assessment based on identification, classification, scoring, prioritization and mitigation of project uncertainties. The methodology was applied to the Solotvyno geothermal project, where more than 100 potential risks were initially identified, 50 were selected as significant, and more than 20 priority risks were incorporated into the project risk matrix. Risk likelihood and impact were assessed on five-point scales, while the overall risk score was calculated as their product. Risks were additionally classified according to controllability as external, internal and mixed. The assessment demonstrates that geological uncertainty dominates the exploration phase, whereas permitting, financing and design risks become more important during development. Construction is primarily exposed to cost and contractor risks, while operational stages are increasingly influenced by equipment reliability, revenue stability and environmental compliance. Integration of critical raw material recovery from geothermal brines can increase project value but introduces additional technological and market uncertainties. The proposed approach supports stage-specific risk management and more robust decision-making under uncertainty.

Keywords: geothermal projects, risk assessment, uncertainty, geological risk, project life cycle, risk management.

Introduction

Geothermal energy projects are inherently associated with substantial uncertainty because their technical and economic performance depends simultaneously on subsurface conditions, reservoir characteristics, drilling results, technology performance, permitting procedures, market conditions and long-term operational parameters. Unlike many conventional energy projects, a significant part of the critical information required for investment decisions cannot be fully confirmed before drilling and reservoir testing.

The uncertainty is particularly important during the early stages of geothermal development, when temperature, reservoir productivity, permeability, fluid chemistry and sustainable production rates are commonly estimated from incomplete geological and geophysical datasets. As the project advances, the relative importance of individual risk categories changes: geological uncertainty gradually decreases, whereas engineering, construction, financial and operational risks become more significant. The complexity further increases for integrated geothermal projects where heat or electricity generation is combined with recovery of critical raw materials from geothermal brines. Such projects create additional economic opportunities but simultaneously introduce uncertainties related to mineral concentration, recovery efficiency, technological maturity, chemical processing, product quality and commodity prices.

The objective of this study is to develop and demonstrate a structured methodology for identification, classification and management of uncertainty in geothermal projects using the Solotvyno geothermal project as a case study.

Risk assessment methodology

The proposed methodology follows the general principles of ISO 31000 risk management and the risk assessment techniques described in ISO 31010 (*Risk management – Guidelines*, 2018; *Risk management*, 2019). The procedure consists of five main stages:

1. identification of potential project risks;
2. classification of risks according to their origin and controllability;

3. quantitative or semi-quantitative assessment of likelihood and impact;
4. prioritization of risks using a risk matrix;
5. definition of mitigation and monitoring measures.

For the Solotvyno basin, risks were classified into seven principal categories: geological, technical, environmental, regulatory, financial, social, operational. Each identified risk was assessed according to two parameters: likelihood and potential impact. Both parameters were evaluated using a five-point scale from 1 to 5. The overall risk score was determined as Risk Score = Likelihood × Impact. Consequently, the calculated scores provide a consistent basis for classifying risks as low, medium or high priority and identifying those requiring immediate mitigation measures (*Gambini, R.,* 2025; *Kassem, M. A.,* 2025; *Liu, W., & Ramirez, A.,* 2017; *Sanyal, S. K., & Morrow, J. W.,* 2020).

The assessment process initially identified more than 100 potential uncertainties and risk factors. Fifty risks were subsequently considered significant for project development, while more than twenty priority risks were included in the detailed project risk matrix. For each priority risk, the register includes its category, project stage, risk level, expected impact, proposed mitigation action and acceptable outcome.

An additional classification was introduced according to the level of project control:

- External risks include geological conditions, changes in legislation, market and currency conditions and community-related factors.
- Internal risks include technology selection, operations, project management and budget control.
- Mixed risks, which can only be partially controlled by the project developer, include drilling performance, induced seismicity, project revenues and reputation.

The analysis indicates that approximately 60–70% of the key project risks belong to external or only partially controllable categories. This emphasizes the importance of early geological investigations, stakeholder management, contractual mechanisms and risk-sharing instruments.

Evolution of risks through the geothermal project life cycle

The risk profile of a geothermal project is dynamic and changes substantially during project development.

During the exploration phase, geological uncertainty represents the dominant risk. The principal uncertainties concern reservoir geometry, temperature, permeability, fluid productivity and resource sustainability. Insufficient geological information may result in unsuccessful drilling, lower-than-expected flow rates or inadequate reservoir temperatures.

Resource validation therefore represents the key risk-reduction activity at this stage. Geological and geophysical investigations, test drilling and well testing progressively convert geological assumptions into measured project parameters.

During the development phase, the relative importance of geological risk decreases, while regulatory, financial and engineering risks increase. Major uncertainties are associated with permitting procedures, project financing, well-field configuration, plant design and technology selection.

The construction phase is dominated by execution risks, particularly cost overruns, schedule delays, contractor performance and technical integration. Effective procurement strategy, experienced contractors, contingency budgeting and construction monitoring therefore become major instruments of risk management.

During the operational phase, the project risk profile shifts toward equipment reliability, reservoir performance, maintenance requirements, revenue stability and environmental compliance. Continuous monitoring of production wells, reservoir pressure, fluid chemistry and plant performance becomes necessary to identify deviations from expected operating conditions.

At the end-of-life stage, the principal uncertainties concern well abandonment, site restoration, environmental liabilities and compliance with regulatory closure obligations.

Thus, the general evolution of the geothermal risk profile can be described as a transition from subsurface uncertainty through project execution risk toward operational and environmental management.

Geological confidence as the principal early-stage risk

Geological uncertainty has the strongest influence on geothermal project viability during exploration. Even when regional geological conditions indicate geothermal potential, commercial success depends on confirmation of several interrelated parameters, including reservoir depth, temperature, permeability, pressure, flow rate and fluid chemistry.

The Solotvyno assessment considers several potential development depths, including approximately 1,000 and 2,000, corresponding to expected temperatures of approximately 55, 90 and 115 °C (*Virshylo, I., Mishuris, G., Topór, T., Karpenko, O., & Duchuk, S.,* 2026). Such variation directly influences potential energy production, drilling costs and the choice of technological configuration. The project therefore requires progressive geological validation rather than reliance on a single deterministic resource estimate. Scenario-based assessment allows geological uncertainty to be represented explicitly by minimum, average and maximum values for the most important technical parameters.

This approach is particularly relevant when the geothermal resource is assessed together with dissolved mineral components.

Additional uncertainties associated with critical raw material recovery

The possibility of recovering critical raw materials from geothermal brines can significantly modify both the economic potential and the risk profile of a geothermal project.

In the Solotvyno case, lithium is considered among the potential mineral by-products. Available scenarios demonstrate substantial variability of lithium concentrations and recovery efficiencies. The assessment considers different concentration scenarios and recovery rates ranging approximately from 70 to 90%.

Mineral recovery introduces several additional risk groups.

- resource risk, because concentrations of dissolved elements may vary between wells, depths and production periods.
- technology risk -d irect lithium extraction and other selective recovery technologies depend strongly on brine composition, competing ions, temperature, scaling potential and required product purity.
- market risk, because project economics become exposed to commodity price fluctuations and potential changes in demand for critical raw materials.
- chemical and environmental risk, associated with additional treatment stages, reagents, waste streams and reinjection requirements.

Therefore, critical raw material recovery should be treated as an additional project opportunity rather than incorporated into the base-case economics without appropriate sensitivity and risk analysis.

Risk mitigation strategy

Risk mitigation should correspond to both the nature of uncertainty and the stage of project development. For geological risks, the primary measures include additional geological investigation, resource modelling, test drilling, reservoir testing and progressive updating of the geological model. Technical risks can be reduced through selection of proven technologies, pilot testing, detailed engineering and involvement of experienced contractors. Regulatory risks require early engagement with permitting authorities and integration of regulatory requirements into the project schedule. Financial risks should be addressed through contingency budgeting, sensitivity analysis, cost control and appropriate financing structures. Market exposure can be partly reduced through long-term sales arrangements and offtake agreements, particularly where mineral co-products are planned. Environmental and social risks require continuous environmental monitoring, transparent stakeholder engagement and integration of community considerations into project planning. Particular attention should be given to risks that cannot be fully controlled. For external and mixed risks, the objective of risk management is not necessarily elimination but reduction of exposure through better information, contractual risk allocation, insurance, financial reserves and adaptive project design.

Risk Assessment Results

The risk assessment of the Solotvyno geothermal project identified more than 100 potential risk factors. Following screening and prioritization, 50 risks were classified as significant, while more than 20 priority risks were included in the detailed risk matrix. The identified risks were grouped into seven main categories: geological, technical, environmental, regulatory, financial, social, and operational. The detailed risk register links each risk to its type, project phase or milestone, risk level, expected impact, mitigation measures, and acceptable outcome. This structure makes it possible not only to rank uncertainties according to their significance but also to connect each major risk with a specific management response. The highest-priority risks identified at the early stages of the project are mainly related to geological uncertainty and drilling performance, whereas operational risks become increasingly important during project implementation.

Table 1. Example of the priority risk register for the Solotvyno geothermal project

No.	*Type*	*Project phase / milestone*	*Risk*	*Level*	*Impact on*	*Mitigation measures*	*Acceptable outcome*
1	External	Geological exploration	Insufficient temperature potential	High	Project economics	Additional studies, test drilling	Resource meets target parameters
2	External	Geological model	Low well productivity	High	Plant capacity	Backup wells	Stable flow rate per feasibility study
3	External	Geological model	Geological heterogeneity	Medium	Production stability	3D modelling	Predictable reservoir behaviour
4	Internal	Drilling	Drilling complications	High	Schedule and budget	Experienced contractors	Drilling completed without incidents
5	Internal	Operation	Equipment failure	Medium	Operational continuity	Backup systems	Continuous system operation
6	Internal	Operation	Corrosion and scaling	Medium	Equipment lifetime	Anti-corrosion materials	Normal operation within planned lifetime

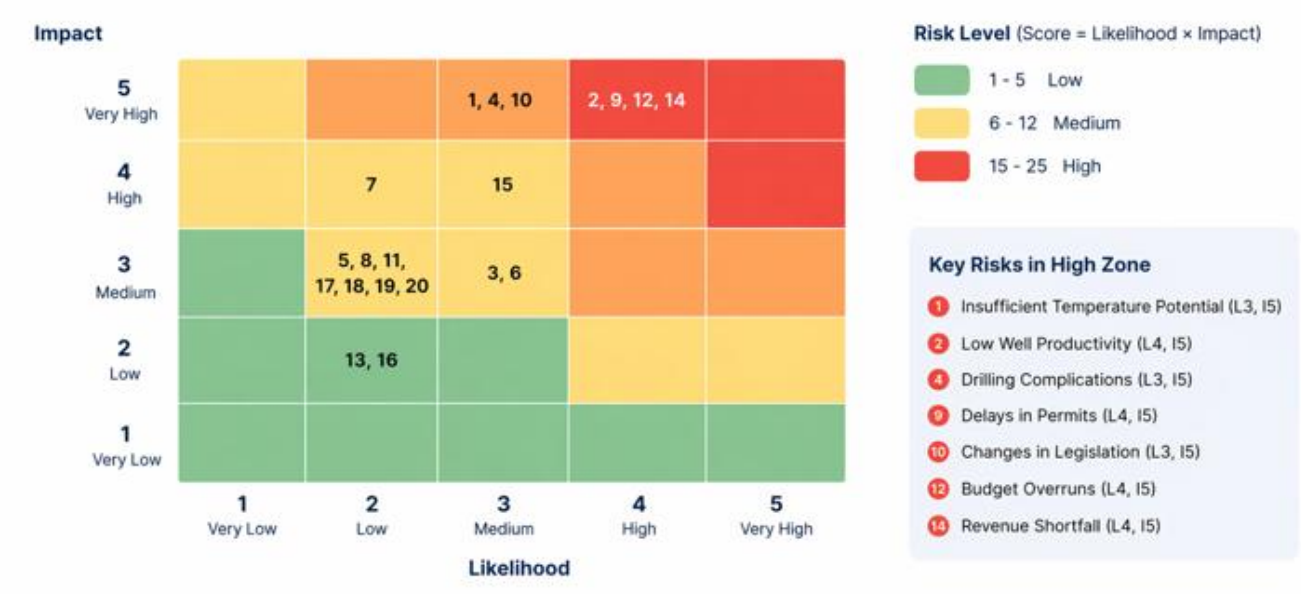

Figure 1. Part of Risk Matrix

Discussion

The results demonstrate that geothermal project risk cannot be adequately represented by a single risk indicator. Instead, the risk structure changes as the project progresses and new information becomes available.

Early-stage decision-making is dominated by uncertainty in subsurface parameters. Therefore, investment in additional geological information can have substantial value because it may prevent premature commitment of large capital expenditures.

At later stages, project management increasingly focuses on execution reliability, cost and schedule control. Consequently, the risk management system should evolve together with the technical maturity of the project. Another important conclusion is that a significant proportion of geothermal project risks remain external to direct management control. According to the Solotvyno assessment, approximately 60–70% of key risks may be classified as external or partially controllable. This reinforces the importance of scenario analysis and adaptive decision-making rather than reliance exclusively on deterministic technical-economic models. Integration of critical raw material recovery provides additional economic upside, but it should be assessed separately because it introduces a new group of technological, processing and market uncertainties.

Conclusions

A structured risk assessment framework is an essential component of geothermal project evaluation and investment decision-making. The proposed methodology combines identification of risk categories, likelihood-impact scoring, classification according to controllability, life-cycle analysis and development of project-specific mitigation measures.

The Solotvyno case study demonstrates that geological is the dominant risk during exploration, while regulatory and financial uncertainties become increasingly important during project development. Construction is primarily exposed to cost, contractor and technical risks, whereas operational stages are characterized by equipment reliability, revenue stability and environmental compliance. The incorporation of critical raw material recovery from geothermal brines can improve the overall project value proposition but simultaneously increases technological complexity and exposure to commodity markets.

The most effective risk management strategy is therefore based on progressive reduction of uncertainty through geological validation, test drilling, pilot studies, early permitting engagement, contingency budgeting, environmental monitoring and stakeholder management. The proposed framework provides a practical basis for integrating uncertainty directly into technical-economic evaluation of geothermal projects and supports more robust decision-making throughout their life cycle.

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