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Integrated Play Fairway Analysis and Monte Carlo Simulation for De-risking Target Selection: A Case Study of the Cisolok-Cisukarame Geothermal Field, Indonesia

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Abstract

Geothermal exploration faces significant risks due to subsurface uncertainties and high costs. Selecting drilling targets requires integrating diverse geoscientific data with operational constraints, but the weighting of these factors often relies on subjective judgment, potentially inducing bias. The Cisolok-Cisukarame geothermal area in Indonesia is selected for a case study to address this challenge. This study aims to present and demonstrate a robust well-targeting approach that integrates Play Fairway Analysis (PFA) with Monte Carlo simulation used uniquely for objective parameter weighting, thereby reducing subjectivity and de-risking target selection. PFA utilized extensive survey data to map key factors grouped into 1) Reservoir & Permeability potential using magnetotelluric (MT) survey for caprock/structure, geological structures, surface manifestations, and alteration zones, and 2) Drilling Feasibility & Infrastructure for conservation status, slope, and water/urban proximity. Monte Carlo simulation generated objective P50 (median) weights for parameters in each group and for the overall combination of Group 1 (subsurface potential) versus Group 2 (feasibility). These objective weights were used in a GIS-based weighted overlay analysis to produce a final drilling favorability map. The simulation assigned approximately 65% weight to the subsurface potential and 35% to the feasibility factors. The resultant favorability map objectively identifies the most promising target zones primarily 1-2 km NNE from the high-temperature Cisukarame manifestations, effectively balancing geological merit with operational viability. This integrated methodology offers a transparent, data-driven, and de-risked approach superior to conventional deterministic targeting methods.

Keywords: Geothermal Exploration, Play Fairway Analysis (PFA), Favorability Mapping, Uncertainty Analysis.

1 INTRODUCTION

The Cisolok-Cisukarame geothermal prospect is located in the Sukabumi Regency, West Java Province, Indonesia, roughly 100 km SSW of Jakarta near the southern coast of Java (Ditjen EBTKE and Kementrian Energi Sumber Daya Mineral 2017). Situated within a region known for significant geothermal potential related to the Sunda Arc volcanism (Hochstein and Sudarman 2008), an approximately 155 km^2 concession area features rolling hills, river valleys, and prominent surface geothermal manifestations, particularly around Cisolok and Cisukarame, making it a key area for Indonesia's renewable energy development.

The prospect area lies in a complex geological setting shaped by the subduction of the Indo-Australian Plate. It is composed of a Miocene volcano-sedimentary basement, including limestone and fractured volcanics acting as a potential reservoir, overlain by Pliocene-Quaternary volcanic sequences (breccias and lavas) which can form altered, low-permeability caprocks(Ditjen EBTKE and Kementrian Energi Sumber Daya Mineral 2017). A significant N-S trending graben structure, interpreted from integrated geological and geophysical surveys, appears to control the higher-temperature Cisukarame system and influence regional permeability. These elements provide the framework for potential geothermal resources but require systematic spatial analysis to delineate favorable exploration targets.

Play Fairway Analysis (PFA) provides a structured methodology to integrate such multiple datasets on geology, geochemistry, and geophysics and map subsurface potential based on critical geothermal system elements (DeAngelo et al. 2024; Garchar et al. 2016; Pauling et al. 2014). However, practical target selection necessitates combining this subsurface assessment with surface and operational constraints, e.g., conservation status, terrain slope, and distance to urban area. The inherent challenge lies in objectively weighting these often-disparate factors, a process typically reliant on subjective expert judgment (Nielson et al. 2015; Pauling et al.

2014). This study improves this issue by employing Monte Carlo simulation, specifically for deriving objective parameter weights (Vose 2008), and integrating subsurface indicators and feasibility factors within the PFA framework to generate a quantitatively de-risked drilling favorability map of Cisolok-Cisukarame.

2 METHODOLOGY

The methodology integrates spatial PFA mapping with Monte Carlo simulation for deriving weights used in a Geographic Information System (GIS) based weighted overlay analysis as shown in Figure 1.

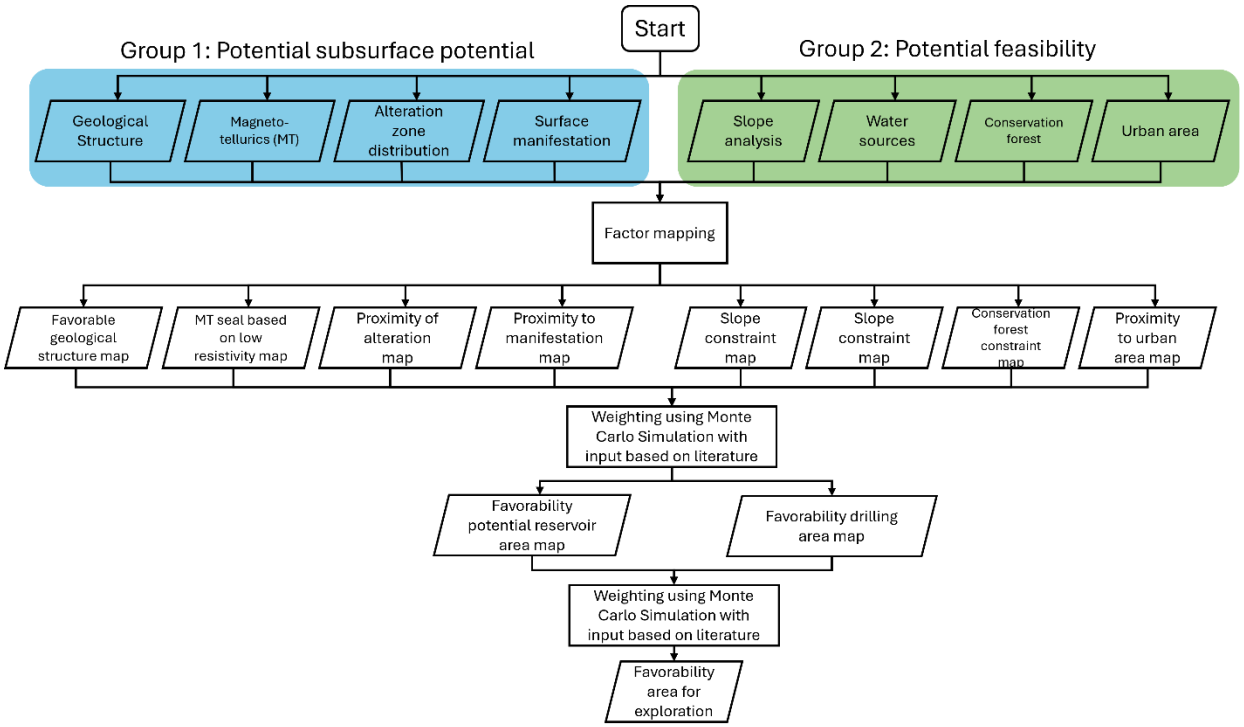


Figure 1. Flowchart showing PFA mapping, MC Weighting, and Weighted Overlay.

2.1 Play Fairway Analysis (PFA) - Factor Mapping

Geospatial datasets representing evidence for factors influencing geothermal potential and drilling feasibility were prepared and normalized to a 0-10 scale, where 10 is most favorable. These were categorized into two main groups:

A. Group 1: Reservoir and Permeability Potential (Subsurface Indicators):

These factors provide evidence for the presence and quality of the geothermal system itself.

- Seal/Cap Rock Integrity from magnetotelluric (MT) survey: The low-resistivity (< 10 Ohm·m) layer by MT surveys was interpreted as the clay cap and mapped. Favorability scores were assigned based on lower resistivity values, greater thickness, and lateral continuity, indicating a more effective seal.

- Favorable Geological Structure (Permeability Proxy): Faults, fracture zones, and the main N-S graben structure identified from geological mapping, and geophysical interpretations were mapped. Higher favorability was assigned to areas with higher fault density, proximity to major faults, especially within the graben, and fault intersections, representing potential high-permeability zones.

- Proximity to Manifestations: locations of hot springs, boiling pools, and fumaroles were mapped. Favorability decreased with distance, with higher initial scores assigned to the higher-temperature, neutral-pH Cisukarame manifestations indicative of a deeper, hotter source.

- Proximity/Intensity of Alteration: favorability scores were assigned to mapped surface hydrothermal alteration zones based on proximity and interpretation of alteration type.

B. Group 2: Drilling Feasibility and Infrastructure (Surface/Feasibility Factors):

These factors influence the practicality and cost of accessing and drilling a target.

- Conservation Forest Constraint: areas designated as National Park or production forest with restrictions were assigned very low or zero favorability.
- Slope Constraint: a slope map was derived from a Digital Elevation Model (DEM). Areas with steep slopes (e.g. > 25–30%) received low favorability scores due to increased costs and risks associated with road and drill pad construction.
- Proximity to Water Source: buffers were created around major rivers (Cisukarame, Cisolok, etc.), assigning higher favorability closer to potential water sources needed for drilling operations.
- Proximity to Urban Areas/Infrastructure: buffers around existing roads and villages. A non-linear favorability might be applied, peaking at a moderate distance (> 500 m) to balance ease of access with potential social and permitting impacts that are too close to settlements.

2.2 Monte Carlo Simulation for Parameter Weighting

To objectively determine the relative influence of the mapped factors, Monte Carlo simulation with 50,000 iterations per simulation using Python was employed. Probability distributions, uniform ranges reflecting perceived importance and uncertainty based on literature and case-study specifics: Group 1 factors from 10–40% and Group 2 factors 15–30%, were defined for potential weights a priori. The simulations sampled from these input distributions, normalized the sampled weights within each iteration to sum to 1, and generated output probability distributions for the weights of (a) each parameter within Group 1, (b) each parameter within Group 2, and (c) the overall Group 1 versus Group 2 contribution. The P50 (median) values from these output distributions were then selected as the objective, probabilistically derived weights for the subsequent overlay analysis, minimizing subjective bias in the integration process.

2.3 Integrated Favorability Mapping

The normalized factor maps within each group were combined using a weighted sum based on their respective intra-group P50 weights derived from the MC simulation. This produced Map_1 (Composite Subsurface Potential) and Map_2 (Composite Feasibility/Infrastructure).

The two composite maps were combined using the inter-group P50 weights of W_1 and W_2 as:

$$\text{Final Favorability} = (Map_1 * W_1) + (Map_2 * W_2) \quad (1)$$

A final Exploration Favorability Map where pixel values represent objectively weighted suitability, integrating geological promise and operational viability. Higher values indicate more favorable drilling targets.

3 RESULTS AND DISCUSSION

3.1 Monte Carlo Weighting Results

The Monte Carlo simulations yielded the P50 (median) objective weights as summarized in Table 1 and 2. These results quantify the relative importance based on the defined input ranges. The equal weighting within Group 2 reflects the identical input ranges used, while the different weights in Group 1 reflect the varying ranges assigned based on perceived significance. The overall 65/35 split between Group 1 and Group 2 reflects the input prioritizing subsurface potential while giving substantial consideration to feasibility.

3.2 Integrated Favorability

The PFA combined with Monte Carlo parameter weighting provided a traceable and objective methodology for geothermal target de-risking in Cisolok-Cisukarame. Deriving weights probabilistically resulted in ca. 65% emphasis on subsurface potential and ca. 35% on feasibility, with specific weights for individual factors as ca. 32% for the MT-defined seal. The approach reduces subjectivity inherent in expert-based weighting. The resulting favorability map (Figure 2Figure 2. Final favorability exploration area map showing high, medium, low favorability zones in the Cisolok-Cisukarame area.) objectively confirms the area NNE of the Cisukarame springs as the prime target, optimally balancing strong subsurface indicators by robust MT seal, favorable structure, and high-temperature manifestations with manageable operational constraints as outside strictest conservation zones and acceptable depth/slope. This method effectively de-risks exploration by quantitatively highlighting zones where both geological potential and operational viability are high, while deprioritizing areas constrained by either poor geology or prohibitive surface factors. The flexibility and transparency of this approach, critically dependent

on the quality of input data, especially MT in this case (Ditjen EBTKE and Kementrian Energi Sumber Daya Mineral 2017), offering significant advantages for exploration decision-making. However, initial definition of uncertainty ranges for weighting still requires careful expert consideration.

Table 1. P50 (median) parameter weights from Monte Carlo Simulation.

Group	Parameter	P50 Weight (%)
Group 1 (Subsurface)	Reservoir Area (MT Seal)	32.4%
	Geological Structure	27.4%
	Surface Manifestation	22.4%
	Altered Zone	17.7%
Group 2 (Feasibility)	Conservation Forest	25.0%
	Slope	25.0%
	Urban Area	25.0%
	River (Water Source)	25.0%

Table 2. P50 (median) group weights from Monte Carlo Simulation.

Group	Weight Variable	P50 Weight (%)
Group 1 (Subsurface)	W_1	65.0%
Group 2 (Feasibility)	W_2	35.0%

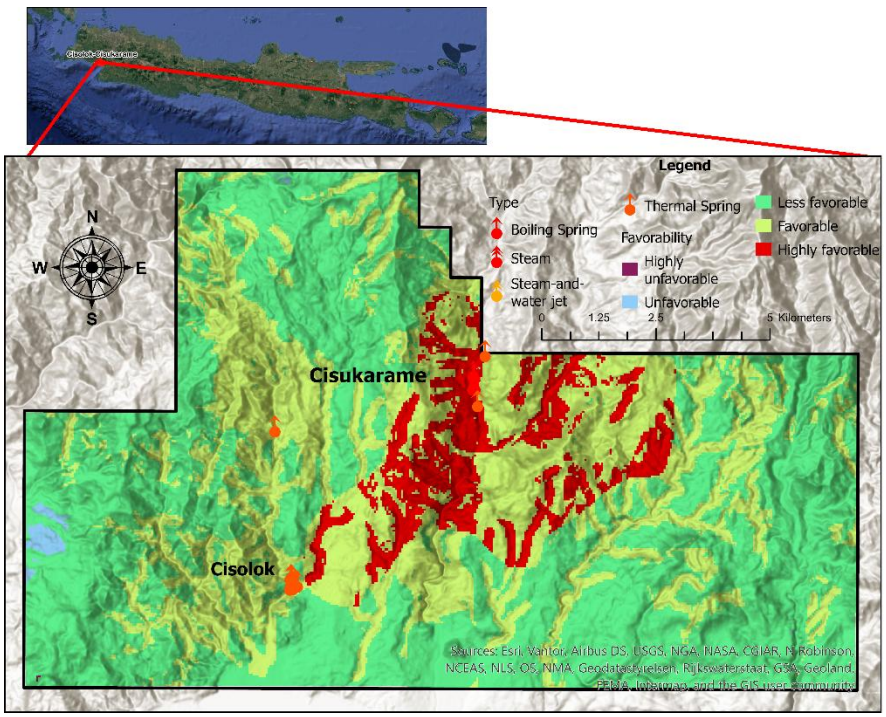


Figure 2. Final favorability exploration area map showing high, medium, low favorability zones in the Cisolok-Cisukarame area.

4 CONCLUSION

Selecting optimal drilling targets in geothermal exploration requires integrating complex subsurface assessments with practical surface and operational constraints. Subjectivity in weighting these diverse factors can hinder effective de-risking. This study demonstrated an integrated Play Fairway Analysis methodology incorporating Monte Carlo simulation specifically for deriving objective parameter weights.

By selecting the Cisolok-Cisukarame prospect for a case study, the method systematically combined evidence from MT surveys, crucial for the seal definition, geological mapping, surface manifestations, alteration, conservation status, slope, and distance to urban areas. Monte Carlo simulation provided objective weights, confirming the primary importance of subsurface indicators, ca. 65% overall weight, while incorporating feasibility factors, ca. 35% weight.

The resultant Drilling Favorability Map objectively identified the most promising target area, located 1–2 km NNE from the Cisukarame manifestations, where strong geological potential coincides with acceptable operational conditions. This confirms previous interpretations but provides a more transparent and quantitatively justified basis for the conclusion. The integrated PFA with Monte Carlo parameter weighting represents a valuable, enhanced approach for de-risking geothermal exploration targets by providing a more objective, balanced, and defensible framework for decision-making.

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