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Infolitika Journal of Data Science

Vol. 2, No. 1, 2024

Optimizing Geothermal Power Plant Locations in Indonesia: A Multi-Objective Optimization on The Basis of Ratio Analysis Approach

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Article History

Received 2 March 2024
Revised 21 April 2024
Accepted 3 May 2024
Available Online 9 May 2024

Keywords:
MOORA
Renewable energy
Multi-objective methods
Decision support system

Abstract

As the global energy landscape shifts towards sustainable sources, geothermal energy emerges as a pivotal renewable resource, particularly in regions with abundant geothermal potential like Indonesia. This study focuses on Mount Seulawah in Aceh Province, a region rich in geothermal resources, to optimize the selection of geothermal power plant (GPP) sites using the Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) method. Our approach integrates environmental, technical, and accessibility criteria, including distance to settlements, land slope, proximity to fault lines and heat sources, and road access. By employing a structured decision matrix and applying MOORA, we systematically evaluated and ranked potential sites based on their suitability for GPP development. The results highlight the site at Ie Brôuk as the most optimal due to its minimal environmental impact and superior geological and accessibility conditions. This study not only contributes to the strategic deployment of geothermal resources in Indonesia but also provides a replicable model for other regions with similar geothermal potentials, emphasizing the importance of a balanced and informed approach to renewable energy site selection.

1. Introduction

In recent years, the global energy crisis has become increasingly evident. The rising energy demand has led to the gradual depletion of fossil fuel resources. Additionally, the combustion of primary fuels hurts the environment [1, 2]. There has been a growing emphasis on producing renewable energy sources in recent years. International collaborative efforts are now to develop and harness carbon-free energy sources to combat potential climate change causes [3–5].

Renewable energy includes geothermal energy and various forms of solar energy, such as bio-energy (bio-fuel), hydroelectric, wind energy, photovoltaic, and solar-thermal energy [6, 7]. These energy sources are converted into heat or electricity [8]. Among these renewable options, geothermal energy stands out for its minimal environmental footprint and vast potential as a sustainable energy resource [9, 10]. This form of energy, generated from the Earth's natural heat, offers a cleaner alternative to fossil fuels, contributing significantly to environmental preservation. It holds particular promise due to its virtually limitless availability and the ongoing advancements in extraction technologies [11].

The most obvious manifestations of this energy flow on the Earth's surface are active volcanoes and high-temperature geothermal fields [12]. Geothermal studies are conducted only in specific countries or regions, while the distribution of active volcanoes worldwide is well-known [13]. Since volcanoes and high-temperature geothermal fields are manifestations of the same energy flow, the distribution of active volcanoes should reflect the potential for global geothermal energy [14].

Indonesia, with its abundant geothermal reserves, is a prime candidate for the development of geothermal energy, housing 13% of the world's volcanoes, 80% of which are believed to possess geothermal production potential [15, 16]. Aceh Province, particularly Mount Seulawah Agam, stands out as one of the areas rich in geothermal resources [17]. Previous explorations have identified numerous manifestation locations [18]. Almost half of Indonesia's geothermal potential is concentrated on the island of Sumatra, including Seulawah Agam in Aceh. Nevertheless, the selection of optimal sites for geothermal power plants necessitates a comprehensive and systematic approach, taking into account a variety of factors and objectives.

Recognizing the urgent need for environmentally sustainable energy solutions, this study focuses on optimizing the site selection for Geothermal Power Plants (GPP) in Mount Seulawah, Aceh Province, Indonesia. Given Indonesia's substantial geothermal reserves, particularly in Aceh, there is a significant opportunity to develop this clean energy source. Mount Seulawah specifically offers several advantages for geothermal power generation. Its geological characteristics, including high heat flow and suitable reservoir conditions, make it a prime location for efficient geothermal operations [17, 19].

This study employs the Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) method, a robust decision-making tool designed to handle complex decision environments by integrating and optimizing multiple criteria and objectives [20]. The choice of the MOORA method is driven by its ability to provide a balanced evaluation of diverse factors such as environmental impacts, resource availability, and technical feasibility [21], making it particularly suitable for the comprehensive analysis required in selecting optimal GPP sites in Seulawah Aceh Besar.

The application of the Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) method has been increasingly prominent in the field of renewable energy, with several studies highlighting its effectiveness in addressing complex optimization problems. Prior research has applied MOORA to various aspects of energy management, including the optimization of wind farm locations, solar panel installations, and biomass plant operations. For instance, a study by Ergul and Genç demonstrated MOORA's capability to optimize the spatial arrangement of wind turbines to maximize energy output while minimizing ecological disturbances [22]. Similarly, Wankhede and Hole employed MOORA to balance cost efficiency and energy efficiency in the deployment of solar energy systems [23].

This study aims to develop a computationally robust framework for GPP site selection that mitigates environmental impacts while enhancing geothermal extraction capabilities. This approach addresses critical deficiencies in current methodologies by integrating environmental considerations with geothermal potential maximization, setting a new standard for site selection protocols in renewable energy sectors. This framework promotes sustainable development and introduces a scalable model for future energy projects.

Furthermore, this paper contributes to computational decision support systems in renewable energy management by detailing the application and effectiveness of MOORA in geothermal site selection. As the interest in renewable energy sources heightens globally, the methodologies developed here offer valuable insights into the computational aspects of multi-criteria decision-making. Expected outcomes include facilitating sustainable growth in geothermal energy and enhancing decision-making architectures, thereby improving infrastructure development practices for geothermal energy both in Indonesia and globally.

2. Materials and Methods

2.1. Data Collection

Data collection was conducted based on criteria obtained from the research conducted by Hariyanto & Robawa [24]. The criteria considered for GPP development included distance to settlements, land slope, distance to fault lines, road access, and the location of hot springs. The data collection process utilized the ArcMap 10.5 application. Data processing involved satellite imagery, fault maps, and land slope maps. Satellite images were obtained using the SAS Planet application. The slope dataset was acquired from the Indonesian Seamless Digital Elevation Model (DEM) and National Bathymetry (DEMNAS). The fault dataset was obtained from the Indonesian GeoMap Ministry of Energy and Mineral Resources (ESDM).

The coordinates of the geothermal hotspots were referenced from the research conducted by Idroes et al. [18, 25]. Satellite imagery was employed to determine the distance from the hotspots to settlements and road access. The required land slope in this study was below 15% or 6.75°, categorized into different levels based on the degree of slope. The researchers decided to choose alternative locations within the 0°-8° slope range.

2.2. Criteria Prioritization Using Ordinal Priority Approach

In the process of identifying optimal sites for GPP development, the Ordinal Priority Approach (OPA) plays an important role in prioritizing various criteria. This method systematically transforms qualitative expert judgments into quantitative weights, thus streamlining decision-making processes. By doing so, OPA helps ensure that decisions are based on a structured evaluation of site characteristics, which are crucial for both the feasibility and sustainability of GPP projects.

Experts from geology, environmental science, and renewable energy rank criteria like geological features, environmental impact, and technical aspects. OPA then translates these rankings into quantitative weights, reflecting expert consensus. To ensure comprehensive decision-making, opinions from five experts in geothermal energy and power generation were gathered to weigh each criterion. This inclusive approach forms a solid foundation for further analysis in site selection.

2.3. Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA)

This study chose the MOORA method as the primary decision-making tool for assessing potential GPP sites. MOORA offers distinct advantages over alternative methodologies, particularly in its ability to comprehensively evaluate multiple criteria and objectives simultaneously [23].

Implementing the MOORA method to assess potential GPP sites is straightforward and thorough. It begins with identifying key attributes essential for decision-making, such as geological conditions, environmental impact, energy yield, accessibility, and infrastructure availability. Each attribute plays a vital role in determining site suitability. After identifying these attributes, the next step is to collect data and input criteria values for each potential site. For example, geological conditions might include soil stability, seismic activity, and geological formations, while environmental impact could encompass factors like habitat disturbance, carbon footprint, and visual impact. Energy yield assessment may involve parameters such as solar irradiance, wind speed, or hydrological flow rates.

The collected data is then structured into a MOORA Decision Matrix, facilitating a systematic comparison of sites based on multiple criteria. Each site corresponds to a row in the matrix, and each criterion corresponds to a column. To ensure fair comparison across diverse criteria, the data in the MOORA Decision Matrix is normalized. This process involves scaling the data within a specific range, typically from 0 to 1, to eliminate bias due to differences in measurement units or scales among the criteria [21].

Using the normalized data, the MOORA method calculates optimization values for each site based on the criteria. This calculation considers predetermined weights assigned to each criterion. It aggregates the normalized values for each site across all criteria, resulting in an optimization value indicating the overall performance of each site. These optimization values are then used to determine ranking values for each site. Sites with higher ranking values are considered more suitable for GPP development, indicating better performance across the selected criteria.

2.4. Validation on the Jaboi Sabang Geothermal Energy Source

To validate the efficacy of the MOORA method in determining optimal GPP locations, we conducted a validation test on the Jaboi Sabang geothermal energy source. This validation aimed to assess whether the rankings generated by MOORA align with the actual performance and suitability of existing GPPs.

The Jaboi Sabang geothermal energy source, with its established GPP infrastructure, serves as a pertinent case study for validation purposes. By comparing the MOORA-derived rankings with the actual operational efficiency and environmental impact of the existing GPPs in Jaboi Sabang, we can evaluate the accuracy and reliability of the MOORA method in predicting optimal GPP sites.

This validation process involves analyzing various factors, including energy production efficiency, environmental impact mitigation measures, and socioeconomic considerations. By correlating the MOORA rankings with empirical data gathered from the operational GPPs in Jaboi Sabang, we aim to ascertain the consistency and

Table 1. Criteria and alternative site for GPP development in the Mount Seulawah.

Alternative GPP Site	Criteria				
	Distance to Settlements (m)	Distance to Fault Lines (m)	Land Slope (°)	Distance to Geothermal Heat Source (m)	Distance to Road Access (m)
A1	926	260	0-8°	10	418
A2	1.237	517	0-8°	383	837
A3	860	723	0-8°	200	10
A4	760	488	0-8°	85	22
A5	444	180	0-8°	236	10
A6	731	1	8-15°	404	644
A7	510	1.177	0-8°	644	10
A8	210	234	0-8°	185	104
A9	660	234	0-8°	252	10
A10	1.000	287	8-15°	551	573
A11	50	188	0-8°	1.091	10
A12	423	219	0-8°	918	10
A13	100	1.519	0-8°	144	73
A14	290	1.152	0-8°	285	10
A15	60	1.722	0-8°	317	85
A16	233	1.983	0-8°	609	10
A17	140	838	0-8°	448	10
A18	134	1.262	0-8°	419	10
A19	150	100	0-8°	1.291	10

effectiveness of the MOORA method in guiding GPP site selection.

3. Results and Discussion

3.1. Data Collection Results

Data collection was conducted at three geothermal heat source locations in Seulawah Aceh Besar: Ie Seu'um, Ie Brôuk, and Ie Jue, with a total of 19 alternative locations. Ie Seu'um had seven alternatives, while Ie Brôuk and Ie Jue had 12 alternatives. The alternatives avoided locations with land slopes exceeding 15% and those above fault lines to mitigate potential disaster risks. However, three alternatives in unsuitable locations for GPP construction were identified in this study. These alternatives had land slopes exceeding 15% or above fault lines, specifically A6, A10, and A19. This was done to test the performance of the MOORA method. The data used in this study can be observed in Table 1.

Each criterion had different levels of importance. Distance to settlements and distance to fault lines required longer distances, where larger values were considered better. Conversely, the geothermal heat source location and road access required shorter distances, where smaller values were considered better. As the ranking was calculated based on the largest values, data normalization was necessary to transform criteria values, with the smallest requirement becoming the largest value. Land slope criteria were classified into two categories: areas with slopes of 0-8° were assigned a value of 1, and slopes >8° were assigned a value of 0.

3.2. OPA Weighting Results

The experts provided their opinions by ranking the criteria based on their level of importance. These opinions were then processed using OPA tools to generate the weightings for the criteria in the construction of the GPP. In this weighting process, the researchers established cost and benefit criteria. Cost criteria were assigned to two criteria with the smallest weight values: the distance to settlements and road access. Benefit criteria were assigned to criteria such as the distance to the geothermal heat source, distance to fault lines, and land slope. The weight values for each criterion can be observed in Table 2.

The resulting weightings were then ranked, with rank 1 representing the highest importance and rank 5 indicating the lowest. The results revealed that the distance to the geothermal heat source was ranked first with a weight of 0.350, while the distance to settlements was ranked last with a value of 0.112.

3.3. MOORA Calculation Results

The MOORA method calculations began by creating criterion and alternative values matrices. Subsequently, the data was normalized, where each alternative's response to an attribute was compared to the denominator representing all alternatives regarding that attribute. This denominator is the square root of the sum of squares of each alternative per chosen attribute. The normalized results were then multiplied by the criterion

Table 2. Criteria ranking and weights according to experts.

Expert	Criteria				
	Distance to fault lines	Distance to geothermal heat source	Land Slope	Distance to settlements	Distance to road access
Expert 1	2	1	4	5	3
Expert 2	1	2	3	4	5
Expert 3	5	1	3	4	2
Expert 4	2	1	4	3	5
Expert 5	1	2	3	4	5
Weight	**0.280**	**0.350**	**0.131**	**0.112**	**0.126**
Optimization	**Benefit**	**Benefit**	**Benefit**	**Cost**	**Cost**

Table 3. Ranking results using the MOORA method for the development of GPP in the Mount Seulawah.

Rank	Alternative	Value
1	A1	0.353
2	A15	0.158
3	A13	0.154
4	A16	0.130
5	A18	0.086
6	A14	0.075
7	A7	0.061
8	A4	0.057
9	A17	0.055
10	A8	0.054
11	A3	0.025
12	A2	0.023
13	A11	0.009
14	A5	0.002
15	A19	-0.002
16	A9	-0.004
17	A12	-0.005
18	A10	-0.018
19	A6	-0.024

weights; then, the results were aggregated in the case of maximization (for beneficial attributes) and subtracted in the case of depreciation (for non-beneficial attributes) to obtain optimization values. The maximization values were then subtracted from the minimization values to find the scores for each alternative. The calculated results were then sorted from the highest to the lowest values, as presented in Table 3.

Based on the MOORA method calculations, the most suitable location for the GPP construction is alternative A1 at the Ie Brôuk hotspot, as shown in Figure 1. Alternative A1 achieved the highest score of 0.353, indicating a high level of alignment with the criteria. The distance from this alternative to settlements (926 meters) and the fault line (260 meters) met the required criteria. The land slope for alternative A1 fell within the 0-8° category, meeting the specified conditions.

The proximity of alternative A1 to the geothermal heat source (10 meters) provided a significant advantage, given the highest weight assigned to this criterion (0.350).

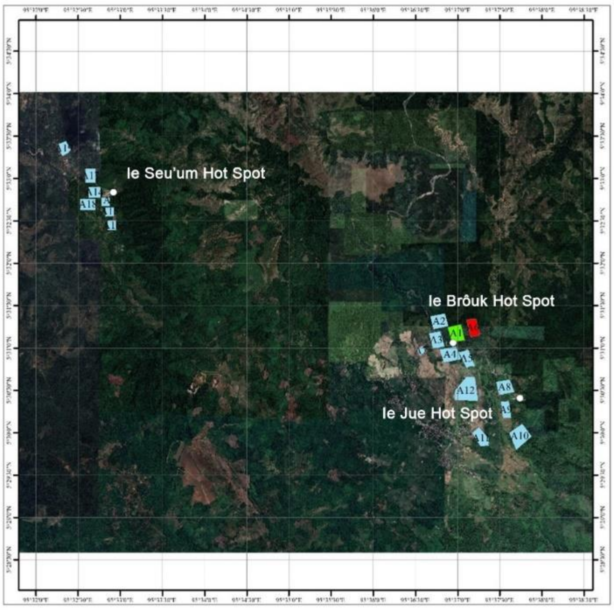

Figure 1. GPP sites recommendations based on the MOORA results. Blue indicates alternative sites; green indicates the best alternative site, and red indicates the worst alternative site. Adapted from [26].

Closer proximity to the heat source is favorable for GPP development. The road access for alternative A1 (418 meters) was less ideal, but its impact was minimal due to its lower weight (0.126) and categorization as a cost criterion. In contrast, there were several alternatives with better road access values. The study conducted by Idroes et al. classified the Ie Brôuk manifestation as a high-temperature geothermal system with temperatures ranging from 289 °C to 291 °C [18].

For alternatives around the Ie Seu'um hotspot, the MOORA method recommends alternative A15 as the second-ranked choice with a score of 0.158. According to Idroes et al. [25], the potential geothermal manifestation at Ie Seu'um is estimated at around 50-100 MW (medium enthalpy) with temperatures ranging from 188.7 °C. The Ie Jue manifestation, characterized by its acidic nature (pH 5.77) and sulfate fluid type, is not recommended due

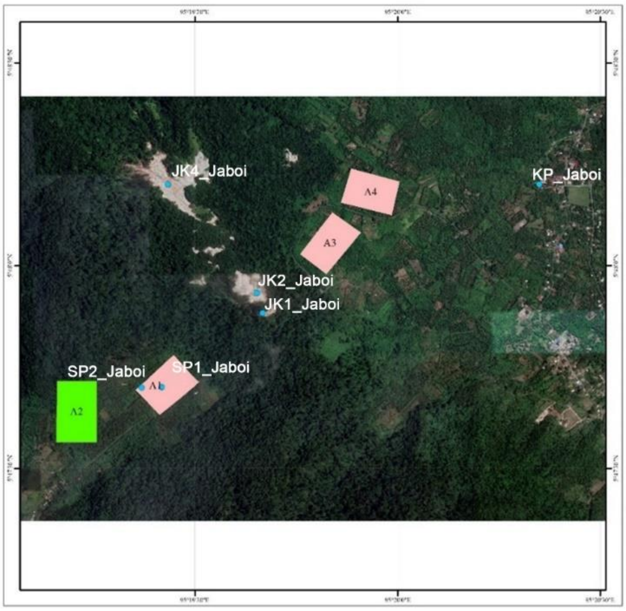

Figure 2. GPPs site recommendation in Jaboi based on the ARAS results. Pink indicates alternative sites; green indicates the best alternative site. Adapted from [26].

Table 4. Ranking results using the MOORA method for the development of GPP in the Jaboi Sabang.

Rank	Alternative	Value
1	A2	0.269
2	A1	0.257
3	A4	0.175
4	A3	0.009

to its location in an area with a land slope greater than 8° and proximity to a fault line [26].

The least suitable location for GPP construction is alternative A6, with the lowest score of -0.024. This alternative is situated directly above a fault line with a land slope greater than 8° and a considerable distance from the geothermal heat source (404 meters). Alternatives A6, A10, and A19 are strongly discouraged for GPP development. MOORA results highly depend on criterion weight values and criteria classification as beneficial or non-beneficial. Therefore, expert opinions on criterion weight values are crucial for optimal results.

3.4. The Results of the MOORA Method on Jaboi Sabang Geothermal Energy Source

The MOORA method was applied to the Jaboi Sabang geothermal source to assess the compatibility of its recommendations with the location of the existing GPP in Sabang. The criteria used in this test align with those in the Seulawah study. Idroes et al. [27] identified three sub-areas in the Jaboi region: production-injection wells (SP1_Jaboi and SP2_Jaboi), hot water pond (KP_Jaboi), and Jaboi crater (JK1_Jaboi, JK2_Jaboi, and JK4_Jaboi). Chemical compositions and water types vary among these sub-areas, with chloride dominating the production-injection wells, sulfate in the Jaboi crater, and a bicarbonate-sulfate mix in the hot water pond. Fluid balance in the production well (SP1_Jaboi) indicates mature water, while the injection well (SP2_Jaboi), Jaboi crater (JK1, JK2_Jaboi, and JK3_Jaboi), and hot water pond (KP_Jaboi) contain immature water. The Jaboi manifestations are categorized as high-temperature geothermal systems suitable for power plant development, with an average reservoir temperature exceeding 225 °C.

In this test, the Sabang GPP location is labeled alternative A1. The geothermal hotspot chosen for this test uses the production well point marked as SP1_Jaboi. The test involves only four alternative locations due to limited areas with a land slope of 0°-8°, as shown in Figure 2. According to the MOORA method calculations for the GPP location alternatives in Jaboi, as presented in Table 4, the recommended location is alternative A2. This differs from the actual GPP location in Jaboi, which holds the second rank. The variation is attributed to the existing GPP in Jaboi being too close to a fault line. At the same time, alternative A2 has the farthest distance to a fault line than other alternatives.

Calculation results heavily depend on criterion weight values and criteria classification as beneficial or non-beneficial. Differences in criteria and expert involvement may explain the variance between MOORA results and the actual GPP location in Jaboi. The latest data, obtained from satellite imagery post-GPP construction, contributes to potential disparities from pre-construction conditions.

3.5. Implication, Limitations, and Future Directions

The findings from this study hold significant implications for the development of geothermal power plants in Indonesia, particularly in regions with high geothermal potential, like Aceh. By employing the MOORA method, this research provides a systematic approach to site selection that balances multiple criteria, including environmental, technical, and socio-economic factors. The methodology ensures that the selected sites not only optimize geothermal production but also minimize environmental impacts and consider proximity to infrastructure, which is crucial for the sustainable development of geothermal resources.

While the MOORA method has proven effective in this study, several limitations must be acknowledged. First, the accuracy of the results is highly dependent on the quality and completeness of the data used. In regions where data on geological and environmental parameters are sparse or outdated, the reliability of the site selection process could be compromised. Additionally, the study primarily focuses on physical and technical criteria. It may not fully account for socio-economic and cultural factors equally vital in planning and developing energy projects.

Future research should focus on several key areas to enhance the robustness and applicability of the findings. Incorporating socio-economic factors such as community acceptance, job creation potential, and local economic impacts is crucial for the sustainability and success of energy projects. Advancing data collection techniques, mainly through remote sensing and geospatial analysis, could significantly improve data accuracy and comprehensiveness, especially in remote areas. Additionally, comparing the MOORA method with other multi-criteria decision-making tools could shed light on the strengths and weaknesses of various approaches, potentially leading to a hybrid model that combines the best features of multiple methods. Finally, conducting longitudinal studies on the selected sites would help assess geothermal power plants' long-term environmental and operational impacts, thereby providing essential feedback for refining future site selection processes.

4. Conclusions

This study has successfully pinpointed optimal locations for geothermal power plants in Aceh, emphasizing environmental considerations, resource availability, and technical feasibility. A critical advancement of this research is applying the MOORA method, which provided a structured, quantitative approach to simultaneously evaluating multiple competing factors. This method's integration showcases a significant contribution to the field, facilitating more informed and balanced decisions in geothermal energy site selection.

Author Contributions: Conceptualization, I.F.R., A.M. I.I. and R.I.; methodology, A.M. and I.I.; software, I.F.R., M.Y. and A.Ma.; validation, A.M., I.I., M.M. and R.I.; formal analysis, I.F.R.; investigation, I.F.R., M.Y. and D.B.D.; resources, M.Y., M.M. and D.B.D.; data curation, A.M., I.I. and R.I.; writing—original draft preparation, I.F.R., A.Ma. and M.Y.; writing—review and editing, A.M., I.I. and R.I.; visualization, M.Y. and M.M.; supervision, A.M. and R.I.; project administration, R.I.; funding acquisition, R.I. All authors have read and agreed to the published version of the manuscript.

Funding: This study does not receive external funding.

Ethical Clearance: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting this study's findings are available upon request from the corresponding author.

Acknowledgments: The authors would like to thank their institution for supporting this study.

Conflicts of Interest: All the authors declare no conflicts of interest.

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