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Evaluating Geothermal Power Plant Sites with Additive Ratio Assessment: Case Study of Mount Seulawah Agam, Indonesia

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Abstract

Indonesia, a country rich in geothermal resources, has yet to fully exploit its potential, particularly in volcanic regions like Mount Seulawah Agam. This study investigates the application of the Additive Ratio Assessment (ARAS) method for the site selection of Geothermal Power Plants (GPP) in Indonesia. The ARAS method provides a systematic approach to evaluating and prioritizing geothermal development sites by integrating multiple criteria, including geological, environmental, and socio-economic factors. The study collects data from various sources and weights criteria using the Ordinal Priority Approach (OPA), incorporating expert opinions. The findings demonstrate the effectiveness of the ARAS method in identifying optimal locations for GPP development, ensuring sustainability and feasibility. The study also tests the ARAS method in existing GPP locations in Jaboi, Sabang, Indonesia, to investigate alignment with the results and validate the approach. Furthermore, the study presents recommendations for GPP site selection. This research emphasizes the significance of multi-criteria decision-making techniques in facilitating renewable energy projects. It promotes a more systematic and informed approach to geothermal energy development in Indonesia and other geothermal-rich regions.

1. Introduction

Indonesia boasts significant geothermal potential, attributed to its rich volcanic landscape, which comprises 13% of the world's volcanoes and 40% of its geothermal resources [1–3]. The country has identified 356 geothermal sites across its vast archipelago, with a total geothermal capacity of 23,356.9 MWe. However, only 10% of these resources are currently utilized for Geothermal Power Plants (GPP) [4].

Geothermal energy offers a sustainable alternative to fossil fuels, potentially reducing greenhouse gas emissions and reducing Indonesia's reliance on energy imports [5, 6]. Despite these benefits, geothermal energy development in Indonesia faces significant barriers,

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primarily due to the high investment and operational costs associated with its implementation [7, 8]. As a result, this valuable resource remains underutilized, mainly hindering the country's progress towards a more sustainable energy future.

Most of Indonesia's geothermal potential is located on Sumatra Island, including Mount Seulawah Agam in Aceh Province, which is estimated to have a 275 MWe geothermal potential [9, 10]. Yet, this potential remains largely untapped. The strategic importance of such sites for geothermal development cannot be overstated, given their substantial contribution towards sustainably meeting the nation's energy demands [11]. However, selecting sites for GPPs requires a comprehensive evaluation of various factors, including geological, environmental, and socio-economic considerations, to ensure the viability and sustainability of these energy projects [12]. Traditional site assessment methods often lack a comprehensive and systematic approach, leading to suboptimal decision-making and potential project failures. Therefore, there is a pressing need for an effective and efficient method to evaluate and prioritize potential geothermal sites in Indonesia.

To address this challenge, Decision Support Systems (DSS) can be utilized to effectively select suitable sites for GPP [13, 14]. These systems integrate diverse data sources and criteria, ranging from geological characteristics and environmental factors to socio-economic indicators, to comprehensively assess potential geothermal sites [15, 16]. One promising DSS method is Additive Ratio Assessment (ARAS), a multi-criteria decision-making technique that allows decision-makers to evaluate and prioritize potential geothermal sites based on various factors [17, 18]. This method provides a structured approach to decision-making, helping stakeholders identify the most suitable locations for GPP in Indonesia.

This study aims to introduce the ARAS method for GPP site selection, ensuring Indonesia's geothermal resources' sustainable and efficient development. Through a detailed analysis of Mount Seulawah Agam, this study provides valuable insights into the ARA method's application in GPP site selection. This method offers a comprehensive framework for assessing the suitability of geothermal sites, facilitating informed decision-making in the pursuit of sustainable energy solutions. This research contributes to the field of renewable energy and offers a practical approach for Indonesia to harness its vast geothermal resources more effectively, supporting its transition to a green energy future.

2. Materials and Methods

2.1. Data Collection

The data for this study was derived from multiple sources, including journal articles, the SAS Planet software, the Indonesian Seamless Digital Elevation Model and Bathymetry National Site (DEMNAS), and GeoMap. All the data collected is centered around Mount Seulawah Agam, Aceh Province, Indonesia. The types of data gathered encompassed fault lines, geothermal source locations, slope gradients, road access, land cover, and alternative points for constructing GPP. Land cover data, road access, and distances to geothermal source locations were obtained using satellite imagery through the SAS Planet application. Slope datasets were acquired from the DEMNAS website, while fault line data were sourced from the GeoMap site. This comprehensive data collection approach ensured a robust foundation for analyzing and selecting optimal sites for GPP development.

2.2. Weighting Through Ordinal Priority Approach

In this stage, weighting was conducted using Ordinal Priority Approach (OPA) tools developed by Amin Mahmoudi [19]. The process involved soliciting the opinions or perspectives of experts in the field, including representatives from the Indonesian State Electricity Company (PLN) and scientists specializing in geothermal energy. This approach allowed for the incorporation of expert knowledge and preferences in determining the relative importance of the criteria used in the site selection process. OPA tools facilitated a structured and transparent method for weighting, ensuring that the decision-making process was grounded in authoritative and relevant insights.

2.3. ARAS Method

The ARAS method is employed in this study as a systematic approach to solve the site selection problem for GPP. The process begins with the determination of criteria values, the assignment of weights to these criteria, the listing of potential site alternatives, and the identification of optimal values for each criterion [20]. The selection criteria are based on a study conducted by Yousefi et al. [21] involving distance to settlements, distance to faults, slope, distance to the heat source location, and distance to access roads. This step ensures that all relevant factors are considered in the decision-making process and their importance is quantified through weighting, thereby setting the stage for a structured comparison of alternatives.

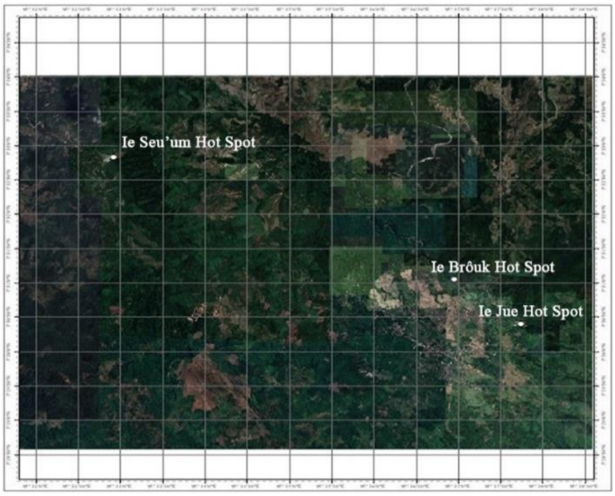

Figure 1. Satellite image of hotspots in Mount Seulawah.

The process progresses with aggregating criteria values for each alternative into a decision matrix, which serves as an essential instrument for evaluation. This matrix thoroughly compares how each site alternative aligns with the defined criteria, promoting informed decision-making through a transparent, juxtaposed assessment [22]. Subsequently, the decision matrix undergoes normalization to adjust the values to a uniform scale, using the Equation 1:

$$a'_{ij} = \frac{a_{ij}}{\max\left(a_{ij}\right)} \quad (1)$$

where a'_{ij} is the normalized value, a_{ij} is the original value, and $\max\left(a_{ij}\right)$ is the maximum value in each criterion column. This normalization eliminates disparities caused by varying units or scales of criteria, allowing for direct comparability. This step not only standardizes the data but also accentuates the relative performance of each alternative against the set criteria.

Following normalization, the utility values for each site alternative are calculated through the Equation 2:

$$U_j = \sum_{i=1}^{n} w_i . a'_{ij} \quad (2)$$

where U_j represents the utility value of alternative j, w_i is the weight of criterion i, and a'_{ij} is the normalized value of alternative j for criterion i. This calculation yields a quantitative measure of each site's potential, based on the predefined criteria, facilitating a clear basis for comparison.

The ARAS method concludes with ranking alternatives based on the computed utility values, where the highest-ranking alternative is identified as the optimal site for GPP development. This structured and equation-driven approach provides a robust and quantifiable framework for evaluating and selecting geothermal site locations, enhancing decision-making with analytical depth and clarity that supports sustainable energy solutions.

3.4. Testing the ARAS Method on the Jaboi Sabang Geothermal Power Plant

We also conducted testing on the Jaboi Sabang Geothermal Power Plant to explore whether the recommendation results produced by the ARAS method corresponded with the current GPP locations in Jaboi, Sabang. This investigation uses criteria aligned with those utilized in the Seulawah research, including distance to settlement, distance to fault, slope, hot spring location, and road access. The primary reason is to validate the method's reliability and accuracy in recommending suitable sites for GPP development. If the ARAS method suggests locations close to or identical to the existing Jaboi Sabang GPP, it validates the method's practical applicability and effectiveness in real-world scenarios.

3. Results and Discussion

3.1. Data Collection Results

Data was collected from three geothermal hotspots around the Seulawah Agam mountain area in Aceh Besar, Indonesia (Figure 1). The Ie Seu'um geothermal potential is estimated to range from 50 to 100 MW with a medium enthalpy level and a temperature of approximately 188.7 °C [23]. Ie Jue manifests acidity with a pH range of 6.61-6.65 and chloride fluid type. Conversely, Ie Brôuk represents a high-temperature geothermal system with temperatures ranging from 289 ℃ to 291 ℃, exhibiting neutrality with a pH range of 7.04-7.13 and bicarbonate fluid type [24]. Ie Jue indicates a high-temperature geothermal system, surpassing 225 °C on average, conducive to power plant development, with a pH of 5.77 indicating acidity and sulfate fluid type [25].

In this study, 19 alternatives were used, labeled A1-A19, as illustrated in Figure 2. Seven alternatives are situated in the Ie Seu'um geothermal source location, while the remaining 12 are located in the Ie Brôuk and Ie Jue geothermal source locations.

The criteria data for alternative site A1-A19 can be seen in Table 1. The data were obtained by processing various maps using the ArcMap 10.5 application, including satellite imagery, land slope maps, and fault maps. Satellite imagery was utilized to determine distances to settlements and access roads. The ideal distance to

Table 1. Alternative site and criteria for GPP development in Mount Seulawah.

Alternative	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

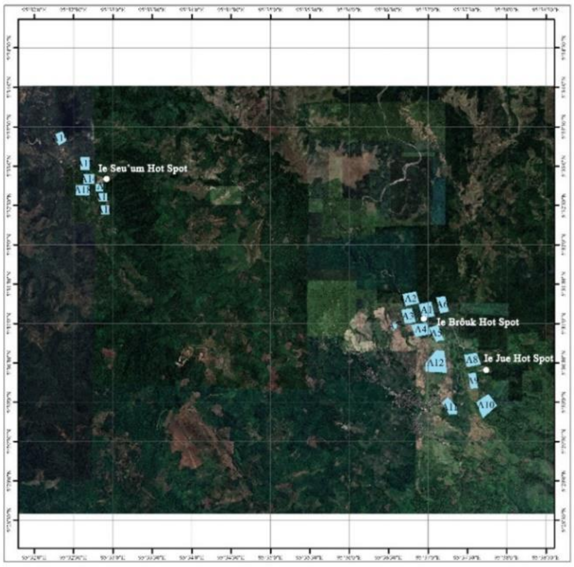

Figure 2. Alternative site map for the development of GPP in Mount Seulawah. Blue indicates alternative sites.

settlements should not be less than 500 m, while for access roads, it should be around 100 m. The ideal distance to faults should not be less than 200 m, and to the geothermal heat source, it should not exceed 100 m. The land slope should not exceed 15% or 6.75°. However, in this research, we used 3 alternatives that are above the 15% slope level and located on fault lines, namely A6, A10, and A19. This was done to test the validity of the ARAS method through black-box testing.

The data for each criterion vary significantly, thus requiring data normalization to facilitate the calculation process. The normalized data ranges from 0 to 1. The normalization process is divided into three parts. First, for criteria such as distance to settlements and distance to faults, the farthest distance is needed, where the greater the distance, the better the value. For normalization, the value of each criterion is divided by the largest criterion value. Second, for criteria such as distance to the heat source location and distance to access roads, the closest distance is required, where the closer the distance, the better the value. For normalization, the smallest criterion value is divided by each criterion value. Third, land slope criteria are divided into two classifications: areas with slopes of 0-8° are given a value of 1, and slopes >8° are given a value of 0.

3.2. OPA Weighting Results

The expertise of individuals involved in the weighting process is determined based on several criteria, including educational background, professional experience, publications in the relevant field, participation in relevant projects or initiatives, and recognition by peers in the industry or academic community. There are five experts involved in the weighting process, with three experts in the geothermal field and two experts in the electrical field. Here, we collected assumptions or opinions from each expert regarding the importance level of criteria in the geothermal power plant development process based on their priority sequence, where 1 represents the highest priority and 5 represents the lowest. The weighting results can be seen in Table 2.

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	**0.2803**	**0.3504**	**0.1314**	**0.1124**	**0.1255**
Optimization	**Benefit**	**Benefit**	**Benefit**	**Cost**	**Cost**

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

Rank	Alternative	Value
1	A1	0.714
2	A15	0.277
3	A13	0.253
4	A16	0.225
5	A2	0.219
6	A18	0.184
7	A14	0.164
8	A4	0.151
9	A7	0.148
10	A17	0.147
11	A11	0.141
12	A3	0.128
13	A10	0.125
14	A8	0.120
15	A6	0.117
16	A5	0.083
17	A9	0.083
18	A19	0.075
19	A12	0.068

The results show that the criteria for distance to the heat source has the highest weight value, which is 0.3504, and the criteria for distance to settlements has the lowest weight value, which is 0.1124. The criterion with the highest weight value represents the criterion with the highest importance level in the geothermal power plant development process, and vice versa.

In determining the criteria for benefits and costs, it is determined based on the weight values of each criterion. The criteria with the highest weight values are included in the benefit criteria, and vice versa. The criteria included in the benefit category are distance to the heat source, distance to faults, and land slope. Meanwhile, the criteria included in the cost category are distance to roads and distance to settlements.

3.3. ARAS Calculation Results

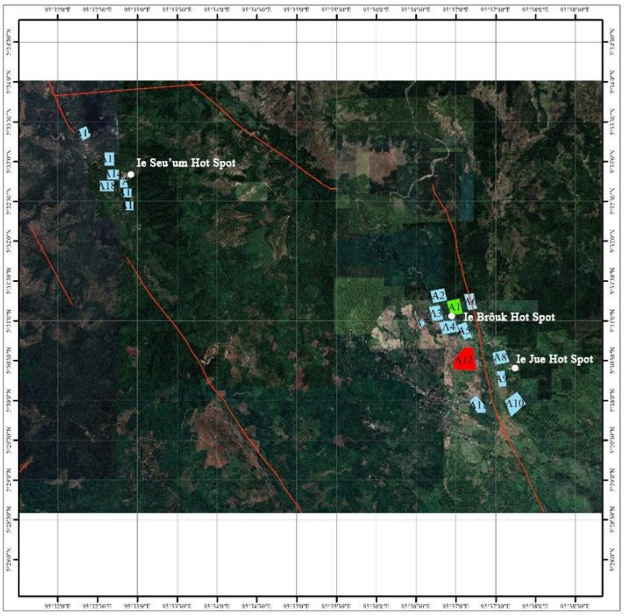

Figure 3. GPP site recommendations based on the ARAS results. Blue indicates alternative sites; green indicates the best alternative site, and red indicates the worst alternative site.

The ARAS calculation process yields a ranking based on the final preference values, with the highest value receiving the top rank and subsequent values following in descending order, as presented in Table 3. Alternative A1 secures the first position with a value of 0.714, while alternative A12 is ranked last with a value of 0.068. The top-ranked alternative, A1, is characterized by a distance to the settlement of 926 m, a distance to the fault of 260 m, a distance to the hot spring location of 10 m, a distance to road access of 418 m, and a slope of less than 15%. Conversely, the last-ranked alternative, A12, features a distance to the settlement of 423 m, a distance to the fault of 219 m, a distance to the hot spring location of 918 m, a distance to road access of 10 m, and a slope of less than 15%.

Figure 3 presents a recommendation map based on the ARAS results, revealing that alternative A1 is situated at the Ie Brôuk manifestation site. This finding is corroborated by the research conducted by Idroes et al. [24], which classifies the Ie Brôuk manifestation as a high-temperature geothermal system with temperatures ranging from 289 °C to 291 °C. Moreover, the Ie Brôuk manifestation exhibits a neutral pH range of 7.04-7.13,

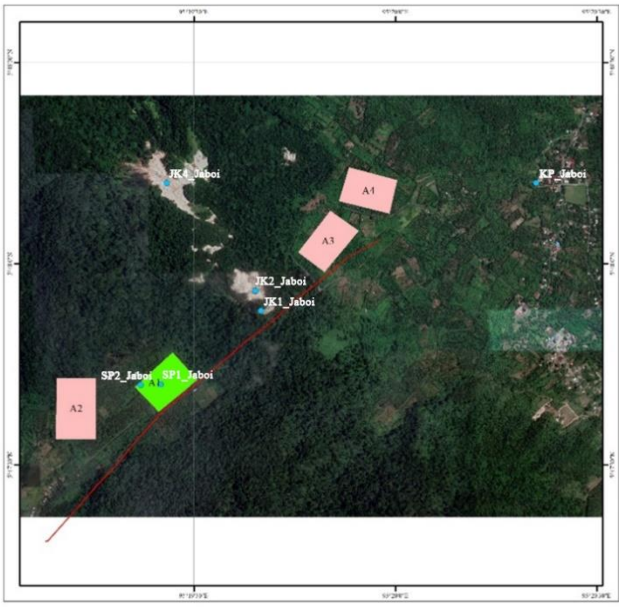

Figure 4. GPPs site recommendation in Jaboi based on the ARAS results. Pink indicates alternative sites; green indicates the best alternative site.

Table 4. Alternative GPPs in Jaboi based on the ARAS results.

Alternative	Value	Rank
A1	0.561	1
A2	0.546	2
A3	0.168	4
A4	0.329	3

which can mitigate corrosiveness in geothermal power plant pipes.

The validity of the ARAS method is confirmed through black box testing, wherein alternatives A6, A10, and A19 do not feature among the top 10 rankings. Prior to conducting the ARAS calculation, the authors anticipated that these alternatives would not secure top positions due to several criteria values that failed to meet the requirements. For instance, these alternatives are located on fault lines and have slopes exceeding 15%, which are unfavorable characteristics for geothermal power plant site selection.

3.4. Results of the ARAS Method on the Jaboi Sabang Geothermal Power Plant

According to research conducted by Idroes et al. [26], there are three sub-areas of geothermal heat sources in the Jaboi area, as shown in Figure 4. These include the production injection wells of PT. Sabang Geothermal Energy (SP1_Jaboi and SP2_Jaboi), the hot spring pool (KP_Jaboi), and the Jaboi crater (JK1_Jaboi, JK2_Jaboi, and JK4_Jaboi). The production-injection wells are selected as the point of interest due to their alkaline pH range of 7.41-7.42. In contrast, the Jaboi crater area has a pH of 2.29-2.66, and the hot spring pool area has a pH of 6.36, both of which are acidic. The water types from the production-injection wells, Jaboi crater, and hot spring pool are a mixture of chloride, sulfate, and bicarbonate-sulfate. The Jaboi manifestation is classified as a high-temperature geothermal system (high enthalpy), with an average reservoir temperature exceeding 225°C, indicating its suitability for power plant development.

The data used in this study is the most recent, obtained from satellite imagery, and represents the conditions after the construction of the Jaboi GPP. Consequently, there may be discrepancies between this data and the conditions that existed prior to the construction of the Jaboi GPP. Table 4 reveals that alternative site A1 is ranked first with a value of 0.561. Alternative A1 is characterized by a distance to the settlement of 530 m, a distance to the fault of 10 m, a distance to hot spring location of 1 m, a distance to road access of 1 m, and a slope of less than 15%.

The recommendation results derived from the ARAS method calculation correspond to the location of the current Jaboi GPP (Figure 4). However, closer examination reveals that alternative A1 is situated near a fault line. Despite this, when included in the ranking process, alternative A1 still achieves the highest value, primarily because it is in close proximity to the hot spring location, which is assigned the highest weight among the criteria.

3.5. Limitation and Future Studies

The study, while innovative in its use of the ARAS method for GPP site selection in Indonesia, particularly at Mount Seulawah Agam, has limitations. These include the reliance on static data that may not fully capture the dynamic nature of geothermal systems, the subjectivity of expert opinions in criteria weighting, and the limited geographic focus.

Future research could address these limitations by incorporating dynamic data sources, expanding the geographic scope, integrating economic and financial analysis, and involving a broader range of stakeholders. Additionally, exploring the integration of ARAS with other decision-making frameworks or developing hybrid models could enrich the decision-making process.

4. Conclusions

The ARAS method, applied to the site selection for GPP in Indonesia, specifically at Mount Seulawah Agam, has proven to be an invaluable tool in the strategic expansion of geothermal energy resources. By considering comprehensive factors, including geological, environmental, and socio-economic criteria, and applying the OPA for weighting these factors, the ARAS method facilitates a structured and holistic evaluation of potential sites. Notably, the results from this study not only corroborate the viability of existing GPP locations but also highlight the method's effectiveness in prioritizing sites that are proximal to geothermal sources and pose minimal environmental impacts. This finding directly stems from the detailed analysis and discussion presented, which emphasized the alignment of the ARAS method's recommendations with the actual conditions and requirements of geothermal site selection, such as the importance of proximity to geothermal sources and fault lines, land slope considerations, and the strategic distance to settlements and road access. Moreover, the application of the ARAS method at the Jaboi Sabang GPP further validated its efficacy in matching the geothermal plant's location with the highest-ranked alternatives, thus underscoring the method's practical utility in real-world scenarios. Overall, this study not only contributes significantly to the field of renewable energy by offering a rigorous multi-criteria decision-making approach but also exemplifies how decision support systems can facilitate informed and sustainable energy development strategies in regions rich in geothermal potential, like Indonesia.

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