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Potential of Lithium Economic Resources in Geothermal Manifestations Based on Geochemical Data (Case Study of Dieng WKP, Central Java Province)

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Abstract

Lithium is one of the elements used as raw material for batteries in electric cars. In this case, lithium is very useful for production, considering that the presence of lithium in geothermal fields and the extraction process also minimizes the risk of air pollution. Based on PSDMBP research in 2019, it is known that lithium from geothermal wells in Dieng reached 99 mg/L. The Dieng geothermal field has the highest lithium content in Indonesia. This is because the geothermal system is water-dominated. During the process of producing geothermal fluid into electrical energy at PLTP, the lithium increases due to air circulation which tends to be closed in the Dieng geothermal system. The method used in this research is a remote sensing method in the form of a map of the distribution of manifestation locations which can show the potential presence of the element lithium based on geochemical and geothermometer data from several locations of the Dieng project area these data which is then processed statistically to determine the potential of the lithium element from geothermal fluid types. Based on the results of geochemical data from several spring points at the Dieng Project Area hot spring, the accumulated lithium levels from 9 samples were obtained at 1.11 mg/L. It can be seen that there is potential for lithium resources that have economic value. This is directly proportional to research conducted by PSDMBP that there is potential for lithium in this area. From this, the potential economic resource for lithium obtained at 9 samples is IDR. 14,947,732, with an air formation flow rate of 70.00 kg/hour and a market selling price of US\$ 17,000/ton. This makes the lithium element in this location a potential resource with economic value and

can maximize added value apart from electrical energy produced by geothermal energy.

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1. Introduction

Indonesia is targeting reductions in carbon emissions as part of its sustainable development strategy and transition to clean energy by 2030, in line with its Nationally Determined Contribution (NDC) commitment. According to the Greenhouse Gas (GHG) Emission Inventory Report, the energy sector is the largest contributor to national greenhouse gas emissions, accounting for approximately 43.8% of the total, while the transportation sector is one of the main subsectors within the energy sector (KLHK, 2021). The transportation sector's significant contribution to national emissions underscores the need for substantial mitigation through a more sustainable transformation of energy and transportation systems, as emphasized in the study on energy transition and sustainable transportation (Sovacool et al., 2020).

The transportation sector is a major user of fossil fuels in Indonesia, with a very high dependence on fuel, along with the increasing number of motorized vehicles year by year (KLHK, 2021). If this trend continues, the transportation sector is expected to remain a major contributor to CO₂ emissions in the future (IEA, 2022). The use of electric vehicles is considered capable of significantly reducing greenhouse gas emissions, especially when supported by cleaner energy generation systems (Hawkins et al., 2013). Electric vehicles use lithium-ion batteries as their energy storage system, making lithium a strategic material in the global energy transition (IEA, 2021).

Lithium is classified as a critical mineral due to its vital role in energy storage technology and electric vehicles, as well as its limited global supply (European Commission, 2020; USGS, 2023). Naturally occurring lithium generally comes from hard rock minerals, brine, clay, and seawater. In the Indonesian context, battery industry development has so far focused more on exploiting mineral resources through conventional mining activities, particularly nickel, whose extraction and refining processes have the potential to generate carbon emissions and significant environmental impacts (Ali et al., 2017; Valenta et al., 2023). This situation drives the need to develop alternative, more environmentally friendly, and sustainable lithium sources and extraction methods.

Utilizing geothermal fluids as a source of lithium is an alternative approach that is increasingly being studied internationally. Geothermal fluids naturally contain various dissolved elements, including lithium, which can be extracted concurrently with geothermal energy production, potentially resulting in a lower carbon footprint than conventional mining activities (Flexer et al., 2018; Scherer et al., 2020). This approach has also been reported to increase the economic value of geothermal systems by utilizing co-produced minerals. The Dieng Geothermal Working Area (WKP) in Central Java Province is one of the active geothermal fields in Indonesia, with surface manifestations in the form of hot springs and fumaroles that exhibit variations in fluid geochemical characteristics, making it a potential study site for lithium content.

Research on the geochemical system of geothermal fluids in the Dieng Working Area (WKP) has been conducted previously by Ramadhan (2013), who identified several types of geothermal

fluids, including bicarbonate, sulfate, sulfate-chloride, and bicarbonate-chloride. However, studies specifically assessing the distribution of lithium based on geochemical data and its relationship to economic resource potential are still limited. Therefore, this study aims to assess the potential distribution of lithium in wells and geothermal manifestations in the Dieng Working Area using geochemical data. The results of this study are expected to increase the value of national lithium resources through a low-emission extraction approach, while also supporting clean energy development policies and Indonesia's carbon-emission reduction targets..

2. Materials and methods

Geological condition

The study area is located within the Dieng Plateau. The lithology of the Dieng region generally consists of andesite and pyroclastic rocks. Andesite lava, andesitic biotite lava, and basaltic lava are three subsurface rock groups that can be identified based on petrographic analysis. Basaltic lava consists of plagioclase (andesine labradorite, predominantly labradorite), pyroxene, and localized olivine embedded in microcrystalline crystals of similar mineralogy, with a groundmass of glassy and opaque crystals. This intercalated unit is considered part of the Old Dieng product. Andesite lava with pyroclastic rocks is considered part of the Middle Dieng product. Composed of andesite and pyroxene, andesite lava is interbedded by microcrystalline plagioclase clumps containing small glassy volcanic rocks. Equivalent pyroclastic rocks have approximately the same composition. Biotite-andesite lavas consist of plagioclase (oligoclase-andesine), microcrystalline plagioclase, opaque crystals, and pyroxene and biotite embedded in a glassy groundmass. These units are considered part of the Younger Dieng product.

Tectonically, the geological structure that controls the research area, taken from the research results of Boedihardi, et al (1991), is a descending fault structure in the Kendil block oriented northeast - southwest, a descending fault structure oriented relatively west - east to the north of Mount Sidede and Mount Bisma, and a descending fault structure that is also oriented west - east to the north of Telaga Merdada, which limits the Sikidang and Sileri geothermal blocks, which can be interpreted as a descending fault structure that has undergone reactivation. The curved scarp structure is taken (Van Bergen et al., 2000), namely the scarp on the southwest cliff of Mount Prau and the scarp on Mount Bisma. The straightness inferred from the image has a relatively north-south direction in the area around Mount Prau and a relatively west-east direction on the slopes of Mount Sikunir.

In Late Neogene, the Sunda orogenesis caused plutonic intrusion and the formation of a volcanic arc, which impacted Java. The Dieng Plateau is part of the Dieng Volcanic Complex, which is part of a Northwest-Southeast-oriented Quaternary volcanic chain. Previous research indicates that the Dieng Plateau lies on a plateau with an elevation between 1,600 and 2,100 square meters, with the highest known volcanic peaks at 2,200 to 2,565 square meters. The oldest known volcanic activity forms the edge of the volcanic complex. Based on research, the eastern edge of Mount Prahu also contains the remains of an ancient caldera, indicating one of the earliest stages of the volcanic complex. In the southwest part of the ancient caldera, smaller eruptive centers later emerged. Pagerkandang, Pangonan-Merdada, and Pakuwaja are eruption sites located from Northwest to Southeast. Radiometric dating indicates that Prahu, Nagasari, and Bisma are the oldest volcanoes in the Dieng Volcanic Complex, which were active in the late Pleistocene. During the Late Pleistocene, several volcanic centers (Pagerkandang and Pangonan-Merdada) emerged in the area between Prahu, Nagasari, and Bisma. The Kendil, Pakuwaja, and Seroja volcanic products in the southeast mark the complex's final phase.

The stratigraphy of the Dieng area and its surroundings is divided into three rock units:

1. The Tuff rock unit, with a Quaternary to Recent age, contains the youngest eruptive

material: tuff, tuff-gravel sandstone, and tuff-mixed breccia.

2. The Andesite rock unit, with a Quaternary to present age, contains andesite and basaltic lava rocks.
3. The Cretaceous rock unit, with an upper Tertiary age, contains argillaceous limestone, tuffaceous sandstone, coral limestone, and andesite.

Rock Formation of Dieng area are influenced by volcanic activity in the Dieng area. Dieng volcanism is divided into three periods, the first occurring in the Middle Pliocene and encompassing Mount Prau and Mount Jimat. The second period occurred in the Late Pliocene and encompassed Mount Nagasari and Mount Bisma. The third period occurred in the Pleistocene and encompassed Mount Sipandu, Mount Pangonan, Mount Merdada, Mount Pakuwaja, Mount Prambanan, and the young mountains surrounding Mount Pakuwaja. The distribution of the Dieng volcanic complex rocks can be seen in. In addition to rocks formed from volcanic activity, there are also altered rocks formed from the reaction of existing igneous and pyroclastic rocks with hydrothermal fluids. These altered rocks are found in Mount Sipandu, Mount Pangonan, and Mount Pakuwaja. Hydrothermal activity also forms new deposits such as sulfur deposits, sulfate mineral deposits, and hydrothermal breccias.

Methods

The method used in this research consists of a literature review from various sources, data collection, verification, and the presentation of the results of data analysis related to the research problem. Therefore, the data sources are secondary, with both qualitative and quantitative data. The data used in this study are secondary data, consisting of geochemical analysis of geothermal water (Y. Ramadhan et al., 2013 ; Dzaky Sotha, 2021) using the Atomic Absorption Spectroscopy (AAS) method. The data were then processed to create a map showing the distribution of lithium elements, indicating areas with significant to low levels of lithium using ArcGIS software. Based on the map of lithium distribution in this research area, an interpretation will be conducted to identify the type and areas with potential to produce lithium.

3. Results and Discussion

The data used in this study are secondary data in the form of geothermal water geochemical data obtained from previous studies. The data were sourced from Ramadhan (2013), which include samples Bit-06, Sh-01, Pul-01, Skd-09, and Kp-01, as well as from Sotha (2021) with sample numbers LP 120, LP 121, LP 123, and LP 106. The results of the geothermal water geochemical analysis, including pH, electrical conductivity, and major ion concentrations, are summarized in Table 1.

Table 1. Results of Geochemical Analysis of Geothermal Water (Ramadhan, 2013; Sotha, 2021)

Sample No.	pH	EC ($\mu\text{S}/\text{cm}$)	Li (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	HCO ₃ ⁻ (mg/L)	B (mg/L)
Bit-06	7.99	693	0.03	17.96	59.50	243.30	1.38
Sh-01	8.37	849	0.05	69.22	76.80	231.90	3.84
Pul-01	4.54	1218	0.02	289.00	289.00	21.74	0.87
Skd-09	3.88	1832	0.01	27.48	27.48	0.00	0.69
Kp-01	8.36	2790	0.88	484.50	484.50	634.09	1.19
LP 120	1.42	11130	<0.01	0.00	2952.86	0.00	2.22
LP 121	8.04	1088	0.01	4.26	319.71	122.06	0.22
LP 123	6.95	1318	<0.01	4.88	372.24	101.50	0.22
LP 106	6.11	4540	0.09	950.77	34.30	34.51	12.56

Geochemical Analysis of Geothermal Manifestation Fluids

By plotting laboratory analysis results on a ternary diagram, the field fluid type can be characterized from geothermal field hot-water samples analyzed in the laboratory. Geochemical analysis was used to determine fluid type from geothermal manifestation data. This analysis was based on Cl, SO₄, and HCO₃ content data obtained at the study site. All manifestations were plotted on a ternary diagram based on the percentage value of their respective chemical compositions. The plotting results are shown in the figure 1.

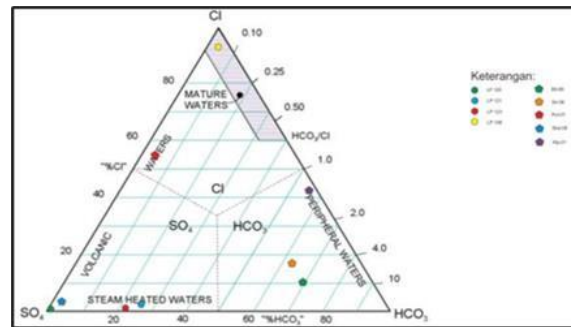


Figure 2. Diagram Cl-SO₄-HCO₃

The ternary diagrams of springs LP120, LP 121, LP 123, and Skd-09 show the presence of sulfate water under steam-heated conditions. This type of water forms at shallow depths due to the condensation of geothermal gas near the surface, not far from the upflow area. It contains abundant sulfate (SO₄) compared to chloride (Cl) and bicarbonate (HCO₃). This is because when this fluid reaches the surface, rock minerals dissolve.

Sulfuric acid hot springs typically form in areas where volcanic eruptions occur. The oxidation of hydrogen sulfide with oxygen results in high SO₄ content in the hot spring samples at the study site. The presence of high sulfate also indicates low levels of bicarbonate and chloride in the hot spring manifestation samples at the study site (Yufita, Isa, & Vijaya, 2020). The Bit-06, Sir-01, and Klp-01 springs are classified as bicarbonate waters under peripheral water conditions, with a higher bicarbonate (HCO₃) content than chloride and SO₄. This type of water is typically found in peripheral zones with a near-neutral pH due to reactions with surrounding rocks. This type of water is often referred to as CO₂-rich water. In situations where CO₂ gas condenses into groundwater, the condensing vapor can heat the groundwater or be heated by steam (heated with fire), forming an HCO₃ solution.

The water plots of LP 106 and Pul-01 indicate that these hot springs are classified as chloride (Cl) padmata waters in older water conditions with high chloride (Cl) content. The emergence of hot springs at the surface is considered an outflow, likely influenced by surface water. Hot springs containing high chloride and low bicarbonate and sulfate content indicate an outflow area in a geothermal reservoir (Powell, 2010).

Geothermal Fluid Origin

To determine the origin of geothermal fluids, a Cl–Li–B ternary diagram based on calculated percentage values was used. Boron (B), together with chloride (Cl) and lithium (Li), provides important information on subsurface conditions due to its conservative behavior during water–rock interaction and phase separation processes (Giggenbach, 1985). The calculated concentrations of Cl, 2Li, and 5B were converted into percentage values and plotted on the ternary diagram to identify geothermal fluid characteristics and their origin. As shown in Figure 2, the distribution of geothermal water samples indicates that LP 106, Pul-01, Skd-09, and Kp-01 are dominated by chloride (Cl). These samples plot within the low B/Cl steam-absorption field, suggesting that the geothermal fluids are influenced by steam-heated processes and originate from deeper reservoir fluids that have undergone phase separation before reaching the surface. This pattern reflects a typical chloride-rich geothermal system associated with mature geothermal reservoirs.

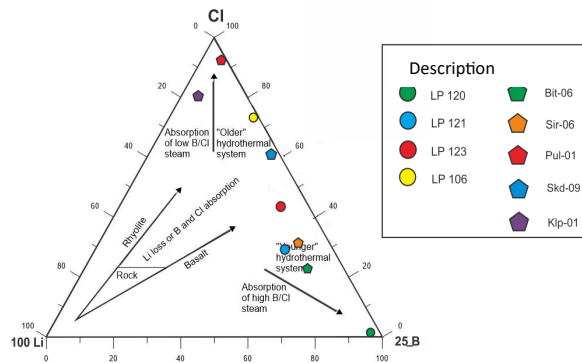


Figure 2. Diagram CI-Li-B

The higher Cl content compared to Li and B indicates that the reservoir conditions are not significantly mixed with meteoric water and are predominantly influenced by volcanic magmatic processes. This condition is consistent with the spatial distribution of geothermal manifestations shown in Figure 3, where the manifestation points are clustered along structural lineaments associated with volcanic activity. The relatively low B content further suggests that, during the ascent from the heat source to the surface, the geothermal fluid experienced dilution through interaction with surrounding rocks along its flow path. The low B concentration also indicates a weak association between geothermal fluids and sedimentary rocks containing organic matter (Nicholson, 1993).

Furthermore, samples LP 121, LP 120, LP 123, Bit-06, and Sir-06 exhibit relatively higher B values compared to Cl and Li. As illustrated in Figure 3, the manifestation points of LP 121, LP 120, Bit-06, and Sir-06 are located close to areas interpreted as having high B/Cl absorption, which suggests the absorption of magmatic gases enriched in boron by basaltic rock components. In contrast, the LP 123 manifestation trends toward the Cl–B field, indicating stronger interaction between geothermal fluids and sedimentary rocks rich in organic matter. This interpretation is supported by the elevated B/Cl ratio observed in the LP 123 sample.

All geothermal manifestations, including LP 121, LP 120, LP 123, Bit-06, and Sir-06, show lithium concentrations below 0.1 mg/L. This condition suggests that the geothermal fluids originate from the upflow zone rather than the outflow zone. In the Cl–Li–B triangular diagram, the samples plot far from the lithium apex, indicating that the hot springs are located relatively far from the primary heat source of the geothermal system. According to Grant and Bixley (2011), deep geothermal reservoirs are generally situated at depths greater than 2 km below the surface. The low lithium concentrations are attributed to the adsorption of Li by secondary minerals such as chlorite, quartz, and clay during fluid migration. Consequently, the longer the migration distance of geothermal fluids toward the surface, the lower the lithium concentration observed. Overall, all manifestation samples exhibit lithium concentrations below 1 mg/L.

Based on the analysis, the dissolved Li content in nine manifestations in the Dieng area is relatively low, even below average. This occurs because the Li content in geothermal manifestations, fluids that rise to the surface after being diluted by adjacent rocks as they move towards the surface from the heat source. This is different when measurements are made on brine exiting the silencer, because the brine produced is usually from the reservoir zone. The high dissolved Li content in brine is due to both concentration processes and source-rock factors within the reservoir. Therefore, the dissolved Li content in geothermal manifestations and the element content in brine differ in value. However, this can be an economic value in the form of the potential of dissolved elements such as Li in geothermal systems. Lithium is highly useful for

production, given its presence in geothermal fields and the minimal risk of air pollution during extraction.

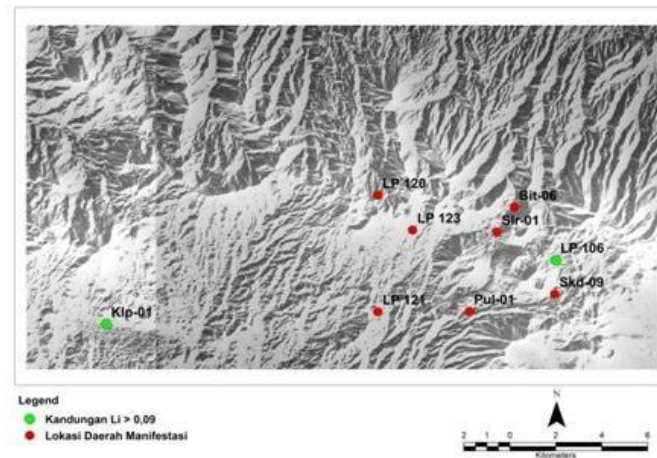


Figure 3. Sample Points of Manifestation

Economic Value of Lithium

Based on geochemical data from several hot spring locations within the Dieng Geothermal Power Plant (WKP), the accumulated lithium content from nine sampling points was 1.11 mg/L. This indicates the potential for economically valuable lithium resources. This aligns with research conducted by the PSDMBP (National Energy and Mineral Resources Development Agency), indicating lithium potential in the area. The formation water flow rate released from the Dieng Geothermal Power Plant is approximately 70 tons/hour. Therefore, it can be assumed that the lithium yield is 1.11 mg/L, assuming 1 liter of water is equivalent to 1 kg of water and a formation water flow rate of 70,000 kg/hour (Ababil et al., 2023). The economic value can be calculated as follows:

$$\begin{aligned} \text{Total lithium at 9 sample points} &= 1.11 \text{ mg/L } 1 \text{ kg of water} \approx 1 \text{ liter of water} \\ 1.11 \text{ mg/kg} \times 70,000 \text{ kg/hour} \\ \text{Lithium recovered} &= 0.077 \text{ kg/hour} \end{aligned}$$

Assuming the required adsorption time is 1 hour and the formation water is fully utilized, the recoverable lithium concentration is calculated over 1 day, 1 month, and 1 year.

$$\begin{aligned} 0.077 \text{ kg/hour} \times 24 \text{ hours/day} &= 1.848 \text{ kg/day} \\ 1.848 \text{ kg/day} \times 30 \text{ days/month} &= 55.44 \text{ kg/month} \\ &= 0.05544 \text{ tons/month} \end{aligned}$$

$$\begin{aligned} \text{Global selling price of lithium per ton} &= \text{US\$}17,000 \\ \text{Selling price} = 0.05544 \text{ tons/month} \times \text{US\$}17,000 &= \text{US\$}942.48 \end{aligned}$$

Revenue from lithium sales within a month reached approximately US\$942.48, equivalent to Rp14,582,427.55, using a selling price of US\$17,000 per ton. This figure covers only lithium sales at nine sample points, excluding revenue from all manifestations in the Dieng Mining Working Area (WKP) and sales of electricity generated from geothermal energy. Based on this selling price assumption, it appears that lithium dissolved in geothermal formation water has significant economic value. This calculation applies only to the Dieng Mining Working Area (WKP). For other areas, further research is needed regarding lithium content and formation water flow rates.

4. Conclusions

Differences in subsurface rock composition, which allow the formation of distinct hydrothermal systems, as well as the location of the aquifer or fluid source depth, can influence the types of

hydrothermal fluids that form each spring in the study area. The content of dissolved elements, such as Li, in the nine manifestations in the Dieng area is relatively low, even below average. This occurs because the Li content in geothermal manifestations, fluids that rise to the surface after being diluted by adjacent rocks as they move towards the surface from the heat source. However, this can indicate the potential for dissolved elements such as Li in geothermal brine; unlike the content in hot spring manifestations, the brine content is likely higher because it comes directly from the reservoir zone. Then, in terms of economic value, the lithium obtained at the nine sample points is 55.44 kg/month based on existing data, which when accumulated with a selling price of US\$17,000 per ton, will obtain an additional US\$942.48. This makes the lithium element at this location a potential resource with economic value and can maximize added value apart from the electrical energy produced by geothermal energy.

5. Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6. Author's contributions

Muhamad Deva Pratama conducted the geochemical data analysis, interpreted the results related to lithium potential in geothermal manifestations, and prepared the original draft of the manuscript. Dwiandra Nugroho contributed to the research conceptualization, methodological framework, and critical revision of the manuscript. Saepul Anwar supervised the study, provided scientific guidance, and reviewed the manuscript for important intellectual content.

All authors have read and approved the final version of the manuscript.

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