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Geothermal Captive Use for Powering Mining Sites: Worldwide Experience and the Potential and Challenges for Implementation in Indonesia

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Abstract

In conventional geothermal electricity trading, geothermal plant operators sell electricity to off-takers, who then distribute it to end users such as industries. However, some industries are located too far from the existing grid for a cost-effective connection, which forces them to generate electricity independently to support their operations. Our study assesses the potential for geothermal captive use in Indonesia's mining sector, where mining companies develop geothermal resources to generate electricity and meet their own energy needs. While previous research has explored the global potential, economic benefits, and environmental advantages of geothermal power in mining—often from broad geographic or regulatory perspectives—few have provided a detailed, site-specific analysis of Indonesia's mining sector. Our study addresses that gap by identifying and evaluating specific mining sites in Indonesia for geothermal captive use. It contributes to the literature by combining practical mining site assessments with targeted insights to support the transition from fossil fuels to geothermal captive use for powering remote mining operations. Examples from Lihir (Papua New Guinea) and Florida Canyon (United States) demonstrate successful applications of this model, yet it remains largely untapped in Indonesia. By reviewing global case studies, we explore captive use mechanisms and extract lessons relevant to the Indonesian context. Although geothermal captive use is still rare in Indonesia, findings indicate several mining sites with potential for its adoption. We underscore the environmental benefits of geothermal energy compared with conventional sources such as diesel and natural gas. However, overcoming technical, economic, and regulatory challenges is crucial for successful implementation. In conclusion, geothermal captive use offers clear benefits for energy-intensive industries in Indonesia, enhancing energy independence, reducing environmental impacts, and supporting broader geothermal adoption in industrial settings.

Keywords: captive use, geothermal energy, industrial activity, mining sector

1. Introduction

Geothermal energy offers key advantages: it is renewable, available around the clock, produces low CO_2 emissions, and requires minimal fuel (Yao et al., 2021). By the end of 2022, Indonesia had 46 geothermal power plant (GPP) units spread across 17 geothermal working areas, with a total installed capacity of 2.3 GW (Pambudi et al., 2023). The conventional business model for GPP operators in Indonesia follows geothermal electricity trading, where generated electricity is sold to the country's sole off-taker, PT Perusahaan Listrik Negara (Persero) (PLN). PLN then transmits and distributes electricity to consumers across various sectors, including industries, offices, and households.

Energy-intensive industries, such as steel and cement factories, as well as mining operations, require a stable and substantial electricity supply to sustain continuous production. Their primary equipment—including electric-arc steel furnaces, concrete grinding machines, and mining smelters—demands reliable energy (Su et al., 2021). Given these characteristics, energy-intensive industries could benefit from geothermal captive use, enabling them to independently meet their power needs without relying on existing electrical grids, particularly when grid connections are economically unfeasible. In such cases, geothermal electricity presents a cost-competitive alternative to other options, such as diesel generators, liquefied natural gas (LNG) engines, or turbines (IESR, 2023).

In the geothermal captive use business model, industries develop GPPs to generate electricity and meet their own energy needs independently. Consequently, these industries typically hold multiple permits covering both geothermal development and their primary industrial activities. Figure 1 illustrates the differences between conventional geothermal electricity trading and the geothermal captive use business models within the industrial sector. Two prominent examples of industrial geothermal captive use are Lihir in Papua New Guinea and Cerro Prieto in Mexico. However, despite Indonesia's significant potential, geothermal captive use has yet to be implemented in the country.

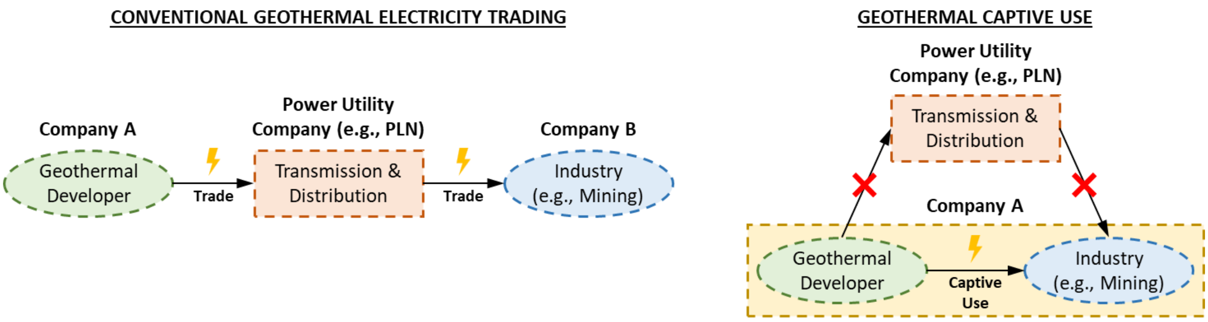


Figure 1. The differences between conventional geothermal power generation and geothermal captive use business models for the industrial sector.

We aim to integrate lessons learned from the mining industry's experience with geothermal captive use in other countries and examine its potential application in Indonesia, along with the challenges associated with implementation. Insights from global case studies are drawn particularly from the Lihir mining site in Papua New Guinea, investigated by Ponyalou et al. (2023b) and Melaku (2005), as well as the Florida Canyon mining site in the United States, studied by Dobson et al. (2023) and Boyd et al. (2015). Additionally, we identify potential mining sites in Indonesia for geothermal captive use and assess the technical, economic, and regulatory challenges to implementation. A comparison of the levelized cost of electricity between geothermal energy and conventional sources such as natural gas and diesel is also presented.

Our study advances the field by focusing specifically on geothermal electricity for captive power in Indonesian mining sites, a context that has not been thoroughly explored in previous research. Patsa et al. (2015) provide global examples, highlighting the operational and environmental benefits of geothermal electricity across various mining project stages. Similarly, NREL (2022) emphasizes the economic advantages of geothermal power for mining, demonstrating its potential to reduce costs compared to diesel generators and presenting successful U.S. case studies. Igogo et al. (2021) further support the concept of geothermal captive use, underscoring the critical role of renewable energy—particularly geothermal—in meeting the growing energy demands and environmental challenges faced by the mining industry, especially in off-grid operations.

While existing studies have established the global potential, economic benefits, and environmental advantages of geothermal power in mining—often from broad geographic or regulatory perspectives—none has provided a detailed, site-specific analysis of Indonesia's mining sector. The novelty of our work lies in identifying and evaluating specific Indonesian mining sites for geothermal integration, addressing a critical regional gap. This contribution enriches the literature by combining practical mining site assessments with targeted insights that support the transition from fossil fuel dependency to geothermal energy in Indonesia's remote mining operations.

2. Methods and Materials

In this study, we adopt a methodological approach that combines a comprehensive literature review with an analysis of geospatial data related to mining and geothermal potential sites. The literature review examines established instances of geothermal captive use within industrial sectors, with a particular focus on the mining industry. This analysis is grounded in detailed case studies from Lihir in Papua New Guinea and Florida Canyon in the United States, providing insights into the operational, economic, and environmental implications of integrating geothermal energy into remote mining operations.

Following this, we conduct a comparative assessment of GPPs alongside other power generation technologies. This comparison considers several key factors, including capital expenditure, land requirements, construction duration, ramp-up rate, average capacity factor, levelized cost of electricity (LCOE), fuel requirements, greenhouse gas (GHG) emissions, and whether these power plants are subject to carbon taxation.

Furthermore, we employ geospatial data from the Indonesian Ministry of Energy and Mineral Resources—specifically the Renewable Energy Map, Electric Utility Map, and Minerba One Map Indonesia (ESDM One Map Indonesia)—to identify potential sites for geothermal captive use in Indonesia. This identification process accounts for mine status and the proximity of mining sites to nearby geothermal resources. Based on this analysis, we establish three key criteria for determining viable mining sites for geothermal captive use. Finally, we examine the legal and regulatory barriers that may hinder the development of geothermal captive use for powering mining operations, providing a framework for understanding potential policy challenges and solutions. This methodological approach enables a practical evaluation of the feasibility of geothermal energy integration within Indonesia's mining industry.

3. Results and Discussion

This section presents the findings from our literature study and geospatial analysis, focusing on global experiences with geothermal captive use—particularly in the mining sector—and its potential implementation in Indonesia. Section 3.1 examines case studies from Lihir and Florida Canyon, highlighting the operational and environmental impacts of geothermal energy in mining operations. Section 3.2 assesses the feasibility of geothermal captive use in Indonesia by comparing the levelized cost of electricity from geothermal sources with conventional energy alternatives and identifying suitable mining sites. Section 3.3 explores the technical, economic, and regulatory challenges that could affect the successful implementation of geothermal captive use in Indonesian mining industries. Finally, we compare our analysis results with previous studies to contextualize findings and validate key insights.

3.1 Worldwide Experience

This section summarizes the literature study on global geothermal captive use applications in industrial activities. Two notable examples highlighted in this study are the Lihir mine in Papua New Guinea and the Florida Canyon Mine in the United States. Both cases uniquely demonstrate mining operations powered by electricity generated from in-situ geothermal captive use within their respective sites. However, the Lihir mine represents a larger-scale application of geothermal captive use compared to the Florida Canyon Mine, both in terms of installed GPP capacity and the longevity of its operation, which continues to this day.

3.1.1 Lihir in Papua New Guinea

Lihir Island is located 800 km northeast of Papua New Guinea's capital, Port Moresby. Since 1997, Newcrest Mining Ltd. has been extracting gold-bearing ore from an open-pit mining operation on the island. The northern and western parts of the mining site are situated within an active geothermal system (Ponyalou et al., 2023a; Sykora et al., 2018). The development of geothermal resources in Lihir was initially driven by the need for pit dewatering, cooling, and depressurizing rock formations to ensure safe and efficient deep open-pit mining. Initially, the site relied on heavy fuel oil (HFO)-fired power plants to generate electricity for mining activities. However, as geothermal drilling progressed and the resource was better understood, its role evolved from mine dewatering and depressurization to providing a more cost-effective and environmentally friendly alternative to HFO-based power generation (Melaku, 2005). The LCOE for HFO ranges from 15 to 17 US¢/kWh (DGE, 2024; Sagel et al., 2022), whereas geothermal LCOE ranges from 3.6 to 13.4 US¢/kWh (IESR, 2023; Ordonez et al., 2022).

Geothermal development at Lihir began in 1999 with the drilling of eight deep (1260–1790 metres Measured Depth (mMD)) standard-hole directional wells (Melaku, 2005). Of these, three wells drilled northward exhibited high permeability and strong production capacity, while three drilled southward yielded lower output. The extracted fluid is characterized by a high pH (~9), significant chloride content (30,000 ppm), and substantial sulphate levels (40,000 ppm), with a low non-condensable gas content (0.6% wt). Geothermal areas within mining sites—such as Lihir—are prone to mineral scaling and mineralization due to the high-temperature hydrothermal fluids dissolving minerals. These minerals precipitate and accumulate as scaling when fluids cool, mix with meteoric water, or undergo pressure changes, leading to mineral deposition on pipes, equipment, and surrounding geological structures (Al Kausar et al., 2018). Due to its high mineral content (Ponyalou et al., 2023b), calcite deposition in wellbores and silica scaling in pipelines caused some wells to clog after sustaining discharge for only a few months. Subsequently, approximately 20 shallow (400–800 mMD) wells were drilled to accelerate pit dewatering and depressurization. Most of these deep and shallow wells encountered steam or high-temperature fluids suitable for power generation. The deep wells primarily produce geothermal fluids at temperatures ranging from 240–250 °C from a feed zone depth of 1000 mMD, classifying them as high-temperature geothermal resources. Similar high-temperature geothermal systems have been developed in Indonesia, where total installed capacity has reached 2.3 GW (Pambudi et al., 2023). The output of the deep wells is summarized in Table 1.

Table 1. The output of Lihir's deep geothermal wells drilled in 1999 (Melaku, 2005).

Well Name	Mass Flow Rate (t/h)	Enthalpy (kJ/kg)	Gas Content (%wt)
GW1	320	1100	n/a
GW2	65	2000	n/a
GW4	95	2750	n/a
GW5	150	2700	2
GW6	180	2700	0.6
GW7	100	2400	0.6
GW8	400	1200	0.7

A 6 MW backpressure GPP was commissioned in 2003 just north of the pit boundary, utilizing steam from four of the 28 geothermal wells. During its first two years of operation, the GPP demonstrated excellent performance, achieving an availability factor of over 95 % (Melaku, 2005). In 2005, a 30 MW flash GPP was commissioned and later expanded to 50 MW in 2007 (Huttrer, 2021). At its peak, the Lihir GPP had an installed capacity of 56 MW, supplying up to 50 % of the gold mine's electricity demand. However, due to the failure to reinject utilized geothermal fluid and the decommissioning of the backpressure GPP in 2009, the current Lihir GPP generates only 15–18 MW. The site layout, including the Lihir gold mine pit, geothermal wells, and GPP, is shown in Figure 2.

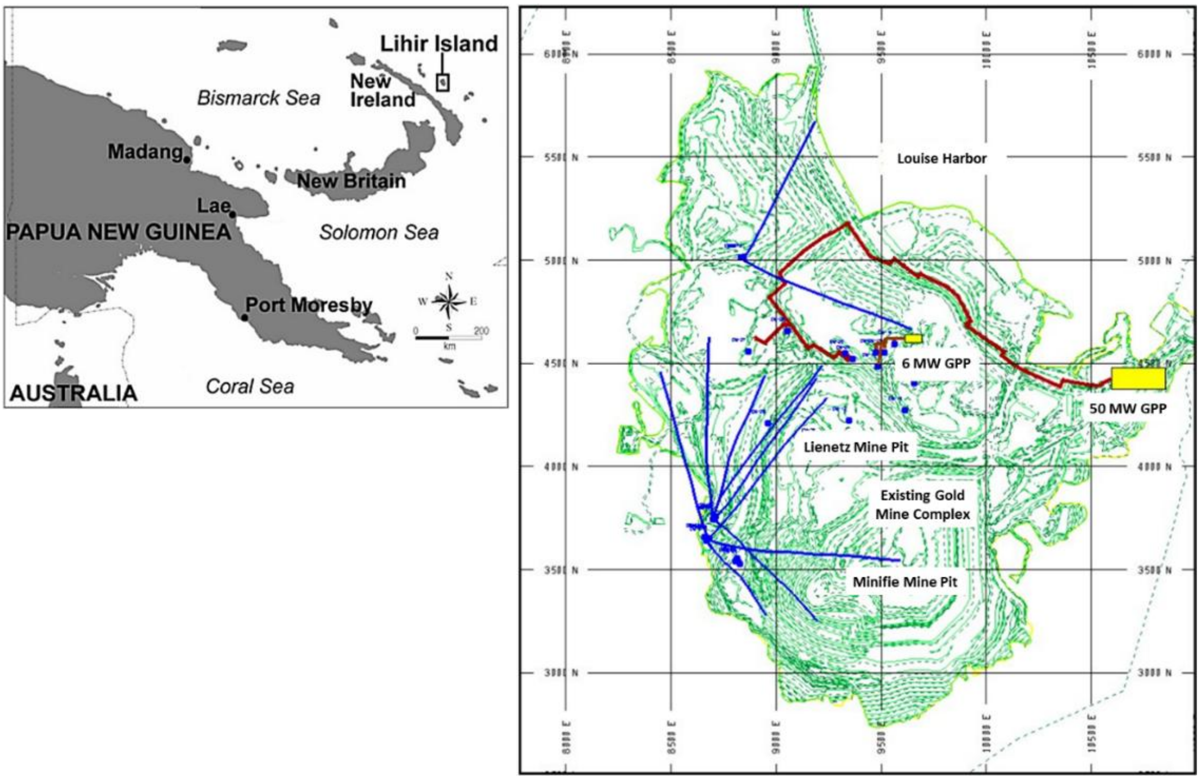


Figure 2. Site layout of the Lihir gold mine and GPP (Melaku, 2005).

The case study of Lihir's geothermal captive use provides valuable insights for mining operations considering geothermal energy. It demonstrates that geothermal energy can enhance safety while reducing reliance on fossil fuels. The GPP at Lihir achieved a high availability factor of over 95 %, supplying up to 50 % of the mine's electricity demand. This case also highlights the importance of effective geothermal reservoir management to sustain production levels and ensure long-term viability. Additionally, proper management of mineral scaling is crucial, particularly in geothermal fields located within mineral-rich mining areas. These lessons offer practical guidance for mining industries looking to implement geothermal captive use, emphasizing both the benefits and challenges of adoption.

3.1.2 Florida Canyon, United States: Using Geothermal Energy in Mining Sites

Florida Canyon is a gold mining site in Nevada, United States, initially owned by Alio Gold Inc., and has been producing gold through open-pit mining for more than 30 years. The site is adjacent to an active geothermal system, classifying Florida Canyon as a hot spring-type epithermal gold deposit (Dobson et al., 2023; Forson, 2014). The mine wells at Florida Canyon discharge 36 t/h of fluids at 100 °C from a depth of 175 m. In 1980, these fluids were first utilized as a heat source for heap leaching (Boyd et al., 2015). Subsequently, two 50 kW binary GPP units were commissioned in 2010 and 2013 to convert the discharged fluid heat into electricity, supplying 5 % of the mining site's electricity demand. However, due to mineral scaling in the piping and the acquisition of Alio Gold Inc. by Argonaut Mine Inc. in 2020, the GPPs have been decommissioned (Fiscor, 2022). Figure 3 shows the location of the pilot GPP within the Florida Canyon mining site.

The Florida Canyon case study underscores the importance of effective mineral scaling mitigation strategies in geothermal fields within mining areas to ensure the sustainability of geothermal power generation for mining activities. It also highlights the need for long-term commitment from mine owners to sustain geothermal energy utilization. These lessons are essential for other mining operations considering geothermal captive use.

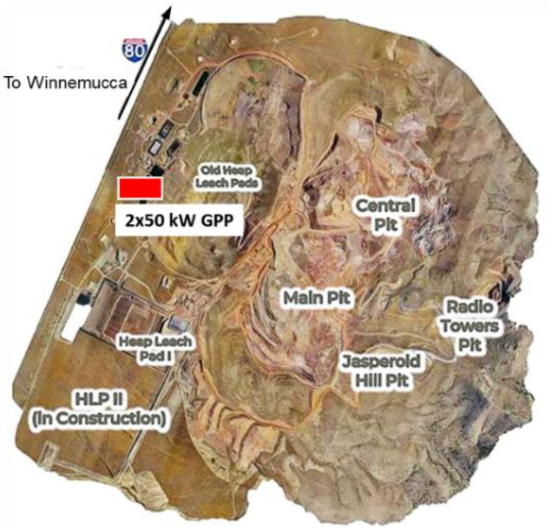


Figure 3. Site layout of Florida Canyon gold mine and GPP (Dobson et al., 2023).

3.1.3 Geothermal Energy in Mining Sites

Patsa et al. (2015) examined the synergy between mining operations and geothermal energy, highlighting both indirect and direct geothermal utilization. Indirect geothermal uses involve converting geothermal heat into electricity to power nearby mining sites, while direct geothermal uses refer to applications such as desalinating seawater for mine operations, extracting minerals from brine, improving mineral processing efficiency in heap leaching of gold, silver, and copper, and heating spaces—either during active mining or as part of a site abandonment plan.

Patsa et al. (2015) also identified several factors that influence the feasibility of integrating geothermal energy into mining operations. These include the geographic isolation and climate conditions of the mining site, the site's proximity to power transmission and distribution networks and the costs associated with alternative energy sources, and the characteristics of the geothermal resource—such as production enthalpy, achievable mass flow rates, and brine mineral content—that determine its potential applications and economic viability. Additionally, the nature of the mining operation itself, its requirements for direct heat usage (such as mineral processing or environmental control), and the presence of nearby communities capable of utilizing the generated energy as part of sustainability initiatives play crucial roles. The operator's commitment to green energy policies and culture further influences integration potential. Geothermal captive use for powering mining sites is particularly appealing for remote mines lacking grid connectivity, possessing accessible and extractable geothermal reserves, and requiring direct heat applications.

Furthermore, the NREL (2022) assessed the potential reductions in geothermal capital expenditures (CAPEX), LCOE, and the time required to reach the commercial operation date (COD) when geothermal resources are developed alongside mineral exploration and extraction activities. Their study assumed the geothermal resource was co-located with an operational mining site, situated on either government-owned or private land, with geothermal electricity utilized to meet on-site mining power needs. This scenario was compared to a conventional geothermal electricity trading model, which follows standard industry cost parameters in the United States.

Table 2 illustrates that geothermal captive use in mining operations can lower CAPEX, reduce LCOE, and shorten the time to reach COD compared to conventional geothermal electricity trading (NREL, 2022). In the mining captive use scenario, CAPEX decreased from 116 million USD to 99 million USD, while LCOE dropped from 8.7 US¢/kWh to 6.2 US¢/kWh. These reductions were primarily due to the elimination of transmission costs and the decreased surface exploration and drilling costs, as mining exploration and development activities had already provided substantial geological data. Additionally, the duration to achieve COD was reduced from 8.2 years in the conventional scenario to 4.2 years in the mining captive use scenario due to prior exploration activities supporting geothermal development.

Table 2. Input and output parameters of a geothermal project economic optimization through the mining captive use scheme according to NREL (2022).

Parameter	Type	Unit	Conventional geothermal electricity trading	Mining captive use: government-owned land	Mining captive use: privately owned land
GPP capacity	Input	MW	20	20	20
Resource temperature	Input	ºC	166	166	166
Resource depth	Input	Metres below ground level	610	610	610
Technology	Input	-	Binary with pumped wells	Binary with pumped wells	Binary with pumped wells
Exploration duration	Input	Year	4	0.75–1	0.75–1
Surface exploration and exploration drilling costs	Input	Million USD	18	1.1–8.8	1.1–7.6
Development drilling costs	Input	Million USD	12.6	14.8	14.8
Land lease costs	Input	USD/hectare	49	2.47	2.47
Transmission costs	Input	USD/km	466,000-621,000	0	0
CAPEX	Output	Million USD	116	101–107	99–106
LCOE	Output	US¢/kWh	8.7	6.5–6.7	6.2–6.5
Duration to reach COD	Output	Year	8.2	4.7–5.2	4.2–4.75

Igogo et al. (2021) examined the integration of renewable energy into mining operations, highlighting the sector's high energy consumption and carbon emissions. As global demand for minerals increases, the industry faces mounting pressure to reduce its reliance on fossil fuels. The study identified opportunities to incorporate renewable energy sources, including geothermal, to support power generation, process heat, and transportation in mining. However, large-scale adoption faces challenges such as energy storage limitations, high-temperature process heat demands, and regulatory barriers. To facilitate renewable energy integration, Igogo et al. (2021) proposed aligning business models, investing in capacity building, and advancing research in energy storage and hydrogen technology. They also emphasized the need for supportive policies and collaborative resource-sharing between mines and local communities. While full decarbonization remains challenging, a phased approach to renewable adoption can progressively reduce emissions and operational costs over time.

3.2 Potential Geothermal Captive Use in Indonesia

This section provides the analysis results of the potential of geothermal captive use in Indonesia in terms of how geothermal LCOE compares to the LCOE of other energy sources, the presence of geothermal prospect areas nearby or within a mining site, as well as the challenges of implementing geothermal captive use in Indonesia.

3.2.1 Comparison of Electricity Generation Costs Between Various Energy Sources

In the absence of nearby electrical grids, industrial captive use typically relies on gas turbines or diesel generators due to their low upfront cost, compact equipment, rapid installation, and short ramp-up period (DGE, 2024). However, these energy sources pose operational challenges, including high fuel costs and unreliable supply chains, particularly for industries located in rural areas or remote islands. Additionally, fossil fuel-based power generation results in significant GHG emissions.

The presence of geothermal resources near industrial sites presents a promising alternative for cost-effective and clean captive energy use, as illustrated in Table 2 and Figure 4. Geothermal LCOE is significantly lower than that of diesel generators and is comparable to gas turbines (IESR, 2023; Ordonez et al., 2022). Moreover, geothermal energy generates negligible GHG emissions compared to diesel and natural gas (Ball, 2020; Marashli et al., 2022).

LCOE calculations for geothermal power generation have been thoroughly evaluated, incorporating exploration risks and drilling costs into investment assessments. Additionally, external economic factors, such as carbon pricing, have been considered, as reflected in Table 3 and Figure 4, further enhancing geothermal energy's economic viability.

Table 3. Comparison between diesel generator, natural gas turbine, and GPP.

Parameter	Units	Diesel Generator	Gas Turbine	Geothermal	References
Capital expenditure	Million USD/MW	0.5–0.8	0.8–0.9	4–6	(DGE, 2024)
Land area	m^2/MW	900	800	5,000-20,000	(Stevens, 2017)
Construction duration	Year	< 1	2–4	5–10*	(DGE, 2024; Pongtuluran et al., 2024)
Ramp-up	Minute	< 1	10–20	10–20	(Abudu et al., 2020)
Capacity factor	-	10–30%	50–60%	70–95%	(Kabeyi 2019)
LCOE	US¢/kWh	12.5–37.1	5.5–12.9	3.56–12.06	(IESR, 2023; Ordonez et al., 2022)
Fuel need	-	Yes	Yes	No	-
GHG emission	kg CO_2e/kWh	0.51–1.18	0.32–0.99	0.02–0.24	(Marashli et al., 2022; Ball, 2020)
Subject to carbon tax	-	Yes	Yes	No	(Pongtuluran, et al., 2024; Ayodele et al., 2021)

*include well drilling and production facility construction

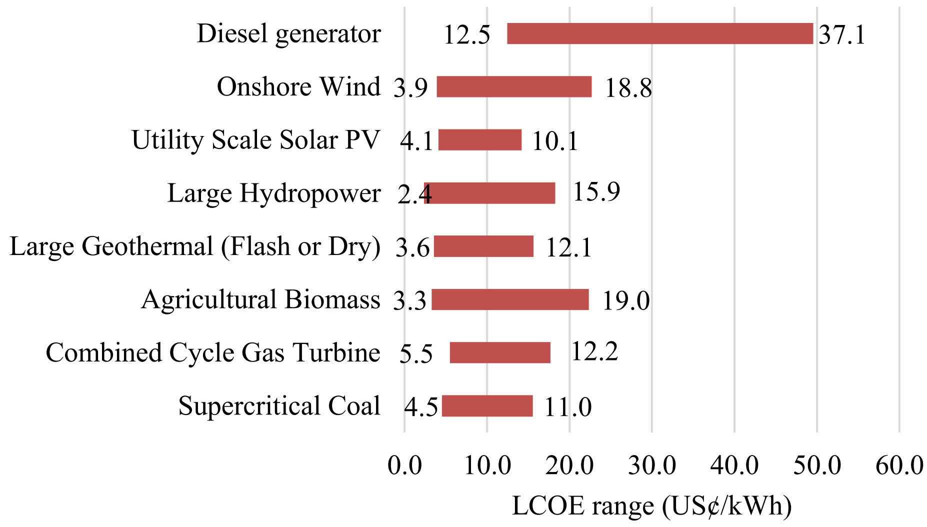


Figure 4. LCOE comparison between geothermal energy and other energy sources (IESR, 2023).

3.2.2 Geothermal Prospect Areas Near Mining Areas Without PLN's Grid Nearby

Geothermal fluid with a wellhead temperature of 100 °C is classified as a low-temperature geothermal resource (Brilian et al., 2025; Sanyal, 2005). In Indonesia, no existing GPP utilize geofluid with a wellhead temperature of 100 °C extracted from shallow wells (< 200 m). However, the Sorik Marapi geothermal field in North Sumatra—a high-temperature field with a reservoir temperature of 240–320 °C—employs a cascaded power plant schematic to optimize geothermal fluid temperature (Hidayat, 2021; Nugraha & Hidayat, 2021). After extracting energy from high-temperature geothermal fluid in the upper cycle, the rejected brine, with a temperature as low as 100 °C, is further utilized in a bottoming binary plant to generate additional power (Nugraha & Hidayat, 2021). Similarly, in the Indonesian mining industry, the Toka Tindung gold mine in North Sulawesi provides an example of geofluid extraction at 100 °C for mine dewatering from a depth of 280 m using electric submersible pumps (Ryanta et al., 2022).

We utilize three criteria to identify mining sites in Indonesia with the potential for geothermal captive use, as summarized in Table 4. These criteria include the working area's auctioning status, proximity to an existing PLN substation, and the distance between the mining site and a nearby geothermal prospect. Relevant information about mining sites and adjacent geothermal resources is gathered from MEMR's Renewable Energy Map, Electric Utility Map, and Minerba One Map Indonesia (ESDM One Map Indonesia), all accessible online. Additionally, approximate distances between mining sites, substations, and geothermal potential areas are measured using Google Earth.

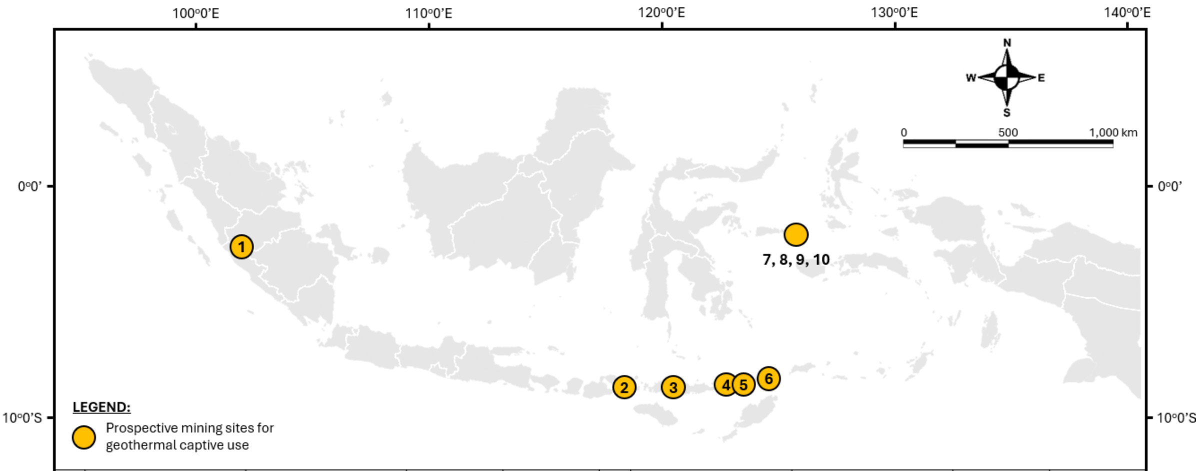
The mapped prospective mining sites for geothermal captive use in Indonesia are presented in Table 5 and Figure 5, revealing a total potential of up to 425 MW across 10 mining sites. Most of these sites are located on remote islands in eastern Indonesia, where no existing or planned electricity grid is available, as indicated in RUPTL 2021–2023. Given these conditions, mining industries in the region should strongly consider adopting geothermal captive use to achieve clean, cost-effective, and independent power generation.

Among the 10 prospective mining sites identified in Table 6, two are still under exploration, while six have entered the production phase, as illustrated in Figure 6(a). The two sites currently in the mineral exploration stage are PT Aneka Tambang Tbk in Sarolangun and Merangin Regencies, located near the Sungai Tenang geothermal site, and PT Sumbawa Timur Mining in Dompu and Bima Regencies, adjacent to the Hu'u Daha geothermal site.

Additionally, four of the prospective mining sites have geothermal potential within their mining boundaries, four others have geothermal potential located 1–5 km away, and the remaining two have geothermal resources 6–10 km from their sites, as shown in Figure 6(b). Examples of two mining sites under exploration (left) and two under production (right) with potential for geothermal captive use are mapped in Figure 7.

Table 4. Three criteria to determine potential mining sites for geothermal captive use in Indonesia.

Parameter	Description
Working area auction status	Most geothermal prospect areas have not yet been auctioned by MEMR, except for Hu'u Daha, which was auctioned in 2024 (STM, 2024). As a result, mining permit holders still have the opportunity to obtain geothermal permits for captive use.
Distance to the nearest existing substation	The distance between the mining site and the nearest existing or planned substation, as outlined in PLN's Electricity Supply Business Plan (RUPTL) 2021–2023, exceeds 30 km, making grid connection economically unfeasible. This distance reflects the average proximity of existing mining sites to substations, as detailed in Table 5. The financial impact of this separation is significant, with transmission line costs ranging from USD 466,000 to USD 621,000 per kilometre, leading to an increase in the LCOE by USD 0.60 to USD 0.80 per MWh (NREL, 2022). Additionally, transmission costs—accounting for 25% of total Engineering, Procurement, and Construction (EPC) expenses—play a crucial role in project economics. Sensitivity analysis confirms that 30 km is the maximum viable distance for maintaining economic feasibility.
Distance between the mining and geothermal sites	The distance between the mining site and the nearest geothermal potential does not exceed 10 km. This guideline is based on observed distances between existing mining sites and nearby geothermal resources, which are typically within this range, as detailed in Table 5. Maintaining a shorter distance significantly reduces transmission and infrastructure costs, enhancing economic viability. Furthermore, keeping the geothermal source close to the mining site maximises thermal efficiency by minimising energy losses during transmission.



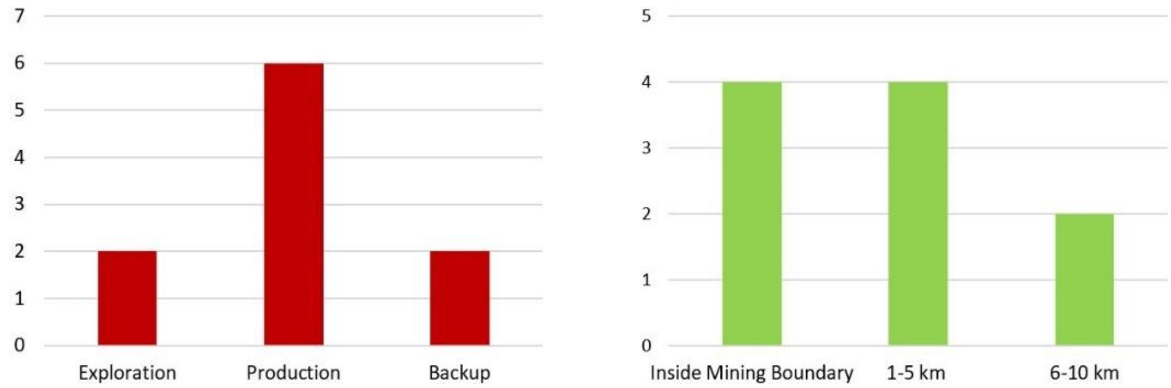
No.	Location	Permit Holder	Commodity	Status	No.	Location	Permit Holder	Commodity	Status
1	Sarolangun and Merangin, Jambi	PT Aneka Tambang Tbk	Gold	Exploration	6	South West Maluku, Maluku	PT Batutua Kharisma Permai	Copper	Production
2	Bima and Dompu, West Nusa Tenggara	PT Sumbawa Timur Mining	Copper and gold	Exploration	7	Sula Island, North Maluku	PT Bintani Karya Bumi Persada	Iron ore	Production
3	East Manggarai, East Nusa Tenggara	PT Istindo Mitra Perdana	Manganese	Production	8	Sula Island, North Maluku	PT Patria Sekarjaya	Iron ore	Production
4	East Flores, East Nusa Tenggara	PT Adisti Indah	Natural gravel sand	Backup	9	Sula Island, North Maluku	PT Indotama Mineral Indonesia	Iron ore	Production
5	Lembata, East Nusa Tenggara	PT Trans Lembata	Excavated gravel	Backup	10	Sula Island, North Maluku	PT Wirabahana Perkasa	Iron ore	Production

Figure 5. Prospective mining sites for geothermal captive use in Indonesia.

Table 5. Details of the prospective mining sites.

Mining Site Location	Mining Permit Holder	Distance to Nearest Substation	Commodity	Mining Status	Mining License Validity	Nearby Geothermal Potential	Geothermal Potential Size
Sarolangun and Merangin Regencies, Jambi	PT Aneka Tambang Tbk	57 km (Tess 150 kV)	Gold	Exploration	2020 – 2024	Sungai Tenang (2 km)	74 MW (hypothetical resource)
Bima and Dompu Regencies, West Nusa Tenggara	PT Sumbawa Timur Mining	37 km (Dompu 150 kV)	Copper and gold	Exploration	2022 – 2023	Hu'u Daha	69 MW (probable reserve)
East Manggarai Regency, East Nusa Tenggara	PT Istindo Mitra Perdana	34 km (Ruteng 70 kV)	Manganese	Production	2016 – 2026	Wai Pesi (9 km)	54 MW (probable reserve)
East Flores Regency, East Nusa Tenggara	PT Adisti Indah	Remote island	Natural gravel sand	Backup	n/a	Oyang Barang (1 km)	37 MW (probable reserve)
Lembata Regency, East Nusa Tenggara	PT Trans Lembata	Remote island	Excavated gravel	Backup	n/a	Adum (9 km)	36 MW (probable reserve)
South West Maluku Regency, Maluku	PT Batutua Kharisma Permai	Remote island	Copper	Production	2018 – 2031	Lurang (2 km)	20 MW (speculative resource)
Sula Island Regency, North Maluku	PT Bintani Karya Bumi Persada	Remote island	Iron ore	Production	2018 – 2034	Kramat (1 km)	10 MW (speculative resource)
Sula Island Regency, North Maluku	PT Patria Sekarjaya	Remote island	Iron ore	Production	2018 – 2034	Losseng*	30 MW (speculative resource)
Sula Island Regency, North Maluku	PT Indotama Mineral Indonesia	Remote island	Iron ore	Production	2018 – 2034	Auponia*	20 MW (speculative resource)
Sula Island Regency, North Maluku	PT Wirabahana Perkasa	Remote island	Iron ore	Production	2018 – 2034	Bruokol*	5 MW (speculative resource)
Total							**425 MW**

*inside the mining boundary



(a) (b)

Figure 6. Prospective mine status (a) and the distance between the mining site and geothermal potential (b).

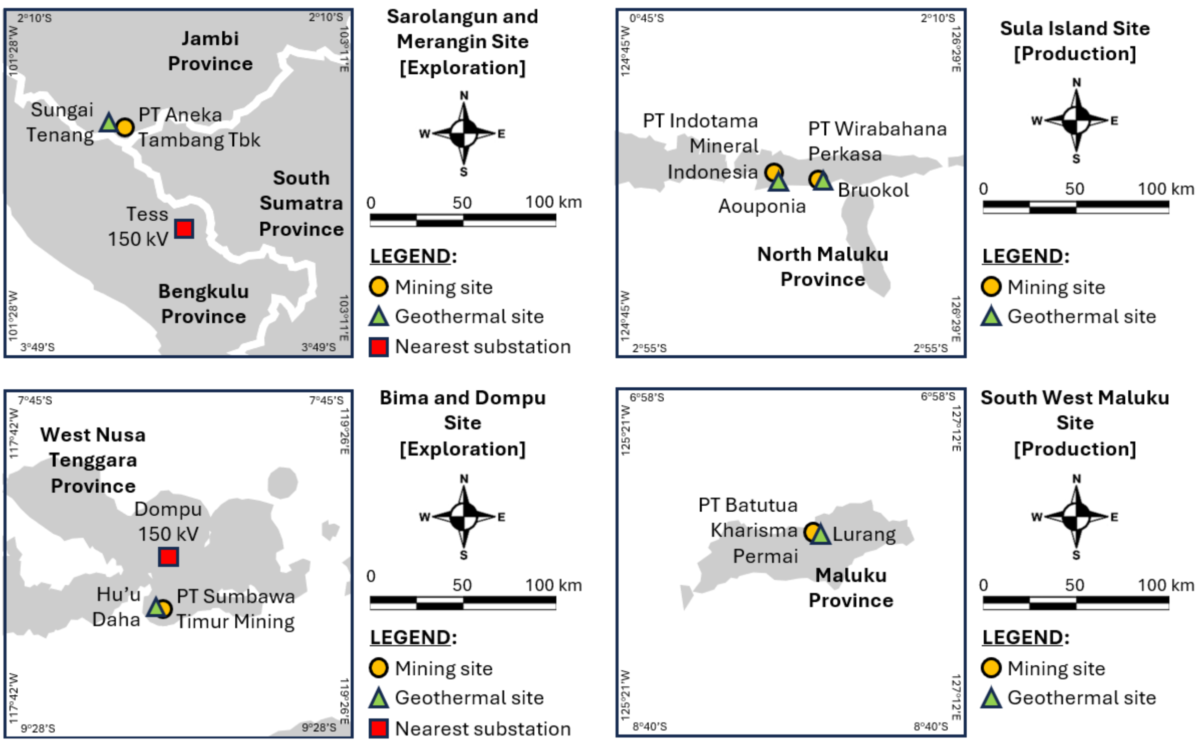


Figure 7. Examples of two mining sites under exploration (left) and two mining sites under production (right), prospective for a geothermal captive use mapped from ESDM One Map Indonesia.

The decision to develop geothermal captive use during either the mining exploration or production phase presents distinct advantages and challenges, as summarized in Table 6. Integrating geothermal planning during the exploration phase allows for strategic alignment with initial site development but requires substantial upfront investment and involves higher uncertainties due to limited subsurface data and a lack of existing infrastructure. Conversely, developing geothermal resources during the production phase benefits from established infrastructure and geological data from prior mining activities, reducing initial risks and financial burdens. However, this approach introduces complexities, such as adapting geothermal plans to an existing mining layout and logistical challenges in equipment mobilization within an active mining operation.

To ensure geothermal captive use remains economically competitive compared to diesel and natural gas, the higher initial costs must be offset by proximity between the mining site and geothermal resources. If the geothermal resource is located beyond 10 km from the mining operation, extensive electrical transmission infrastructure would be required, significantly reducing financial viability relative to fossil fuel alternatives.

Table 6. Comparison between conducting geothermal captive use development during mining exploration and production.

During Mining Exploration		During Mining Production	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
✓ Mining and geothermal site plans could be integrated	× High upfront cost × Uncertainty of mining discovery × No existing infrastructure × Limited subsurface data from mining wells	✓ Existing infrastructure ✓ Mining revenue could be allocated for geothermal captive use development ✓ More available subsurface data from mining wells	× The geothermal site plan should adjust to the existing mining site × Challenging geothermal equipment mobilization due to existing mining activities × The existing mining site may have been connected to the PLN's transmission grid, thus rendering the economic viability of a geothermal captive use.
Action Plan		**Action Plan**	
1. Gather subsurface data as much as possible through both the mining and geothermal exploration wells 2. Create integrated mining and geothermal site plans to ease infrastructure preparation and later operation 3. Allocate more financial resources to enable parallel mining and geothermal exploration activities		1. Gather and evaluate the existing subsurface data from past mining exploration wells 2. Conduct geothermal exploration drilling to gather subsurface data regarding the geothermal system 3. Evaluate the existing infrastructure's readiness to support geothermal development activity 4. Adjust the geothermal site plan to the existing mine site plan	

3.2.3 Challenges of Implementing Geothermal Captive Use in Indonesia

The limited adoption of geothermal captive energy, both in Indonesia and globally, stems from several key challenges spanning technical, economic, and regulatory domains, particularly within the mining industry, as outlined in Table 7. These challenges include mineral scaling, which affects geothermal systems, logistical difficulties in establishing geothermal infrastructure within active mining sites, and a gap in expertise between geothermal and open-pit mining technologies. Other significant hurdles include the complex permitting process, the substantial financial investment required, and competition from cost-effective, rapidly deployable natural gas turbines.

To overcome these obstacles, industries must implement comprehensive action plans. These should focus on mitigating mineral scaling, enhancing infrastructure to support geothermal installations, employing experts to bridge knowledge gaps, collaborating with regulatory bodies to streamline permitting processes, securing necessary funding, and fostering a strong commitment to sustainable energy practices. Thoughtfully addressing these challenges will enable the mining industry to harness geothermal energy more effectively, paving the way for more sustainable and efficient operations.

In geothermal applications, the three common strategies for mitigating mineral scaling are chemical scale inhibition, acid dosing, and cold brine reinjection (Jarrahian et al., 2025; Longval et al., 2024). These methods can also be applied to geothermal operations near mining areas. The selection of an appropriate scaling mitigation strategy should be tailored to site-specific conditions by considering multiple factors, including geothermal brine temperature, pH, dissolved mineral concentration, reinjection strategy for reservoir management, operational approach, mitigation costs, and the availability of service providers in the market.

Table 7. Challenges and proposed action plans to develop geothermal captive use in Indonesia.

Challenges	Potential Action Plans
Geothermal systems within mineral deposits are likely to cause mineral scaling in facilities located within or near mining sites (NBMG, 2014).	Develop a mineral scaling mitigation strategy for geothermal facilities located within or near mining sites.
Mobilizing and installing geothermal equipment within an operational mining site presents significant challenges.	Evaluate whether the existing infrastructure can accommodate the mobilization and installation of geothermal equipment.
A knowledge gap exists between geothermal technology and a company's preexisting core business.	Hire geothermal experts and implement capacity-building initiatives to bridge the knowledge gap between geothermal technology and the company's preexisting core business.
Both mining and geothermal activities require permits, adding regulatory complexity.	Coordinate with MEMR to explore the possibility of acquiring geothermal permits for nearby prospective areas.
Enterprises must have strong financial resources to develop both geothermal energy and their preexisting core business activities.	Secure internal and external financial aid to support the development of geothermal captive use.
Since natural gas turbines offer a similar LCOE and faster installation compared to GPPs, enterprises must demonstrate a strong commitment to utilizing geothermal captive energy as a clean electricity source.	Strengthen commitment to providing clean electricity through geothermal captive use, despite the comparable LCOE and faster installation of natural gas turbines.

Each scaling mitigation strategy has a distinct mechanism for restricting the precipitation of scale minerals in geothermal wells and pipelines. Chemical scale inhibitors disrupt the nucleation and crystal growth of mineral deposits—such as silica and calcium carbonate—preventing or minimising their precipitation, which can clog pipelines and wells (Hoang, 2022). The three primary chemical types of scale inhibitors include polyphosphates, phosphonates, and polymer-based inhibitors (Husna et al., 2022). The chemical scale inhibition method was successfully applied in the Sorik Marapi geothermal field, effectively limiting the amorphous silica scaling rate to below 0.1 mm/year in 2021 under silica-saturated geothermal brine conditions (Nugraha & Hidayat, 2021).

Furthermore, acid dosing increases the silica solubility in geothermal brine by lowering the water's pH. As shown in Figure 8, silica solubility in water increases as the pH decreases (Li et al., 2017). Successful acid dosing operations require careful selection of injection points and acid concentrations to prevent equipment corrosion while optimizing silica scale reduction. Acid dosing using H_2SO_4 was implemented in the Dieng geothermal field, Indonesia (Kencana et al., 2024). Although short-term observations demonstrated promising results in scaling management, long-term evaluations are necessary to assess its effectiveness in reducing scaling without causing significant operational issues.

Meanwhile, cold brine reinjection, also implemented in the Dieng geothermal field, involves holding geothermal brine in a retention pond for a specific duration under atmospheric conditions before reinjecting it into the geothermal reservoir (Al Asy'ari et al., 2023). This process facilitates silica precipitation in the retention pond by reducing the brine's temperature, thereby lowering silica concentration in the reinjected fluid. As shown in Figure 6, the solubility of amorphous silica in water decreases as the temperature declines, aiding in silica precipitation (Longval et al., 2024).

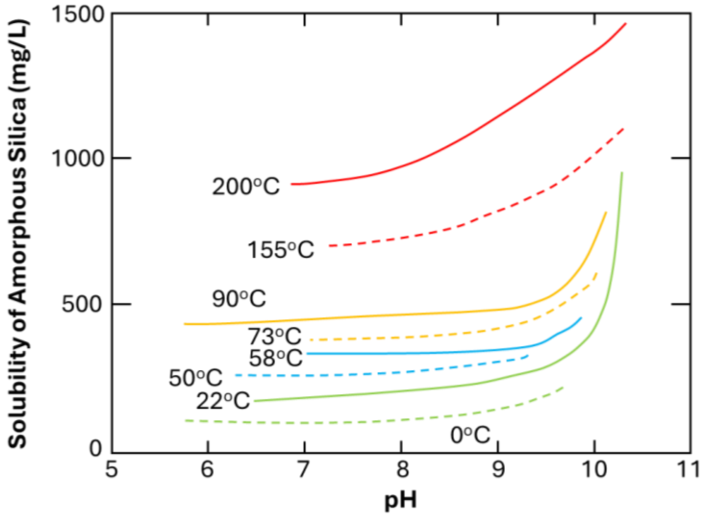


Figure 8. Solubility of amorphous silica in water with temperatures and pH levels (Longval et al., 2024; Li et al. 2017).

3.3 Legal and Regulatory Barriers of Geothermal Captive Use for Powering Mining Sites

As Indonesia expands its renewable energy footprint, geothermal captive use projects present a unique opportunity to harness the country's vast geothermal potential. However, this approach comes with specific legal and regulatory challenges that must be addressed to facilitate geothermal captive uses. Table 8 outlines these challenges and proposes actionable strategies to mitigate their impacts. It serves as a reference for stakeholders looking to navigate the complex regulatory landscape of deploying geothermal resources for captive use.

The successful implementation of geothermal captive use projects requires not only technological adaptation but also a robust regulatory framework that effectively addresses these challenges. By carefully examining the potential obstacles and aligning them with strategic action plans, stakeholders can move toward a more streamlined approach, ensuring efficient geothermal energy utilisation while advancing Indonesia's renewable energy goals. This table acts as a foundational guide for policymakers, investors, and developers as they navigate the complexities of integrating geothermal energy within a captive use framework.

3.4 Comparison with the Results from the Previous Studies

The findings of this study align with previous research by NREL (2022), Igogo et al. (2021), and Patsa et al. (2015) on the use of geothermal electricity for captive power in the mining industry. These studies recognise geothermal energy's potential to provide a stable and reliable power source for mining operations, particularly in remote areas with limited grid access.

However, our study focuses specifically on Indonesia, identifying particular mining sites where geothermal energy can be used for captive electricity. In contrast, Patsa et al. (2015) present global examples, highlighting the operational and environmental benefits of geothermal electricity at various stages of mining projects. Similarly, the NREL (2022) emphasises the economic advantages of geothermal electricity in mining, demonstrating cost reductions compared to diesel generators and showcasing U.S. case studies of successful integration. Igogo et al. (2021) further advocate for geothermal captive use, highlighting the critical role of renewable energy—including geothermal—in addressing the growing energy demands and environmental pressures faced by the mining industry, particularly in off-grid operations.

These studies provide successful examples of geothermal integration in remote mining sites, reinforcing geothermal ability to deliver a continuous baseload power supply. While our study primarily addresses the Indonesian context, other studies take a broader geographic perspective, focusing on data-driven approaches and regulatory challenges. Overall, all studies support the use of geothermal electricity as a means to enhance sustainability and energy independence in mining, although they differ in regional focus and methodological approaches.

Table 8. Potential legal and regulatory barriers in implementing geothermal captive use in Indonesia.

Challenge	Potential Action Plan for Indonesia
Mining companies that hold mining permits do not automatically receive geothermal licenses, requiring additional licensing processes for geothermal development.	1. The Government of Indonesia could implement integrated or streamlined geothermal licensing procedures tailored specifically for mining companies already holding mining permits. 2. Mining companies may consider expanding their Indonesia Standard Industrial Classification (KBLI) or establishing a separate entity for geothermal power production to facilitate transactions for geothermal projects.
Combining the Work and Budget Plan (RKAB) for geothermal and mining operations under a single entity may lead to regulatory complexity and potential confusion.	1. Mining companies may consider expanding their KBLI classification or establishing a separate entity for geothermal power production to facilitate transactions for geothermal captive use, ensuring clear separation of RKAB and assets. 2. Beyond recommending separate operational entities, establish guidelines for optimal asset management to prevent conflicts of interest and ensure financial transparency.
Standard Sale Agreements for Electricity (PJBL) and Steam (PJBU) are not applicable in Indonesia.	1. Develop a contract specifically designed for captive use, ensuring it address the unique requirements that differ from conventional power purchase agreements (PPAs). 2. Define pricing, duration, and the rights and obligations of each party in alignment with captive use needs, considering the geothermal power producer as the supplier and the mining company as the electricity/steam purchaser.
Fiscal obligations are impacted by the non-applicability of Standard Sale Agreements, as the captive scheme generally lacks clear steam or electricity sales transactions, complicating the calculation of non-tax revenue (PNBP). Determining PNBP and Production Bonus becomes challenging when captive geothermal use does not involve explicit steam or electricity sales transactions with the national off-taker (PLN).	1. Collaborate with governmental bodies to develop a special fiscal regime for captive projects, accommodating direct usage without traditional sale transactions. This regime could incorporate modified royalty rates or fixed fee structures based on production capacity rather than sales. 2. Formulate specific regulations or establish standard legal instruments to address captive use scenarios, ensuring clear formulas and calculation methods for PNBP and Bonus Production.
Due to a limited regulatory framework and practical constraints on power wheeling and surplus power sales, all generated power must be fully utilized by the mining company.	1. Advocate for policy clarity and the establishment of implementing regulations for power wheeling. 2. Encourage MEMR and PLN to develop clear regulations, practical guidelines, and implementation frameworks to facilitate power wheeling and excess electricity sales.

4. Conclusions

We examine the feasibility of utilising geothermal energy for captive power in Indonesia's mining sector, where mining companies generate electricity from geothermal sources to meet their operational energy demands. While existing studies have explored the global potential, economic viability, and environmental benefits of geothermal energy in mining—often from a broad geographic or regulatory perspective—detailed, location-specific analyses within Indonesia remain limited. This study fills that gap by identifying and analysing specific mining sites in Indonesia suitable for geothermal captive use. It enhances the existing body of knowledge by offering practical site-level evaluations and actionable insights to facilitate the transition from fossil fuels to geothermal captive use in powering remote mining operations.

In the conventional geothermal power generation business model, electricity is sold by GPP operators to off-takers, who then distribute it to various industries. However, industries located too remotely for economically viable grid connections must generate their own power. Geothermal captive use introduces a novel approach, enabling these industries to access clean, cost-effective electricity, independent of grid access, while avoiding the high costs of diesel and natural gas. This concept has been successfully implemented in Lihir (Papua New Guinea) and Florida Canyon (United States) but remains largely untapped in Indonesia, where up to 10 mining sites have been identified with a potential of 425 MW for geothermal captive use. This study maps these potentials, details the practical integration of geothermal systems into mining operations, and highlights key challenges, as well as the significant environmental and economic benefits over fossil fuel-based power sources. The development of geothermal captive use during either the mining exploration or production phases presents distinct advantages and challenges. Mining permit holders are encouraged to initiate necessary action plans for their development. Additionally, addressing technical, economic, and regulatory challenges is crucial to accelerate adoption in Indonesia, enhancing energy independence and reducing industrial environmental impact.

Geothermal captive use for powering mining sites may be more suitable for existing mining operations still reliant on fossil fuels, such as diesel or heavy fuel oil. These sites can leverage existing infrastructure, subsurface data, and financial resources from mining activities to transition from fossil fuels to geothermal captive use, achieving economic benefits by lowering the LCOE while minimising subsurface, infrastructure, and financial risks.

Prospective mining sites for geothermal captive use can be found in remote islands such as East Nusa Tenggara, Maluku, and North Maluku. However, applying geothermal captive use to mining sites still in exploration—such as PT Aneka Tambang Tbk's mining site in Jambi and PT Sumbawa Timur Mining's site in West Nusa Tenggara—could also be viable if companies possess strong financial and human resources, along with environmental motivations to develop mining and geothermal simultaneously despite limited subsurface data and infrastructure. Future studies should focus on assessing the detailed prioritization of mining sites for geothermal captive use by evaluating site readiness based on multiple criteria, ensuring effective deployment and long-term sustainability.

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References

Abudu, K., Igie, U., Minervino, O. & Hamilton, R. (2020). Gas turbine Efficiency and Ramp Rate Improvement Through Compressed Air Injection. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 235*(4), 866–884.

Al Asy'ari, M. R., Adityatama, D. W. & Purba, D. (2023). Geothermal Field Management: Various Cases from Top Geothermal Producer Countries. In *Proceedings, 48th Workshop on Geothermal Reservoir Engineering Stanford University* .

Al Kausar, A., Indarto, S. & Setiawan, I. (2018). Rock geochemistry related to mineralization processes in geothermal areas. *IOP Conferences Series: Earth and Environmental Science, 118*, 01207. https://doi.org/10.1088/1755-1315/118/1/012071

Ayodele, O. F., Ayodele, B. V., Mustapa, S. I. & Fernando, Y. (2021). Effect of activation function in modeling the nexus between carbon tax, CO2 emissions, and gas-fired power plant parameters. *Energy Conversion and Management: X, 12*, 100111. https://doi.org/10.1016/j.ecmx.2021.100111

Ball, P. J. (2020). A review of geothermal technologies and their role in reducing greenhouse gas emissions in the USA. *Journal of Energy Resources Technology, 143*, 010904. https://doi.org/10.1115/1.4048187

Boyd, T. L., Sifford, A. & Lund, J. W. (2015). The United States of America country update 2015. In *World Geothermal Congress 2015*. International Geothermal Association.

Brilian, V. A., Purba, D. P., Adityatama, D. W., Larasati, T., Al Asy'ari, M. R., Erichatama, N., & Caesaria, T. T. (2025). Technical initiatives to develop low-medium temperature geothermal resources in Indonesia: Lessons learned from the United States. *Geoenergy Science and Engineering, 247*, 213720. https://doi.org/10.1016/j.geoen.2025.213720

DGE. (2024). *Technology data for the Indonesian power sector: catalogue for generation and storage of electricity – March 2024,* Directorate General of Electricity (DGE) of the Ministry of Energy and Mineral Resources.

Dobson, P., Gasperikova, E., Zhang, Y., Mosey, G., Kolker, A., Liu, X., & Polsky, Y. (2023). U.S. DOE clean energy demonstration program on current and former mine land – A review of geothermal energy case studies and opportunities. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

Fiscor, S. (2022). Activity abounds among Nevada's miners. *Engineering and Mining Journal, 223*(8), 36–41.

Forson, C. (2014). Prospecting for a Blind Geothermal System Utilizing Geologic and Geophysical Data, Seven Troughs Range, Northwestern Nevada. *University of Nevada, Reno ProQuest Dissertations & Theses,* Volume 1573203.

Hidayat, R., Simatupang, C. H., Lubis, M. R. S., Setiawan, J., Siagian, H., & Pasikki, R. G. (2021). The characteristic of 320˚C geothermal wells at Sorik Marapi geothermal field. *Proceedings of the Indonesian Geothermal Association Annual Scientific Meeting*.

Hoang, T. A. (2022). Chapter 2 - Mechanisms of scale formation and inhibition. *In Water-formed deposits fundamentals and mitigation strategies* (pp. 13–47). Elsevier.

Husna, U. Z., Elraies, K. A., Shuhili, J. A. B. M. & Elryes, A. A. (2022). A review: the utilization potency of biopolymer as an eco-friendly scale inhibitors. *Journal of Petroleum Exploration and Production Technology, 12*, 1075–1094.

Huttrer, G. W. (2021). *Geothermal Power Generation in the World 2015-2020 Update Report.* In *World Geothermal Congress 2020+1* (pp. 1–17). International Geothermal Association.

IESR. (2023). *Making Energy Transition Succeed: A 2023's Update on The Levelized Cost of Electricity and Levelized Cost of Storage in Indonesia.* Institute for Essential Services Reform (IESR).

Igogo, T., Awuah-Offei, K., Newman, A., Lowder, T., & Engel-Cox, J. (2021). Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches. *Applied Energy, 300*, 117375. https://doi.org/10.1016/j.apenergy.2021.117375

Jarrahian, K., Mackay, E., Singleton, M., Mohammadi, S., Heath, S. M., & Pessu, F. (2025). Scale control in geothermal wells—What are the options for effective and economic scale management? *SPE Journal,* 30(04), 2171–2189.

Kabeyi, M. J. B. (2019). Geothermal Electricity Generation, Challenges, Opportunities and Recommendations. *International Journal of Advances in Scientific Research and Engineering, 5*(8), 53–95.

Kencana, A. Y., Elfina, J. S. A., Fajri, R. J., Supijo, M. C., & Nurpratama, M. I. (2024). Initial State Fluid Geochemistry of the Dieng Geothermal Field, Indonesia: New Constraints for Conceptual Model. In *Proceedings of the 49th Workshop on Geothermal Reservoir Engineering*.

Li, J., McFarlane, A., Klauber, C. & Smith, P. (2017). 3 - Leaching and Solution Chemistry. In M. Gräfe, C. Klauber, A. McFarlane, & D. J. Robinson (Eds.), *Clays in the minerals processing value chain* (pp. 111–141). Cambridge University Press.

Longval, R., Meirbekova, R., Fisher, J. & Maignot, A. (2024). An Overview of Silica Scaling Reduction Technologies in the Geothermal Market. *Energies, 17*(19). https://doi.org/10.3390/en17194825

Marashli, A., Gasaymeh, A.-M. & Shalby, M. (2022). Comparing the global warming impact from wind, solar energy, and other electricity generating systems through life cycle assessment methods (A survey). *International Journal of Renewable Energy Research, 12*(2).

Melaku, M., (2005). Geothermal development at Lihir – An overview. In *Proceedings, World Geothermal Congress 2005*. International Geothermal Association.

NBMG. (2014). Site description: Rye Patch Reservoir. Nevada Bureau of Mines and Geology (NBMG).

NREL. (2022). *Mining G.O.L.D. (Geothermal Opportunities Leveraged Through Data): Exploring Synergies Between the Geothermal and Mining Industries.* National Renewable Energy Laboratory (NREL).

Nugraha, Y. A. & Hidayat, R. (2021). *Success Story of Scaling Silica Treatment in Brine ORC (Study Case Sorik Marapi Geothermal Field).* Jakarta, Indonesian Geothermal Association.

Ordonez, J. A., Fritz, M. & Eckstein, J. (2022). Coal vs. renewables: Least-cost optimization of the Indonesian power sector. *Energy for Sustainable Development, 68*, 350-363.

Pambudi, N. A., Firdaus, R. A., Rizkiana, R., Ulfa, D. K., Salsabila, M. S., Suharno, & Sukatiman. (2023). Renewable energy in Indonesia: Current status, potential, and future development. *Sustainability, 15*(3), 2342. https://doi.org/10.3390/su15032342

Patsa, E., Zyl, D. V., Zarrouk, S. J. & Arianpoo, N. (2015). Geothermal Energy in Mining Developments: Synergies and Opportunities Throughout a Mine's Operational Life Cycle. In *World Geothermal Congress 2015*. International Geothermal Association.

Pongtuluran, S. A., Larasati, T., Fadhillah, F. R., Adityatama, D., Mustika, A. I., & Shalihin, M. G. J. (2024). Assessing the Impact of Carbon Trading to Indonesia Geothermal Project Economic. Stanford University.

Ponyalou, O. L., Petterson, M. G. & Espi, J. O. (2023a). The geological and tectonic evolution of Feni, Papua New Guinea. *Geosciences, 13*(9), 257. https://doi.org/10.3390/geosciences13090257

Ponyalou, O. L., Petterson, M. G. & Espi, J. O. (2023b). The petrology and geochemistry of REE-enriched, alkaline volcanic rocks of Ambitle Island, Feni Island Group, Papua New Guinea. *Geosciences, 13*(11), 339. https://doi.org/10.3390/geosciences13110339

Ryanta, A., Saputra, M. N. W., Senduk, M., Anggoro, D., & Husodo, I. (2022). Successful installation of Indonesia's first dual electric submersible pump system for dewatering applications. IMWA 2022-"Reconnect.

Sagel, V. N., Rouwenhorst, K. H. R. & Faria, J. A. (2022). Green ammonia enables sustainable energy production in small island developing states: A case study on the island of Curaçao. *Renewable and Sustainable Energy Reviews, 161*, 112381. https://doi.org/10.1016/j.rser.2022.112381

Sanyal, S. K. (2005). Classification of geothermal systems - A possible scheme. Stanford University.

STM. (2024) STM Terima Surat Keputusan Pemenang Lelang Terbatas WKP Hu'u. Sumbawa Timur Mining (STM). https://sumbawatimurmining.com/id/stm-terima-surat-keputusan-pemenang-lelang-terbatas-wkp-huu-daha/

Stevens, L. (2017). *The Footprint of Energy: Land Use of U.S. Electricity Production.* Strata.

Su, Z., Zhang, M., Xu, P., Zhao, Z., Wang, Z., Huang, H., & Ouyang, T. (2021). Opportunities and strategies for multigrade waste heat utilization in various industries: A recent review. *Energy Conversion and Management, 229*, 113769. https://doi.org/10.1016/j.enconman.2020.113769

Sykora, S., Selley, D., Cooke, D. R. & Harris, A. C. (2018). The structure and significance of anhydrite-bearing vein arrays, Lienetz Orebody, Lihir Gold Deposit, Papua New Guinea. *Economic Geology, 113*(1), 237–270.

Yao, Y., Xu, J.-H. & Sun, D.-Q. (2021). Untangling global levelised cost of electricity based on multi-factor learning curve for renewable energy: Wind, solar, geothermal, hydropower and bioenergy. *Journal of Cleaner Production, 288,* 123827.