JIMESE
Journal of Innovation Materials, Energy, and Sustainable Engineering
JIMESE 3(1): 40–57
ISSN 3025-0307

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Optimizing geothermal brine for balneological use: An integrated study of health, engineering, social, and economic dimesion

Naufal Fabianito Assariy[1,*], Arief Putra Pratama[1]
[1] *Department of Mechanical and Indutrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Sleman, Special Region of Yogyakarta, 55281, Indonesia.*
*Correspondence: naufalfabianitoassariy@mail.ugm.ac.id

Received Date: July 17, 2025 Revised Date: July 29, 2025 Accepted Date: July 30, 2025

ABSTRACT
Backgorund: Central Java has the only high-enthalpy Geothermal Power Plant complex located in Dieng. The geothermal reservoir stretches across Sileri in the northwest, Sikidang, and Pakuwaja in the southeast. The Dieng area possesses tremendous geothermal energy potential, However, only 10.3% or around 60 MW of its potential is utilized. At the moment, there is still a resource that has not been utilized, namely waste heat. Waste heat appears in the form of liquid-phase hydrothermal (brine) with a pH range of 6-7 and a temperature value of 180°C. The energy from the brine has the potential to be a source of water heating in hot spring facilities (balneology) with the help of heat exchanger technology. **Methods:** This study utilized a treatment process for geothermal brine involving coagulation with Poly Aluminum Chloride (PAC) at a concentration of 10 ppm and a pH adjustment to 8, combined with 1 ppm Polyamide flocculant. Then, the neutralized brine is used in the heat exchange system for balneology. The enthalpy of the geothermal working fluid is transferred to the heat pump working fluid (refrigerant) through the heat exchanger coil, causing the refrigerant to vaporize. Afterward, the refrigerant vapor is compressed to increase pressure and temperature. This high-temperature refrigerant is passed through the condenser pipe to warm the water in the balneology. **Results:** As a result, the hot water from the heat exchange process has a temperature of less than 40°C and can be for hot baths. Hot baths can have physiological effects on the human body by inducing significant improvements in macro and microvascular functions. The habit of taking a hot bath has a good impact on health, giving adequate sleep quality, lowering stress levels, and increasing happiness. The scheme of utilizing brine for balneological facilities can also enrich the tourism aspect of Dieng, open doors to economic activity, and improve social standards for the surrounding community. **Conclusion:** Utilizing waste heat from geothermal brine through treatment with PAC and polyamide flocculant for balneological hot springs is a promising method for harnessing geothermal energy while addressing crustal issues. This approach provides health benefits, supports tourism development, and opens up economic opportunities that improve community well-being. **Novelty/Originality of this article:** This method integrates geothermal energy utilization with health and tourism benefits, offering a multidisciplinary contribution to sustainable socio-economic development in geothermal areas.

KEYWORDS: balneology; geothermal; health; tourism.

1. Introduction

Tourism is one of the sectors that affect the development and increase of a country's income. Tourism is one of the world's most significant and fastest-growing economic sectors (Yakup, 2019). Dieng Plateau is a highland tourism area in Central Java located in Banjarnegara Regency and Wonosobo Regency, which is one of the leading tourist areas that has attractions offered in the form of natural and artificial tourism (Priyanto, 2016). The

Cite This Article:
Assariy, N. F., & Pratama, A. P. (2025). Optimizing geothermal brine for balneological use: An integrated study of health, engineering, social, and economic dimesion. *Journal of Innovation Materials, Energy, and Sustainable Engineering, 3*(1), 40-57. https://doi.org/10.61511/jimese.v3i1.2025.2108

development of the tourism industry in this area is increasing, it can be seen from the increase in tourist attractions, in addition to natural tourism there is also artificial tourism or culinary tourism. Tourism is one of the sectors that affect the development and increase of a country's income. Tourism is one of the world's most significant and fastest-growing economic sectors (Yakup, 2019). Dieng Plateau is a highland tourism area in Central Java located in Banjarnegara Regency and Wonosobo Regency, which is one of the leading tourist areas that has attractions offered in the form of natural and artificial tourism (Priyanto, 2016). The development of the tourism industry in this area is increasing, it can be seen from the increase in tourist attractions, in addition to natural tourism there is also artificial tourism or culinary tourism. Tourism is one of the sectors that affect the development and increase of a country's income. Tourism is one of the world's most significant and fastest-growing economic sectors (Yakup, 2019).

Dieng Plateau is a highland tourism area in Central Java located in Banjarnegara Regency and Wonosobo Regency, which is one of the leading tourist areas that has attractions offered in the form of natural and artificial tourism (Priyanto, 2016). The development of the tourism industry in this area is increasing, it can be seen from the increase in tourist attractions, in addition to natural tourism there is also artificial tourism or culinary tourism that can be seen from Figure 1.

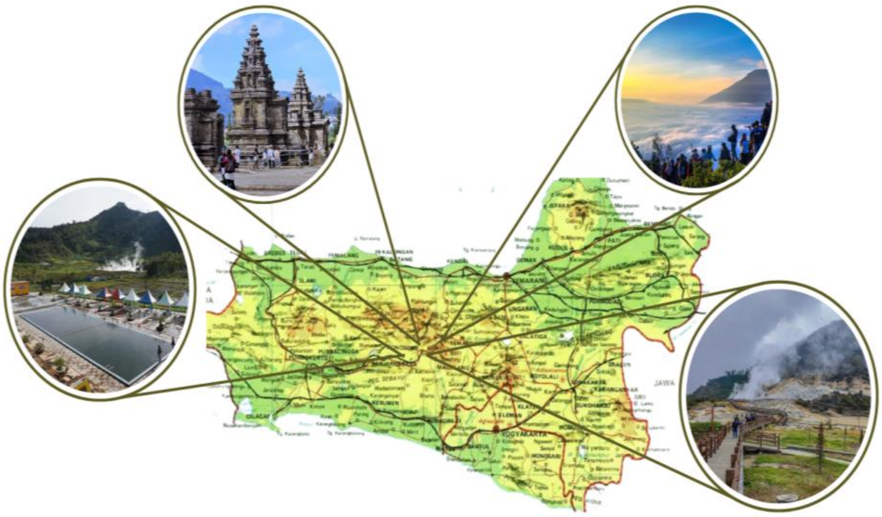

Fig 1. Dieng tourism region

Hot springs or balneology is one type of tourism offered by Dieng. Currently, several places serve hot spring tourism in Dieng, including D'Qiano Hot Spring Waterpark, Toyabira, Sendang Sipandu, and Segar Asri (Aristyan, 2023). These hot springs come from the direct utilization of hot springs located around the tour, due to geothermal activity that occurs in the area. Dieng is an active volcanic area, whose heat from within the earth heats groundwater which then comes to the surface as hot springs. Direct utilization has the challenge that filtration needs to be done first so that the hot water used is safe and free from harmful substances (Herlambang, 2022). The location of hot springs is also influenced by geological factors, which are not available everywhere.

In addition, the Dieng area has great geothermal energy potential, although until now it has only been utilized by 10.3% of its total reserves or around 60 MW of the total geothermal energy potential of 580 MW in the region (Nurrochim, 2021). Currently, the Dieng geothermal field is managed by PT Geo Dipa Energi (Persero) which was established in 2002 to manage the assets of Himpurna California Energy Ltd (consisting of 1 unit of 55 MW geothermal power plant certified in 1998 and 27 wells) which were taken over by the government (Mazaya & Kurniawan, 2022). The Dieng geothermal field consists of 5 areas namely Sikidang area, Sileri area, Siglagah area, Sipandu area, and Bitingan area as can be seen in Figure 2. The Sikidang area manifestation has an estimated temperature of 90°C with a pH of 2-3, the Sileri area has an estimated temperature of 80°C with a pH of 6, the

Siglagah area has an estimated temperature of 70°C with a pH of 6-7, the Sipandu area has an estimated temperature of 80°C with a pH of 6-7, and the Bitingan area has an estimated temperature of 65°C with a pH of 6-7. In addition, Dieng geothermal also releases waste heat which is channeled through the separator outlet in the form of brine (Wisnu et al., 2020).

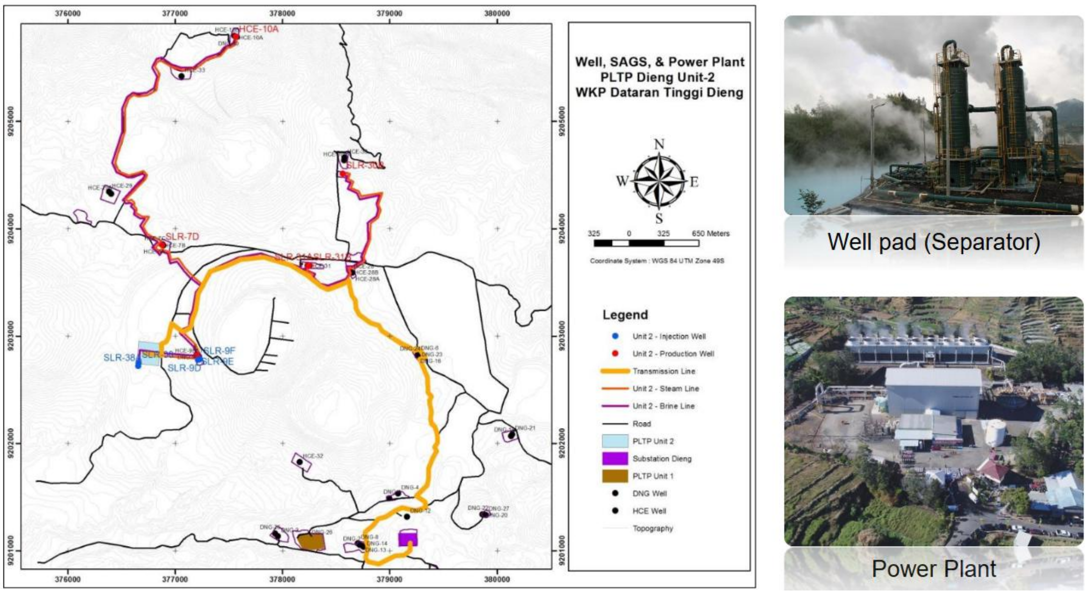

Fig 2. Location of Dieng geothermal field
(Wisnu et al., 2020)

1.1 Trends in balneology usage

Balneology refers to the use of geothermal water for bathing and therapy. It is a long-established tradition that has existed for thousands of years. The Romans were perhaps the first to practice balneology as they already differentiated bathing for leisure and establishments for healing purposes (balneology). In Xiaotangshan Sanitarium, China, balneology has existed as a means of muscular and skeletal therapy for more than five centuries (Saptadji, 2019). Balneology presents in many forms as depicted below.

Fig 3. (a) Balneology for open-communal bathing, (b). Balneology as mud-bathing, (c) Balneo-based spa (balneology association of North America)

Most balneology presents in the form of open-communal bathing and, on some occasions, is developed for spas. Mud/peat therapy commonly exists when geothermal water can mix with volcanic mud, creating a healing and mineral-rich source of balneotherapy (Smith & Puczkó, 2016). The Czech Republic classifies balneology as a central branch of rehabilitative treatment combined with a certain health regimen. Some other countries even include balneotherapy as an insurance-covered health service. However, there has been a shift in the intention of balneology site visitation due to the growing rate of tourism. In Hungary, the locals visit balneology sites for health and medical purposes. On the other hand, international tourists strive to visit the sites for pleasure and satisfaction. Germany, a place with strong-cultured balneology spas, has also changed the labeling of "spa for health" to "spa for wellness". In Indonesia, a glimpse of balneology can be seen in the picture below.

Balneology may present as a medium to gain public acceptance of geothermal energy in Indonesia. Promoting a friendly and economically interesting way for the community to utilize the potential of geothermal energy (Shoedarto et al., 2016).

Fig 4. (a) Communal bathing in Dieng, (b) Balneology-base waterpar
(Shoedarto et al., 2016)

1.2 Balneology in terms of health

The role of balneotherapy as a geothermal bathing area has various benefits to human health, especially for interconnected immune and psychological responses. The effects of hot baths on immunity are directly anti-inflammatory and immunosuppressive at the cellular level. In patients with induced atopic dermatitis, serum levels of pro-inflammatory cytokines such as IL-1β, IL-13 and TNF-α decreased significantly after treatment with high concentrations of spring water. Treated patients also experienced modulation of inflammatory cytokines through an increase in anti-inflammatory IGF-1, while serum levels of pro-inflammatory cytokines TNF-α and IL-1β decreased. Patients with rheumatic diseases experienced reduced concentrations of prostaglandin E2 and leukotriene B4, and C-reactive protein after balneotherapy. Sulfur-containing hot baths can increase the level of Foxp3+ Treg cells that play a role in immunosuppressive activity. In addition, balneotherapy gives a positive influence to the oxidant/antioxidant system by reducing the production of reactive oxygen (ROS) and nitrogen which then impacts immunosuppressive activity (Maccarone et al., 2020).

Balneotherapy using iron-rich hot water and sulfuric acid chloride is ideal at 38–40°C, especially for cardiovascular responses. The correlation between balneotherapy and the ideal temperature is closely related to the difference in the body's response during hot and cold seasons. Balneotherapy in summer is only needed for a short time so as not to increase heart pressure excessively, while in winter balneotherapy activities need to be considered for duration to prevent a significant decrease in blood pressure (Wang et al., 2023).

The physiological effects on cardiovascular health were proven through case study-based research on 98 patients with musculoskeletal diseases. The treatment given was physiotherapy referral with balneotherapy. The results of the application of the method showed that diastolic pressure decreased and pulse rate increased, leading to good changes such as decreased pulse pressure and cardiac stress, and increased vascular elasticity (Şaş et al., 2016). Thus, balneotherapy has the potential to reduce cardiac workload and increase vasodilation. However, the application of this therapy still requires attention to the risks that may be posed to certain body conditions. Individuals with potential chronic cardiovascular and lung diseases are recommended to perform balneotherapy in 1 cycle under 20 minutes (Wang et al., 2023).

1.3 Fluid characteristics in geothermal

The production fluids in the Dieng geothermal field are different from those in other geothermal fields in Indonesia. In addition to mostly being water, the fluids in Dieng have a high concentration of silica, about ± 900 mg/L. The Dieng Geothermal Reservoir has an installed capacity of 60 MW, divided into the Sileri and Sikidang areas (Wahyudityo et al., 2013). The Sileri area has neutral fluids, although there is a chance for magmatic fluids to mix in. Neutralization happens due to strong water-rock interactions within the reservoir. Temperatures here range from 283–338°C, with a chloride content of 69.22 mg/L. The fluid source is rainwater that has been heated, mixed with degassed magmatic fluids, boiled, and interacted with sedimentary or meta-sedimentary rocks (Kencana et al., 2024). The Sileri reservoir is characterized by high chloride content and a boron concentration of 3.84 mg/L, indicating interaction with sedimentary rock formations. Additionally, this reservoir has SiO_2 and Fe concentrations of 41.09 mg/L and 0.12 mg/L, respectively. Other mineral contents include K at 21.3 mg/L, Ca at 13.69 mg/L, and Mg at 58.97 mg/L (Ramadhan et al., 2013). Hydrothermal fluids in the Sileri reservoir move vertically to the upflow zones in Pagerkandang Crater and Merdada Crater. The Sileri area also has a steam cap zone, characterized by excess enthalpy, high non-condensable gas (NCG) content, and The Sikidang area has more acidic fluids with a pH of 3.88, influenced by the dominance of magmatic fluids. This reservoir has two phases, with most wells reaching the steam cap zone and some wells reaching the liquid zone. A boiling zone is estimated between the liquid and steam reservoirs. Fluid temperatures in this reservoir range from 260-324°C, with high non-condensable gas (NCG) content, between 2-21%. Fluid flow in the Sikidang area comes from upflow zones around Pangonan Crater, Sikidang, and Sibanteng manifestations. These upflow zones are linked to acidic fluid zones, indicating potential acidic fluids deep within the reservoir (Kencana et al., 2024). The Sikidang reservoir has lower chloride and boron contents compared to the Sileri reservoir, with concentrations of 27.48 mg/L and 0.69 mg/L, respectively. Additionally, this reservoir contains SiO_2 at 58.68 mg/L, Fe at 11.44 mg/L, K at 51.6 mg/L, Ca at 43.5 mg/L, and Mg at 58.94 mg/L (Ramadhan et al., 2013).

2. Methods

The balneological process begins with the identification and utilization of mineral or hot water sources that have therapeutic potential. Once the source is found, the next stage is water extraction and processing. This process involves a series of methods to purify and optimize the mineral content of water, thereby maximizing its therapeutic benefits (Gianfaldoni et al., 2017). The treated water then enters the storage and distribution phases. This stage is crucial to ensuring water quality is maintained and consistently available for various therapeutic applications.

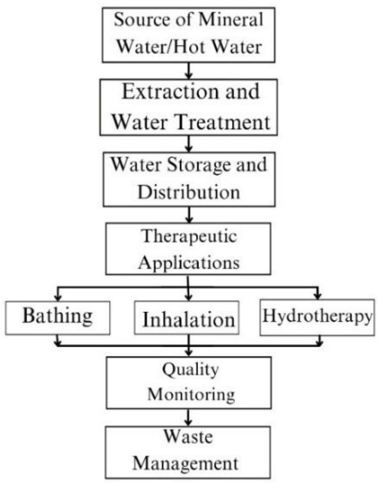

Fig. 5. Balneology scheme

The therapeutic application of mineral water or hot water is divided into three main methods: soaking, inhalation, and hydrotherapy. Soaking involves immersing the body in mineral water, allowing the absorption of minerals through the skin, and providing a relaxing effect (Nasermoaddeli & Kagamimori, 2005). Inhalation uses mineral water vapor for respiratory therapy, potentially treating respiratory tract problems. Hydrotherapy includes a variety of techniques for using water for healing, including pressurized water massage and temperature contrast therapy. Each of these methods is designed to optimize the therapeutic benefits of mineral water, tailored to the specific needs of the patient or user.

After therapeutic application, the balneological process continues with two important stages, namely quality monitoring and waste management. Quality monitoring is a vital step to ensure the consistent effectiveness and safety of the use of mineral water in therapy. This includes regular testing of mineral composition, pH, and other water quality parameters. The final stage, waste management, is a sustainable aspect of balneology. This process involves treating used water to minimize its environmental impact, including recycling or safe disposal. Thus, the balneological cycle not only focuses on health benefits but also pays attention to aspects of environmental sustainability, creating a holistic approach to the use of mineral water resources for health (Gutenbrunner et al., 2010).

This research uses a descriptive research approach to provide an actual picture of the geothermal conditions, potentials, and challenges that will be researched and planned. According to Faridi et al. (2021) Descriptive research is research that aims to describe existing phenomena, namely natural phenomena or man-made phenomena, or which is used to analyze or describe the results of a subject, but is not intended to provide broader implications. The methods used in the preparation of this scientific work are literature studies from books, journals, and relevant articles.

3. Results and Discussion

3.1 Brine waste processing

The process of flowing hot water from geothermal production wells to balneological facilities is carried out using pipes. The pipes used must be strong against corrosion, high pressure and temperature, and salinity. According to Nogara & Zarrouk (2018), several types of materials help prevent corrosion, such as carbon steel, stainless steel, and other corrosion-resistant alloys (CRA) which contain iron, nickel, chromium, and molybdenum in varying amounts. The salinity of geothermal hot water is very high which causes scaling to occur. Scaling in pipes occurs due to the formation of deposits which can hinder the water distribution process, besides that scaling reduces thermal conductivity and all heat transfer coefficients (Baba & Ármannsson, 2006). The common scaling is amorphous silica scale (SiO_2) (Agustinus et al., 2018). Figure 6 is an example of an image of scaling occurring.

Fig 6. Amorphous Silica Scale on Re-injection Pipes
(PT. Geodipa Energi, 2009)

It is necessary to prevent scaling from occurring in order to reduce obstacles to the hot water flow process. There are 3 methods studied to prevent scaling in pipes, below is an explanation of each method.

3.1.1 PAC (Poly Aluminium Chloride)

Research from Syafri & Rosana (2018) on preventive techniques to minimize scaling in the Dieng geothermal area using PAC (Poly Aluminum Chloride) coagulant is considered effective. The optimum dose required is a PAC concentration of 10 ppm, pH conditions of 8, and the addition of a Polyamide flocculant concentration of 1 ppm. Mixing or stirring treatment can increase the effectiveness of preventing scaling because the added coagulants and flocculants can be homogeneous so they work optimally. Flocculant is polyelectrolyte such as Polyamide compounds which serves to accelerate the larger formation of the floc core. The floc-floc density becomes greater than the density of water so that the floc-floc will form a precipitate sludge. This method can be seen in Figure 7.

Fig 7. Comparison of the effectiveness of coagulant types on precipitation (Agustinus et al., 2018)

To maximize efficiency, a geothermal heat pump with a Coefficient of Performance (COP) of 4 is employed, amplifying the heat output to 16.4 MW. This system not only enhances energy utilization but also minimizes operational costs. However, the high mineral content in the brine poses a risk of scaling and corrosion in pipelines. To mitigate this, Poly Aluminium Chloride (PAC) is introduced at a dosage of 10 ppm, requiring 8.64 kg per day to maintain system integrity and prolong infrastructure lifespan.

3.1.2 pH modification

Concentrated H_2SO_4 is injected into the brine in Hatchobaru, Japan, and at pH 5-6, the silica scaling rate was reduced significantly (Kiyota & Uchiyama, 2011). Because most geothermal liquids have extremely large buffer capacity, even for a small decrease, a large amount of acid is required (Topçu et al., 2019). For the mitigation of amorphous silica and metal silicates, pH modification with concentrated sulphuric acid (H2SO4) has been used in the Mak-Ban (Bulalo, Philippines). To reduce the scaling rate, the pH was modified to slightly lower, but it was difficult to lower the pH in terms of corrosion problems of equipment. Corrosion is a serious issue, particularly in the elbow part of the pipeline, when such inorganic acids are dosed in the system. Apart from that, the hazards of sulfuric acid are also a factor in considering the use of this method.

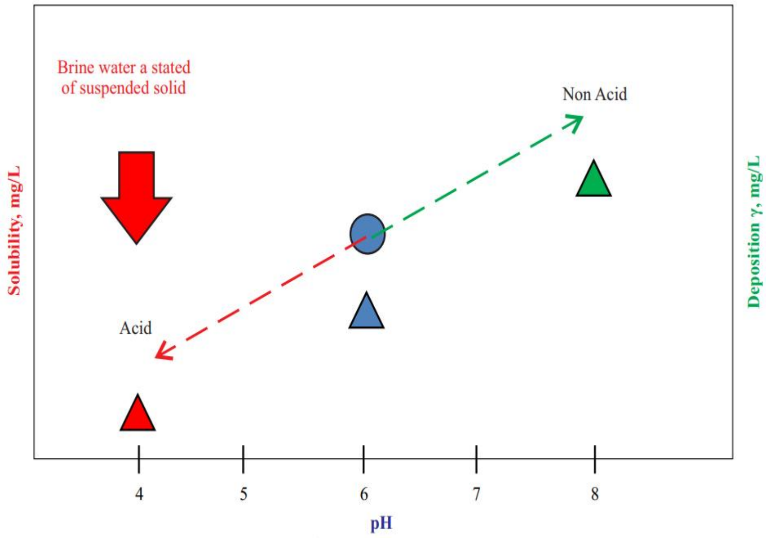

Fig 8. Graph of the Relationship between pH with Solubility and Deposition
(Agustinus et al., 2018)

pH modification system has been adopted as an alternative scale prevention method since 2003. The purpose of this method is to reduce the silica-scaling rate by adjusting brine pH with sulfuric acid. This effect can be seen in Figure 8 and Figure 9.

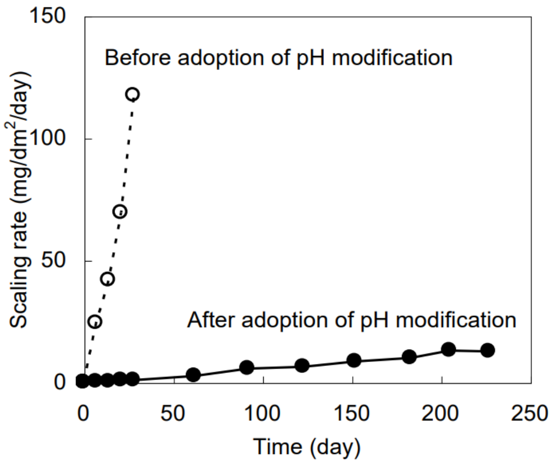

Fig 9. Effect of pH modification on the scaling rate
(Kiyota & Uchiyama, 2011)

3.1.3 *Carbon dioxide (CO_2) Injection*

Moreover, CO_2 injection is another approach to prevent metal silicate scaling. Topçu et al. (2019) injected CO_2 gas into the TGPP with various flow rates, and the results emphasized that 20.6 m^3 /s CO_2 injections showed a better performance than 55 ppm formic acid injection, and less corrosion is observed in CO_2 gas injection (Topçu et al., 2019). In this way, a sustainable route can be achieved in geothermal systems by capturing the released CO_2 from the system and injecting it through the wells. As a new perspective on the pH modification and antiscalant application in geothermal systems, there is a patent application for the usage of CO_2 as an antiscalant (Baba et al., 2020). The need for high capital and complex machine systems are challenges in implementing CO_2 injection. This method can be seen in Figure 10.

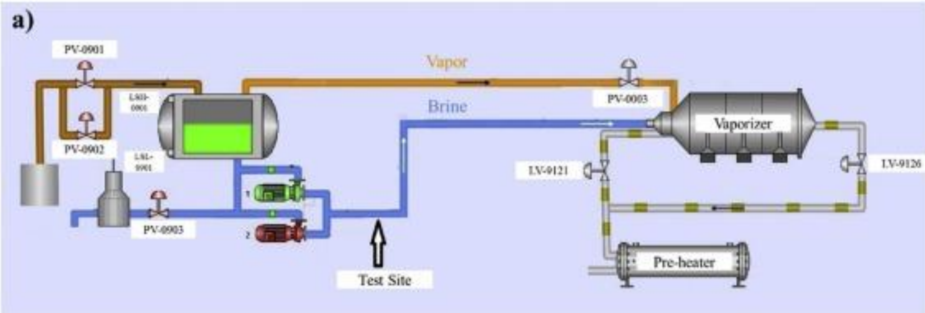

Fig 10. Scheme of the system CO_2 injection
(Topcu et al., 2019)

Each method has its own advantages and disadvantages, so it needs to be considered in terms of economics, sustainability, and level of hazards. Table 1 is a table of comparison levels between parameters and scaling prevention methods.

Table 1. Comparison levels between parameters and scaling prevention methods

Parameter	Methods of scaling prevention		
	PAC	pH Modification	CO_2 Injection
Complexity	Medium	Low	High
Corrosion Tendency	Low	High	Low
Environmental Hazard	Low	High	Low
Investment	Medium	Low	High
Sustainability	Medium	Medium	High

From the three methods, taking into account the existing aspects, the recommended method to use is PAC coagulant, because it is seen from the side effects and costs required. As for the optimum conditions dose required is a PAC concentration of 10 ppm, pH conditions of 8, and the addition of a Polyamide flocculant concentration of 1 ppm.

3.2 Balneology scheme of brine waste

From Figure 11 can be seen that the brine temperature from the separator's outlet in Dieng geothermal reaches 180°C (Wisnu et al., 2020). In this temperature range, Dieng geothermal can be utilized through direct geothermal use, such as space heating or domestic hot water supply, as shown in the Lindal diagram (Chiasson, 2016). Therefore, the geothermal utilization of Dieng can be done by using a Geothermal Heat Pump (GHP) system.

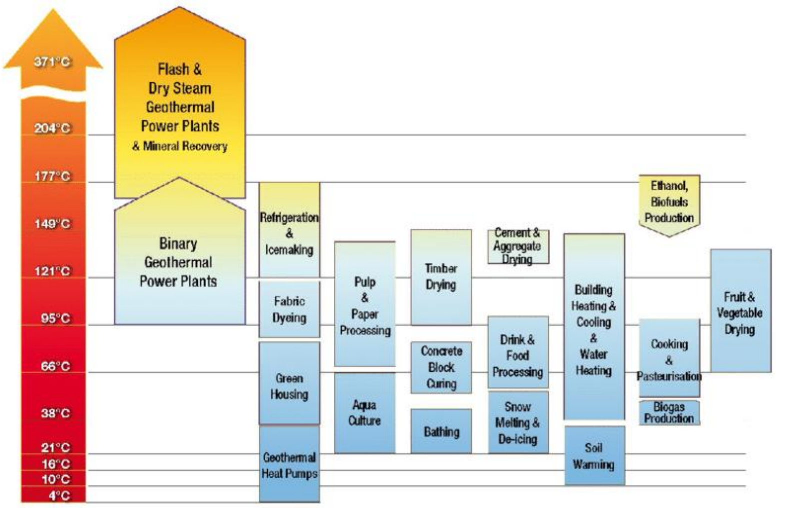

Fig 11. Lindal diagram
(Climo et al., 2015)

 https://doi.org/10.61511/jimese.v3i1.2025.2108

The heat exchange process in the Geothermal Heat Pump starts by transferring enthalpy from the Dieng geothermal working fluid to the heat exchanger working fluid in the evaporator that can bee seen in Figure 12.

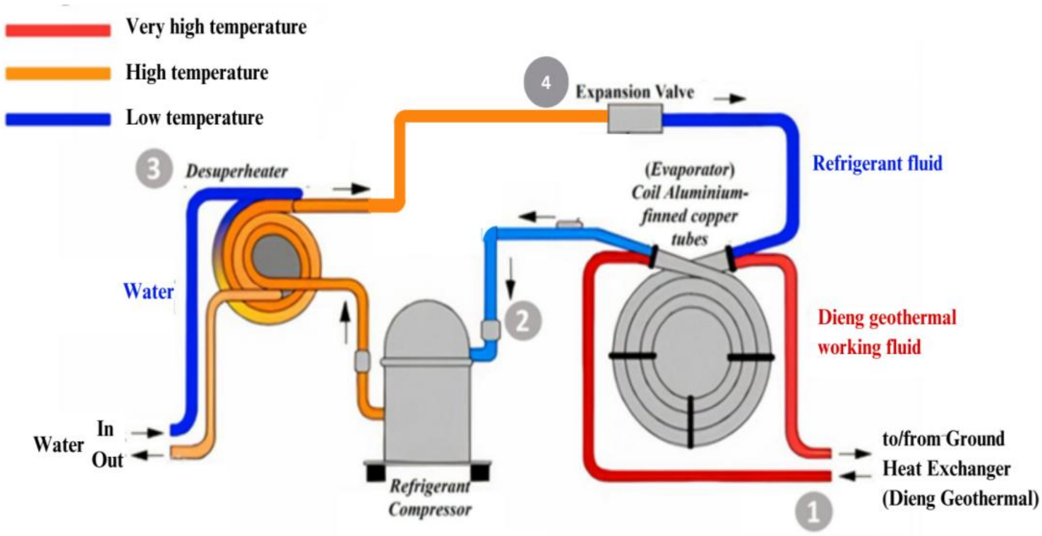

Fig 12. Geothermal heat pump (GHP) system in geothermal Dieng
(Modified from Lund et al., 2004)

The aluminum-finned copper tubes of the refrigerant heat exchanger in Figure 13 act as a medium for heat exchange between the geothermal working fluid and the refrigerant (Chiasson, 2016).

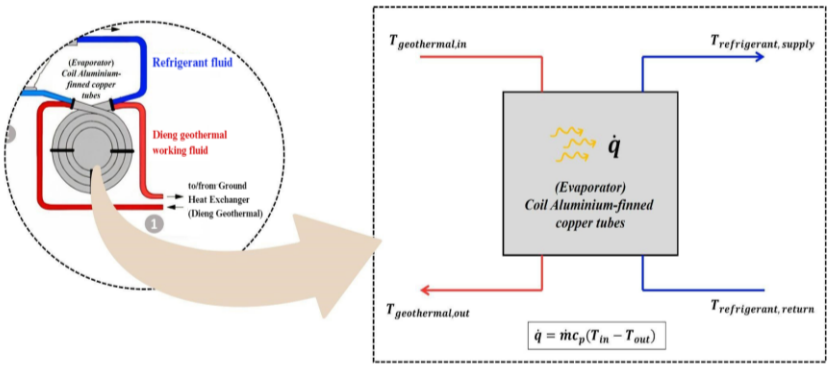

Fig 13. Displacement arrow of aluminum-finned copper tubes coil

Proper refrigerant selection in aluminum-finned copper tube coils is critical to ensure optimal performance and heat exchange efficiency in heat exchangers (Greco et al., 1997). Factors considered in refrigerant selection include thermal efficiency, chemical stability, environmental impact, and safety. Table 2 shows refrigerant that can be used for aluminum-finned copper tube coils.

Table 2. Characteristics of refrigerant types R410A & R407C

Refrigerant Type	Key Properties	Physical Properties	(GWP*)	Source
R410 (R32 and R125 hydrofluorocarbon (HFC) mixtures)	-Non flammable -Non-toxic -Used in home air conditioning systems	-Critical Pressure: 4.92 MPa (713 psi) -Critical Temperature: 72.8 °C (163.0 °F) -Liquid Density: 1.21 kg/L	2.088	Lee et al. (2012)

R407C	-Non flammable -Non-toxic -Used in home air conditioning systems	-Critical Pressure: 4.62 MPa (669 psi) -Critical Temperature: 87.3°C (189.1°F) -Liquid Density : 1.16 kg/L	1.774	Greco et al. (1997)

*GWP (Global Warming Potential) is a number that measures the impact of these gases on global warming compared to CO_2 over a given period.

After the refrigerant working fluid undergoes vaporization in the evaporator, the resulting vapor enters the compressor to be increased in pressure and temperature. The compressor is responsible for increasing the pressure and temperature of the refrigerant to increase the heat exchange efficiency in the condenser. The high temperature of the compressed refrigerant is then flowed to the desuperheater to absorb excess heat from the refrigerant which is in a superheat condition after passing through the compressor (Hengel et al., 2016). Desuperheaters are effectively used as a heat source in domestic hot water supply by transferring excess heat from the refrigerant into domestic water. The hot water produced is around 50.43°C (Chahartaghi et al., 2019), which is utilized for hot springs or balneology.

Next, the refrigerant will enter the expansion valve. Inside the expansion valve, the temperature and pressure of the refrigerant will be lowered significantly. This process causes the refrigerant to experience a drastic drop in temperature and pressure, preparing it to return to the evaporator. After passing through the expansion valve, the refrigerant which is now in its initial low-pressure and low-temperature state, will then enter the evaporator to absorb heat from the geothermal fluid again. This process will continue to repeat in the cycle and this process can be seen in Figure 14.

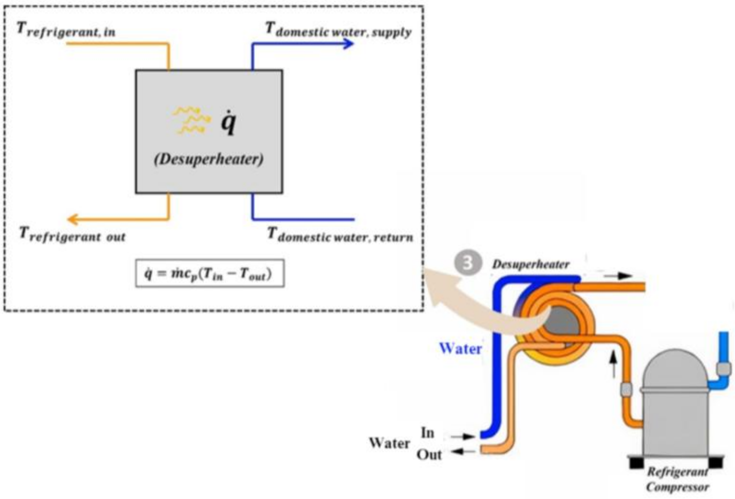

Fig 14. Heat transfer from desuperheater

The development of a balneology facility powered by geothermal brine waste offers a sustainable solution for energy recovery, economic growth, and community development. This analysis examines the project's technical, social, and financial aspects, providing a detailed assessment of its feasibility and long-term viability.

The geothermal brine, discharged at 180°C, contains substantial residual heat that can be harnessed for balneology purposes. With a mass flow rate of 10 kg/s and a specific heat capacity of 4.18 kJ/kg°C, the recoverable thermal energy amounts to 5.85 MW. Factoring in a 70% system efficiency, the usable energy reduces to 4.1 MW, which is sufficient to heat approximately 2,827.7 cubic meters of water daily, raising its temperature from 25°C to 40°C. This capacity ensures a consistent supply of warm water for therapeutic and recreational use.

 https://doi.org/10.61511/jimese.v3i1.2025.2108

3.3 Biological analysis

Warm bath therapy through balneotherapy can cause dilation vessels blood, reducing viscosity blood and reduces tension resulting muscle improve blood circulation, so that can help lower blood pressure. This is also the best way and hassle-free side effects after use so it can be used as an alternative for reducing blood pressure (Fembi et al., 2019). The effects of balneotherapy generally appear as thermal, mechanical or chemical effects. Balneotherapy can be an alternative treatment method for treating health problems such as respiratory, cardiovascular, endocrine and neurological problems (Galvez et al., 2018). The thermal effect produced by the body is in the temperature range of 35-40 degrees Celsius. In this temperature range, blood flow in the body will increase, causing increased blood flow to the heart, lungs and brain (An et al., 2019). Hot water therapy in this temperature range can cause the body's rectal temperature to increase, namely to 38 degrees Celsius, and also cause the pulse rate to increase to 127 ± 18 beats/minute (Brunt et al., 2016).

Balneotherapy, the therapeutic use of warm baths, has been recognized for its potential benefits in improving cardiovascular health, particularly in reducing blood pressure. The mechanism behind this effect involves vasodilation, reduced blood viscosity, and enhanced muscle relaxation, which collectively improve circulation (Fembi et al., 2019). The absence of significant side effects further supports its use as a non-pharmacological intervention for hypertension (Galvez et al., 2018). This analysis explores the physiological effects of balneotherapy, its clinical implications, and its role as an adjunct therapy for cardiovascular and metabolic conditions.

The therapeutic effects of balneotherapy are attributed to thermal, mechanical, and chemical mechanisms. Immersion in warm water (35–40°C) induces peripheral vasodilation, which reduces systemic vascular resistance and enhances blood flow (An et al., 2019). This thermal effect increases cardiac output and circulation to vital organs, including the heart, lungs, and brain, while simultaneously lowering blood pressure (Brunt et al., 2016). The rise in core body temperature (up to 38°C) and elevated heart rate (127 ± 18 bpm) indicate an adaptive cardiovascular response, suggesting improved hemodynamic efficiency (Brunt et al., 2016). Additionally, the reduction in blood viscosity facilitates smoother circulation, decreasing the workload on the heart (Fembi et al., 2019).

Several studies highlight balneotherapy's efficacy in managing hypertension. Fembi et al. (2019) observed significant blood pressure reductions in patients undergoing regular warm bath therapy, attributing the effect to decreased sympathetic nervous activity and enhanced endothelial function. Galvez et al. (2018) further noted that balneotherapy could serve as an alternative treatment for cardiovascular disorders due to its ability to modulate autonomic nervous system activity. The absence of adverse effects makes it particularly suitable for elderly patients or those with medication sensitivities (An et al., 2019).

Unlike pharmacological treatments, balneotherapy presents minimal risks, making it a viable complementary therapy. While antihypertensive drugs may cause side effects such as electrolyte imbalances or fatigue, warm water immersion offers a non-invasive approach with comparable benefits (Galvez et al., 2018). However, its efficacy may vary based on individual factors such as baseline blood pressure, immersion duration, and water temperature. Optimal results are typically observed with consistent therapy sessions in controlled thermal conditions (Brunt et al., 2016).

Beyond cardiovascular benefits, balneotherapy has demonstrated positive effects on endocrine and neurological health. The thermal stress from warm water immersion activates heat shock proteins (HSPs), which play a role in reducing inflammation and improving insulin sensitivity (An et al., 2019). This mechanism suggests potential applications in metabolic syndrome and type 2 diabetes management. Additionally, the relaxation response induced by balneotherapy may alleviate stress-related neurological conditions, including anxiety and mild depression (Galvez et al., 2018).

Despite its advantages, balneotherapy is not universally accessible, and its long-term efficacy requires further investigation. Most studies have short-term follow-ups, necessitating longitudinal research to assess sustained benefits (Fembi et al., 2019).

Additionally, variations in water composition (e.g., mineral-rich vs. plain water) may influence outcomes, warranting comparative studies (An et al., 2019).

3.4 Socio-economic analysis

The application of brine waste in balneology in the Dieng area has complex social impacts, especially given the characteristics of the area as a tourist destination and geothermal site. One of the main problems that arises is the tension between the use of geothermal resources for electricity generation and their potential for balneological development. Local communities that have long relied on tourism as a source of income may feel threatened by changes in the economic landscape brought about by large-scale geothermal projects (Sukhyar et al., 2016). The problem that needs to be resolved concerns the use of brine waste for balneology in order to bridge this gap, create new jobs in the health and tourism sectors, and still utilize the potential of geothermal energy.

Another social aspect that needs to be considered is changes in land use patterns and community access to natural resources. The development of balneological facilities that utilize brine waste changes the dynamics of land ownership and management around geothermal sources. This problem has the potential to cause conflict if not managed well, especially if there is a perception that local communities are marginalized in the development process. A concrete case can be seen in complex negotiations between geothermal companies, regional governments, and local communities regarding land use rights and the sharing of economic benefits from balneological projects.

Social acceptance of geothermal projects is a key factor. Experience in various regions of Indonesia shows that community acceptance of geothermal projects often depends on perceptions regarding the direct benefits that can be felt by local communities (Nugroho, 2019). In Dieng, the integration of balneology in geothermal utilization could be a catalyst for increasing social acceptance. By demonstrating that brine waste can be used to create health and tourism facilities that benefit local communities, geothermal projects have the potential to gain wider support. However, the success of implementing brine waste-based balneology depends on transparent communication, involving the community in decision-making, and implementing a fair and sustainable benefit sharing program. If managed well, the development of brine waste-based balneology in Dieng can become a model for harmonization between the interests of the energy industry, tourism, health, and the aspirations of local communities (Oktavia et al., 2021).

A balneological review from an economic aspect in the Dieng area needs to consider the existence of several operating hot springs, such as D'Qiano Hot Spring Waterpark, Tegalsari, Sendang Sipandu, Legok Munggang, and Segar Asri. These facilities have become an integral part of Dieng's tourism landscape, attracting local visitors as well as tourists from outside the area. The existence of hot springs shows that there is a market being formed for balneological services in the region, which is a positive indicator for the potential development of brine waste-based balneology (Oktavia et al., 2021).

In the context of balneological development using a brine waste system, economic analysis is crucial for assessing the feasibility and sustainability of the project. The initial investment costs to implement a brine waste processing system in balneological facilities can be quite substantial, including water treatment infrastructure, the construction of bathing facilities, and the development of supporting amenities (Lund, 2006). Utilizing brine waste, which is a by-product of geothermal power plants, can produce long-term cost efficiencies compared to conventional hot springs, which require natural hot water sources or artificial heating.

The project’s implementation influences land-use patterns and resource accessibility, potentially leading to conflicts if not managed properly. Local communities must be actively engaged in negotiations regarding land rights and economic benefits to prevent marginalization. Transparent governance and equitable profit-sharing mechanisms are essential to fostering trust and ensuring long-term cooperation.

Environmental sustainability is another critical consideration. The facility must incorporate water conservation strategies to avoid depleting local resources. Additionally, proper treatment of waste brine is necessary to prevent ecological harm. By adopting responsible practices, the project can align with broader environmental goals while supporting regional tourism and wellness industries.

To assess the economic feasibility of this project, several economic indicators need to be considered. Break Even Point (BEP) is achieved within 3-5 years, depending on the scale of investment and level of tourist visits (Shortall et al., 2015). Levelized Cost of Energy (LCOE), to calculate the cost per visitor or per balneology session by considering the total cost over the life of the project divided by the number of visitors served (Yasukawa et al., 2018). The payback period is estimated to be between 5-7 years, considering the existing market potential and added value from the use of brine waste (Lund & Boyd, 2016). The project's internal rate of return (IRR) reaches 15-20%, making it attractive for investors (Lund, 2006). The benefit-cost ratio (BCR) is expected to be greater than 1, around 1.3–1.5, indicating that the economic benefits exceed the costs (Shortall et al., 2015). Based on calculations made by researchers, this project has a payback period of 4.39 years and an internal rate of return (IRR) of 29%, making it attractive to investors. The benefit-cost ratio (BCR) is expected to be greater than 1, at 1.44, indicating that the economic benefits exceed the costs incurred. Assuming a 12% discount rate, the net present value (NPV) is calculated to be IDR 614,013,482.00. The initial capital investment for the facility totals IDR 330,727,333, covering infrastructure, utilities, and amenities. Key expenditures include heat exchangers (IDR 29,844,000), VIP bathing chambers (IDR 18,000,000), and administrative buildings (IDR 51,000,000). Operational costs, such as electricity (IDR 2,461,090/month) and labor (IDR 14,000,000/month), are offset by revenue streams from ticket sales.

The facility generates daily income through two ticket tiers: standard (IDR 8,000) and VIP (IDR 35,000). With an estimated 60 standard and 8 VIP visitors per day, daily revenue reaches IDR 760,000, accumulating to IDR 273,600,000 annually in the first year. Over a nine-year period, revenue growth is projected to reach IDR 674,226,898, driven by increasing visitor numbers and potential expansions.

Financial metrics confirm the project's profitability. The Return on Investment (ROI) stands at 43.78%, while the Benefit-Cost Ratio (B/C) of 1.44 indicates that revenues significantly exceed expenditures. The payback period is achieved in 4.39 years, with a Net Present Value (NPV) of IDR 614,013,482 at an 8% discount rate, underscoring the venture's strong financial foundation.

The application of the brine waste system in balneology in Dieng not only has the potential to create long-term operational cost efficiencies, but the application of the brine waste system in balneology can open up opportunities for product differentiation. Balneological facilities that utilize brine waste can promote themselves as eco-friendly destinations, attracting market segments that care about the environment and health. Through this balneology, economic value will be increased through premium pricing and increased occupancy. In addition, integration with the geothermal energy sector can create economic synergies, where waste processing costs from power plants can be offset by income from balneological facilities. This holistic approach has the potential to create a business model that is more sustainable and resilient to fluctuations in the conventional tourism market (Oktavia et al., 2021).

4. Conclusions

The integration of geothermal heat pump technology with Dieng's geothermal energy source not only provides a clean and efficient solution for hot springs (balneology), but also has the potential to improve the overall health of Dieng communities and tourists and support sustainable tourism growth. With the active involvement of the younger generation in encouraging the utilization of clean and sustainable energy, Dieng can become a pioneer in maintaining a balance between economic growth and environmental preservation. By taking concrete action in utilizing Dieng's geothermal energy as a source of hot springs (balneology), we can realize easy access to clean energy to support sustainable tourism.

Acknowledgement

The authors would like to express their deepest gratitude to PT Geo Dipa Energi (Persero) for providing access to relevant data and valuable insights into the geothermal system in Dieng. Appreciation is also extended to all colleagues and experts who contributed to the improvement of this manuscript through technical suggestions constructive critism, and language editing. The authors acknowledge the support of the academic community at Universitas Gadjah Mada for facilitating literature access and discussion forums related to geothermal and balneology research.

Author Contribution

Each authors is expected to make substantial contributions to the design or design of the work; or to the acquisition, analysis, or interpretation of the data; or to the creation of new software used in the work; or to the drafting or substantive revision of the work; and to the approval of the version submitted (and the version substantially modified by the staff of the journal, which includes the contribution of the author to the work).

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest

The authors declare no conflict of interest.

Open Access

References

Agustinus, E. T. S., Syafri, I., Rosana, M. F., & Zulkarnain, I. (2018). Scale prevention technique to minimized scaling on re-injection pipes in Dieng geothermal field, Central Java Province, Indonesia. *Indonesian Journal on Geoscience*, *5*(2), 129-136. https://doi.org/10.17014/ijog.5.2.129-136

An, J., Lee, I., & Yi, Y. (2019). The thermal effects of water immersion on health outcomes: an integrative review. *International journal of environmental research and public* *health*, *16*(7), 1280. https://doi.org/10.3390/ijerph16071280

Aristyan, A. (2023). *4 Pemandian Air Panas Di Dieng Ini Cocok Untuk Relaksasi Tubuh, Wisatawan Harus Kesini!.* https://www.wonosobozone.com/berita/4679585699/4-pemandian-air-panas-di-dieng-ini-cocok-untuk-relaksasi-tubuh-wisatawan-harus-kesini?page=3

Baba, A., & Ármannsson, H. (2006). Environmental impact of the utilization of geothermal areas. *Energy Sources, Part B*, *1*(3), 267-278. https://doi.org/10.1080/15567240500397943

Baba, A., Demir, M. M., Koç, G., & Avcı, İ. (2020). Geothermal power plant system used as a line inhibitor to prevent the scaling of greenhouse gases emitted from the system. *Patent number: WO2021145839A3*.

Brunt, V. E., Jeckell, A. T., Ely, B. R., Howard, M. J., Thijssen, D. H., & Minson, C. T. (2016). Acute hot water immersion is protective against impaired vascular function following forearm ischemia-reperfusion in young healthy humans. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *311*(6), R1060-R1067. https://doi.org/10.1152/ajpregu.00301.2016

Chahartaghi, M., Kalami, M., Ahmadi, M. H., Kumar, R., & Jilte, R. (2019). Energy and exergy analyses and thermo-economic optimization of geothermal heat pump for domestic water heating. *International Journal of Low-Carbon Technologies*, *14*(2), 108-121. https://doi.org/10.1016/j.renene.2020.06.150

Chiasson, A. D. (2016). *Geothermal heat pump and heat engine systems: Theory and practice*. John Wiley & Sons.

Climo, M., Hall, J., Coyle, F., Seward, A., Bendall, S., Carey, B. & White, B. (2015). *Direct Use: Opportunities and Development Initiatives in New Zealand.* In Proceedings World Geothermal Congress.

Faridi, A., Susilawaty, A., Rahmiati, B. F., Sianturi, E., Adiputra, I. M. S., Budiastutik, I., ... & Hulu, V. T. (2021). *Metodologi penelitian kesehatan.* UIN Mahmud Yunus Batusangkar.

Fembi, P.N., Pora, Y.D., Vianiatiz P & Zale, Z. (2017). Pengaruh terapi mandi air hangat terhadap penurunan tekanan darah pada penderita hipertensi di RW 10 kelurahan waioti kecamatan alok timur kabupaten sikka. *Jurnal Keperawatan dan Kesehatan Masyarakat*, *4*(2), 99-124. https://nusanipa.ac.id/jkkmfikesunipa/index.php/hlj-Unipa/issue/view/1/7.

Galvez, I., Torres-Piles, S., & Ortega-Rincón, E. (2018). Balneotherapy, immune system, and stress response: A hormetic strategy? *International Journal of Molecular Sciences, 19*(6), 1687. https://doi.org/10.3390/ijms19061687

Gianfaldoni, S., Tchernev, G., Wollina, U., Roccia, M. G., Fioranelli, M., Gianfaldoni, R., & Lotti, T. (2017). History of the baths and thermal medicine. *Journal of Medical Sciences*, *5*(4),566-568. https://doi.org/10.3889/oamjms.2017.126

Greco, A., Mastrullo, R., & Palombo, A. (1997). R407C as an alternative to R22 in vapour compression plant: An experimental study. *International journal of energy research*, *21*(12), 1087-1098. https://doi.org/10.1002/(SICI)1099-114X(19971010)21:12%3C1087::AID-ER330%3E3.0.CO;2-Y

Hengel, F., Heinz, A., & Rieberer, R. (2016). Performance analysis of a heat pump with desuperheater for residential buildings using different control and implementation strategies. *Applied Thermal Engineering*, *105*, 256-265. https://doi.org/10.1016/J.APPLTHERMALENG.2016.05.110.

Herlambang, D. (2022). *Pengolahan Air Terkontaminasi Fluida Panas Bumi Untuk Kebutuhan Air Domestik Di Dusun Darum, Desa Candi, Kecamatan Bandungan, Kabupaten Semarang, Provinsi Jawa Tengah.* UPN Veteran Yogyakarta.

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*. https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2024/Kencana.pdf

Kiyota, Y., & Uchiyama, N. (2011). Silica scale prevention effects of brine pH modification at

Hatchobaru power station, Japan. In *Proceedings, International Workshop on Mineral Scaling, Phillippines*.

Lee, H. S., Kim, H. J., Kang, D. G., & Jung, D. (2012). Thermodynamic performance of R32/R152a mixture for water source heat pumps. *Energy*, *40*(1), 100-106. https://doi.org/10.1016/j.energy.2012.02.024

Lund, J. W. (2006). Geothermal spas in the Czech Republic and Slovakia. *GHC Bulletin*, *27*(3), 25-29. http://digitallib.oit.edu/digital/api/collection/geoheat/id/11034/download

Lund, J. W., & Boyd, T. L. (2016). Direct utilization of geothermal energy 2015 worldwide review. *Geothermics, 60*, 66-93. https://doi.org/10.1016/j.geothermics.2015.11.004

Lund, J., Sanner, B., Rybach, L., Curtis, R., & Hellström, G. (2004). Geothermal (ground-source) heat pumps: a world overview. *Geo-Heat Center Quarterly Bulletin*, *25*(3). https://www.diva-portal.org/smash/get/diva2:984734/FULLTEXT01.pdf

Mazaya, A., & Kurniawan, T. (2022). COLLABORATIVE GOVERNANCE PEMANFAATAN ENERGI PANAS BUMI SEBAGAI SUMBER PEMBANGKIT LISTRIK (Studi Kasus Pembangkit Listrik Tenaga Panas Bumi Dieng, Jawa Tengah). *Jurnal Inovasi Penelitian*, *3*(4). https://ejournal.stpmataram.ac.id/JIP/article/view/1949/1512

Nogara, J., & Zarrouk, S. J. (2018). Corrosion in geothermal environment Part 2: Metals and alloys. *Renewable and Sustainable Energy Reviews*, *82*, 1347-1363. https://doi.org/10.1016/j.rser.2017.06.091

Nurrochim, W. F., & Harmoko, U. (2021). Analisa Optimalisasi "Abandoned Well Production" Menggunakan "Downhole Heat Exchanger (DHE)" Sebagai Sumber Energi Baru di Lapangan Panas Bumi Dieng. *Jurnal Energi Baru dan Terbarukan*, *2*(1), 14-26. https://doi.org/10.14710/jebt.2021.10041

Oktavia, J., Mulyani, R., & Supriatna, J. (2021). Sustainable geotourism development in Dieng Plateau: Balancing conservation, community empowerment, and economic benefits. *Journal of Environmental Management, 292,* 112730. https://jurnalpariwisata.iptrisakti.ac.id/index.php/Proceeding/article/download/1264/117/

Priyanto, P., & Safitri, D. (2016). Pengembangan Potensi Desa Wisata Berbasis Budayatinjauan Terhadap Desa Wisata Di Jawa Tengah. *Jurnal Vokasi Indonesia*, *4*(1), 7. https://doi.org/10.7454/jvi.v4i1.53

PT. Geodipa Energi. (2009). *Rencana Pengelolaan Lingkungan dan Rencana Pemantauan Lingkungan (RKL-RPL) Triwulan II, Laporan Pelaksanaan, Dieng, Jawa Tengah.* PT. Geodipa Energi,

Şaş, S., Çelenay, Ş. T., & Kaya, D. Ö. (2016). The effects of balneotherapy on acute, process-related, and cumulative peripheral cardiac responses and pulmonary functions in patients with musculoskeletal disorders. *Turkish Journal of Medical Sciences*, *46*(6), 1700-1706. https://doi.org/10.3906/sag-1505-31

Shoedarto, R. M., Aries, F. R., Irawan, D., Perdana, F., Arisbaya, I., & Indrawan, B. (2016). Raising public acceptance of geothermal utilization through direct application in Indonesia. In *Proc. 41st Stanford Workshop on Geothermal Reservoir Engineering, SGP-TR-209*. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2016/Shoedarto.pdf

Shortall, R., Davidsdottir, B., & Axelsson, G. (2015). Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and sustainable energy reviews*, *44*, 391-406. https://doi.org/10.1016/j.rser.2014.12.020

Sukhyar, R., Priadi, B., & Sudarman, S. (2016). *The development of geothermal energy in Indonesia: An overview of industry status and future growth.* Proceedings World Geothermal Congress.

Topcu, G., Koç, G. A., Baba, A., & Demir, M. M. (2019). The injection of CO_2 to hypersaline geothermal brine: A case study for Tuzla region. *Geothermics*, *80*, 86-91. https://doi.org/10.1016/j.geothermics.2019.02.011

Wahyudityo, R., Harto, A. W., & Suryopratomo, K. (2013). Analisis Scaling Silika pada Pipa Injeksi Brine di Lapangan Panas Bumi Dieng dengan Studi Kasus di PT. Geo Dipa

Energi. *Teknofisika*, *2*(1), 7-14. https://journal.ugm.ac.id/teknofisika/article/view/5813

Wang, P. C., Song, Q. C., Chen, C. Y., & Su, T. C. (2023). Cardiovascular physiological effects of balneotherapy: focused on seasonal differences. *Hypertension Research*, *46*(7), 1650-1661. https://doi.org/10.1038/s41440-023-01248-4

Wisnu, Agung., Marza, Supriadinata., Lory Phil., Shannon Cowlin., (2020). *Geothermal Direct Use in Dieng, Indonesia.* Asian Clean Energy Forum 2020. https://asiacleanenergyforum.adb.org/wp-content/uploads/2020/06/nursanty-banjarnahor-geothermal-direct-use-in-dieng-indonesia.pdf

Yakup, A. P. (2019). *Pengaruh Sektor Pariwisata terhadap Pertumbuhan Ekonomi di Indonesia*. Universitas Airlangga.

Yasukawa, K., Kubota, H., Soma, N., & Noda, T. (2018). Integration of natural and social environment in the implementation of geothermal projects. *Geothermics*, *73*, 111-123. https://doi.org/10.1016/j.geothermics.2017.09.011

Biographies of Authors

Naufal Fabianito Assariy, is a student of Universitas Gadjah Mada, located in Yogyakarta. His academic background is in the field of Mechanical Engineering, with a research focus on Energy Conversion and Heat and Mass Transfer.

- Email: naufalfabianitoassariy@mail.ugm.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Arief Putra Pratama, is a student of Universitas Gadjah Mada, located in Yogyakarta. His academic background is in the field of Mechanical Engineering, with a research focus on Energy Conversion and Heat and Mass Transfer.

- Email: ariefputrapratama2003@mail.ugm.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A