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Study of Environmental Impacts of the Operation of the Geothermal Power Plant

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Abstract

A geothermal power plant is a renewable energy facility that utilizes geothermal energy to generate electricity, typically by using geothermal steam to drive turbines. During operation, geothermal fluid extracted from production wells may be separated into steam and brine using a steam separator, depending on the power plant configuration. This study aimed to review the environmental impacts associated with geothermal power plant operations, particularly those related to geothermal wastewater, steam emissions, noncondensable gases (NCGs), and potential changes in water and air quality. A literature review was conducted by examining relevant books, peer-reviewed journal articles, environmental regulations, and official documents. The findings indicated that geothermal wastewater may contain potentially hazardous constituents, including arsenic, mercury, ammonia, and dissolved sulfide, and may exhibit elevated temperatures. Previous research on the Ulumbu Geothermal Power Plant reported an arsenic concentration of 0.0365 mg/L in geothermal wastewater, which was below the referenced total arsenic regulatory limit of 0.5 mg/L. Furthermore, arsenic concentrations in the Waekokor River, both upstream and downstream of the wastewater discharge point, were reported to be below 0.0002 mg/L. Nevertheless, comprehensive environmental management remains essential because potential environmental risks depend not only on arsenic concentrations but also on wastewater temperature, pH, sulfide, ammonia, mercury, discharge rates, and atmospheric emissions of hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), and ammonia (NH_3). Accordingly, environmental management at the Ulumbu Geothermal Power Plant should prioritize geothermal fluid reinjection, routine monitoring of water and air quality, prevention and detection of pipeline leaks, and the implementation of environmental management measures consistent with environmental impact assessment requirements and applicable environmental quality standards.

INTRODUCTION

According to Law No. 21 of 2014 concerning Geothermal Energy, geothermal energy is defined as a source of thermal energy contained in hot water, steam, rocks, associated minerals, and other gases that are genetically inseparable from a geothermal system. Geothermal energy is a renewable energy resource that plays a significant role in supporting national development, strengthening energy security, and reducing dependence on fossil fuels (Republic of Indonesia, 2014).

Geothermal energy utilization is generally classified into two categories: direct use and indirect use (Aneke & Menkiti, 2016; Islam et al., 2022). Direct applications include space

heating, agricultural product drying, bathing, and various industrial processes, whereas indirect utilization primarily involves electricity generation through geothermal power plants (Ranjit, 2022; Yadav et al., 2024). In geothermal power generation, geothermal fluids are extracted from underground reservoirs through production wells and transported to the surface, where their thermal energy is converted into electrical energy using appropriate power generation technologies (Saptadji, 2018).

A geothermal system typically consists of several interconnected geological components, including a heat source, reservoir rock, geothermal fluids, an impermeable or low-permeability cap rock, and fractures or permeable pathways that facilitate subsurface fluid circulation (Khan et al., 2025). In many hydrothermal geothermal systems, meteoric water infiltrates the subsurface, is heated by geothermal heat sources, and circulates through permeable reservoir formations, where thermal energy is accumulated and subsequently extracted for utilization. The interactions among these components determine the characteristics, productivity, and sustainability of geothermal resources (Saptadji, 2018).

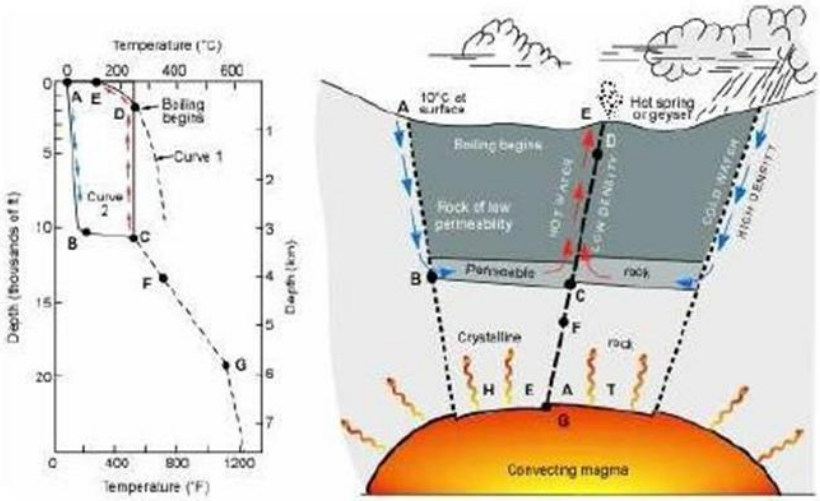


Figure 1. Model of a geothermal system

Source: Saptadji (2018).

In a geothermal power plant, geothermal fluid extracted from production wells may consist of steam, hot water, or a two-phase mixture of steam and water, as illustrated in Figure 1. When the produced fluid consists of a two-phase mixture, the steam and liquid phases are separated using a steam separator. The separated steam is directed to the turbine to generate mechanical energy, which is subsequently converted into electricity by a generator, while the liquid phase, commonly referred to as geothermal brine, is typically directed to the reinjection system. After passing through the turbine, the exhaust steam is condensed into liquid condensate. Where technically feasible, both geothermal brine and condensate are reinjected into the geothermal reservoir to support reservoir pressure maintenance, minimize surface wastewater discharge, and promote the long-term sustainability of geothermal production (DiPippo, 2016; Saptadji, 2018).

Geothermal power plants are generally considered more environmentally sustainable than conventional fossil fuel-based power plants because electricity generation does not require the direct combustion of fossil fuels. According to the U.S. Energy Information Administration, geothermal power plants may release gases such as carbon dioxide (CO_2) and sulfur-containing

compounds, including hydrogen sulfide (H_2S), although their atmospheric emissions are generally lower than those associated with fossil fuel-based electricity generation. Furthermore, many geothermal power plants employ reinjection systems to return geothermal fluids to underground reservoirs, thereby supporting reservoir sustainability and reducing potential environmental impacts associated with wastewater disposal (U.S. Energy Information Administration [EIA], n.d.).

Nevertheless, geothermal power plant operations may generate environmental impacts if geothermal fluids, brine, condensate, and noncondensable gases (NCGs) are not adequately managed. Geothermal fluids may contain dissolved chemical constituents, including arsenic, mercury, sulfide, ammonia, boron, silica, and chloride, depending on the geological and geochemical characteristics of the geothermal reservoir. In addition, geothermal steam may contain NCGs, particularly carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4), and other trace gases. Ammonia (NH_3) may also occur in geothermal fluids and be released into the atmosphere under certain operating conditions. Among these substances, hydrogen sulfide is a major environmental and occupational health concern because of its characteristic odor, toxicity, and potential adverse health effects at elevated exposure concentrations (Barbier, 2002; Kristmannsdóttir & Ármannsson, 2003).

The Ulumbu Geothermal Power Plant is located in Manggarai Regency, East Nusa Tenggara, Indonesia. Its operations may generate atmospheric emissions and liquid effluents that require appropriate environmental management. Potential emission sources include geothermal steam releases and NCG emissions, while liquid waste streams may consist of geothermal brine and condensate that are not returned to the reservoir. According to Yuniarto et al. (2016), wastewater generated by the Ulumbu Geothermal Power Plant originated from geothermal fluids that were not reinjected into the reservoir and were discharged into the Waekokor River. Such discharges require careful environmental assessment because geothermal wastewater may alter the physicochemical characteristics of receiving waters, potentially affecting aquatic ecosystems, water quality, and public health.

Based on these considerations, this study aimed to review the environmental impacts associated with geothermal power plant operations, with particular emphasis on geothermal wastewater, steam releases, NCG emissions, and potential changes in surface water and ambient air quality. The review also examined environmental management strategies, including geothermal fluid reinjection, emission control, wastewater management, and environmental monitoring, to identify measures that could minimize environmental risks and support geothermal electricity generation in accordance with clean energy principles and long-term environmental sustainability.

METHOD

This study employed a descriptive qualitative literature review to examine the environmental impacts of geothermal power plant operations. The review focused on geothermal power generation processes, the physicochemical characteristics of geothermal brine and condensate, wastewater management, noncondensable gas emissions, potential impacts on water and air quality, and environmental management practices.

Relevant literature was obtained from scientific books, peer-reviewed journal articles,

conference proceedings, environmental regulations, and official publications issued by government agencies and international institutions. The assessment of environmental impacts at the Ulumbu Geothermal Power Plant primarily referred to the findings of Yuniarto et al. (2016), particularly regarding geothermal wastewater characteristics and associated environmental risks. Wastewater quality was evaluated with reference to the Regulation of the Minister of Environment No. 08 of 2009 concerning Wastewater Quality Standards for Thermal Power Plant Businesses and/or Activities (Ministry of Environment, 2009).

The review was conducted in four stages. First, geothermal power generation processes associated with potential waste generation were identified, including geothermal fluid extraction, steam–brine separation, turbine operation, condensation, cooling, and fluid management. Second, waste streams were categorized into liquid effluents and atmospheric emissions. Third, potential environmental impacts were evaluated using published findings, secondary environmental data, and applicable regulatory standards. Finally, environmental management measures were identified, emphasizing geothermal fluid reinjection, emission control, water and air quality monitoring, and compliance with environmental management requirements.

No primary field measurements or laboratory analyses were conducted. Consequently, the findings were based entirely on descriptive and qualitative assessments of secondary data, published scientific literature, and relevant environmental regulations.

RESULTS AND DISCUSSION

Separated Steam in Geothermal Power Plant Systems

In a geothermal power plant system using two-phase geothermal fluid, the fluid produced from the wellhead consists of a mixture of steam and hot water. This fluid must be separated before the steam can be used to rotate the turbine. The separation process is carried out by passing the fluid through a separator. Inside the separator, the steam phase is separated from the liquid phase or brine. The separated steam is then directed to the turbine to produce mechanical energy, which is subsequently converted into electrical energy by the generator (DiPippo, 2016; Saptadji, 2018).

This system is known as a separated steam cycle because the steam used to rotate the turbine is obtained through the separation of a two-phase geothermal fluid. The water or brine produced from the separation process should be directed to reinjection wells so that it can be returned to the reservoir. Brine reinjection is important for maintaining reservoir pressure, reducing the risk of production decline, and preventing the disposal of geothermal fluid into the surface environment (Saptadji, 2018).

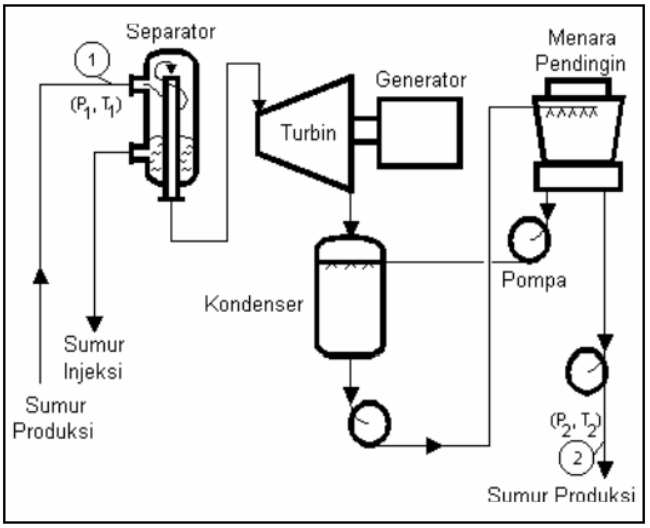


Figure 2. Schematic diagram of a power plant for water-dominated geothermal fluid

Figure 2 illustrates that geothermal fluid from the production well is directed to the separator. After separation, steam flows to the turbine, while water or brine is directed to the reinjection well. After passing through the turbine, the steam enters the condenser and is converted into condensate. The condensate is then directed to the cooling system and may be reinjected into the reservoir.

Brine Fluid in Geothermal Fields

Pipelines in geothermal fields generally consist of steam pipelines, water or brine pipelines, and two-phase flow pipelines. In water-dominated geothermal fields, two-phase pipelines are used to transport the mixture of steam and water from production wells to the separator. After the separation process, steam pipelines transport steam from the separator to the turbine, while brine pipelines transport the separated liquid to reinjection wells. In addition, condensate pipelines are used to transport condensate from the power plant unit to reinjection wells (Saptadji, 2018).

The position of brine in the operation of a geothermal power plant. Brine is the liquid phase produced from the separation of two-phase geothermal fluid in the separator. Steam flows to the turbine, while brine is directed to the reinjection system. If brine is not reinjected and is instead discharged into the environment, it may become geothermal liquid waste.

Brine Fluid

Brine is the liquid phase resulting from the separation of geothermal fluid in a separator. In high-enthalpy geothermal systems, brine temperature can be relatively high, potentially reaching approximately 150°C depending on reservoir characteristics and field operating conditions (Afriandi & Hantoro, 2018). Brine contains various dissolved minerals and chemical constituents because the fluid has been in direct contact with reservoir rocks over a long period.

The chemical composition of brine varies among geothermal fields. These variations are influenced by reservoir temperature, pressure, rock type, fluid residence time in the subsurface, and water-rock interaction processes. Elements and compounds that may be found in brine include chloride, silica, boron, arsenic, mercury, sulfide, and other dissolved constituents (Arnórsson, 2000; Nicholson, 1993). Therefore, brine should not be discharged into the environment without proper treatment or without meeting applicable quality standards.

In an ideal geothermal power plant operation, brine is directed to reinjection wells. Brine reinjection has two main functions. First, reinjection maintains the mass balance and pressure of the reservoir. Second, reinjection prevents the disposal of geothermal fluid into surface water bodies, thereby reducing the risk of environmental pollution (Saptadji, 2018).

Condensate Fluid

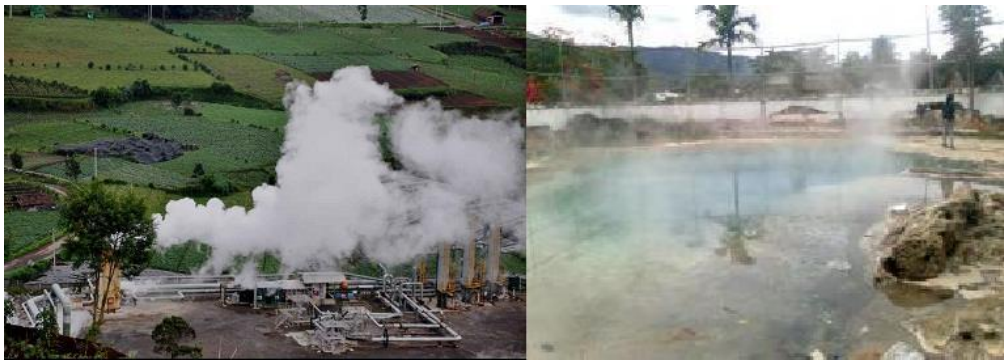
Geothermal condensate is water formed from the condensation of steam after the steam has been used to rotate the turbine. Steam that has passed through the turbine enters the main condenser. In the condenser, the steam is cooled and converted into condensate. The condensate is then directed to the cooling tower to reduce its temperature before being reused in the cooling system or directed to reinjection wells (Saptadji, 2018).

Although the mineral content of condensate is generally lower than that of brine, condensate may still contain dissolved gases or certain chemical components. Therefore, condensate must also be managed properly. If condensate is discharged directly into the environment in large quantities or at high temperatures, it may affect surface water quality and aquatic ecosystems.

Waste in Geothermal Power Plant Operations

Ideally, geothermal power plant operations do not generate liquid waste that is directly discharged into the environment because the fluid used to rotate the turbine should be reinjected into the reservoir. Reinjection is an essential part of geothermal operations because it helps maintain reservoir sustainability and reduces the risk of environmental pollution. The EIA states that most geothermal power plants reinject used steam and water back into the earth to help sustain geothermal resources and reduce environmental impacts (EIA, n.d.).

However, if condensate and brine are not reinjected, they may become liquid waste. Geothermal liquid waste must be carefully managed because it may contain certain chemical constituents and have relatively high temperatures. In the case of the Ulumbu Geothermal Power Plant, the waste generated generally consists of steam waste and liquid waste. Steam waste is released into the atmosphere, while liquid waste has been reported to be discharged into the Waekokor River (Yuniarto et al., 2016).



A B

Figure 3. Geothermal steam waste (A) and geothermal liquid waste (B)

Source: Yuniarto et al. (2016).

Figure 3 shows two forms of waste generated by the Ulumbu Geothermal Power Plant: steam waste and geothermal liquid waste. Steam waste may contain non-condensable gases such as H_2S, CO_2, CH_4, and NH_3. Meanwhile, liquid waste may contain chemical parameters such as dissolved sulfide, ammonia, mercury, arsenic, and physical parameters such as

temperature and pH. These parameters must be controlled so that they do not exceed applicable quality standards.

Wastewater quality standards for thermal power plant activities, including geothermal power plants, are regulated by the Regulation of the Minister of Environment Number 08 of 2009. This regulation establishes several important parameters for produced water and drainage wastewater, including dissolved sulfide, ammonia, total mercury, total arsenic, temperature, pH, oil and grease, and total organic carbon (Ministry of Environment, 2009).

Table 1. Chemical Constituents and Quality Standards for Geothermal Wastewater

Type of Wastewater	Parameter	Maximum Concentration
Produced water	Dissolved sulfide as H_2S	1 mg/L
Produced water	Ammonia as NH_3	10 mg/L
Produced water	Total mercury (Hg)	0.005 mg/L
Produced water	Total arsenic (As)	0.5 mg/L
Produced water	Temperature	45°C
Produced water	pH	6–9
Drainage wastewater	Oil and grease	15 mg/L
Drainage wastewater	Total organic carbon	110 mg/L

Source: Ministry of Environment (2009).

Based on Table 1, geothermal wastewater should not be assessed based on only one parameter. It must be evaluated comprehensively. High temperature may alter the thermal condition of the receiving water body. pH levels that are too low or too high may disturb aquatic organisms. Meanwhile, arsenic, mercury, sulfide, and ammonia may have toxic effects if present at high concentrations.

Sources of Geothermal Waste at the Ulumbu Geothermal Power Plant

Steam waste generated by the Ulumbu Geothermal Power Plant originates from several sources. The first source is steam produced from brine flashing in the atmospheric flash tank or silencer. The second source is residual steam and non-condensable gases from the cooling tower, which are released through the fan. The released steam may contain non-condensable gases such as H_2S, CO_2, CH_4, NH_3, and other gases in varying amounts (Yuniarto et al., 2016).



A B

Figure 4. Steam from the atmospheric flash tank (A) and steam from the cooling tower (B)

Source: Yuniarto et al. (2016).

Figure 4 shows steam sources from the atmospheric flash tank and cooling tower. The atmospheric flash tank or silencer functions to reduce pressure and dampen the release of pressurized fluids or steam. However, if the released gases are not properly controlled, steam emissions may cause odor problems and potential air quality degradation, especially if they

contain hydrogen sulfide at certain concentrations.

Liquid waste from the Ulumbu Geothermal Power Plant also originates from several sources. The first source is condensate resulting from the condensation of geothermal steam that was previously used to rotate the turbine. The second source is water used in the cooling process of the power plant. At the Ulumbu Geothermal Power Plant, cooling water is taken from the Waekokor River. After use, this water may experience changes in temperature or chemical quality if it mixes with geothermal fluids (Yuniarto et al., 2016).



Figure 5. Condensate in the sump

Source: Yuniarto et al. (2016).

Figure 5 shows condensate collected in the sump. This condensate must be properly managed to prevent it from becoming a source of pollution. Management measures may include directing it to the reinjection system, controlling its temperature, and monitoring its chemical quality before any discharge into the environment.

Impacts of Geothermal Wastewater on Water Quality

During the operation of the Ulumbu Geothermal Power Plant, liquid waste that is not reinjected into the reservoir has been reported to be discharged into the Waekokor River. Discharging liquid waste into a water body may alter the chemical composition of river water, particularly when the waste contains high concentrations of chemical parameters or has a temperature that exceeds the assimilative capacity of the environment. One of the elements of concern in geothermal wastewater is arsenic (Yuniarto et al., 2016).

Arsenic is an element that may affect human health when exposure occurs over a long period. Long-term arsenic exposure may cause skin disorders, pigmentation, keratosis, vascular disorders, and an increased risk of certain diseases. Therefore, the presence of arsenic in geothermal wastewater must be regularly monitored (World Health Organization [WHO], 2017).

The examples of geothermal wastewater discharged from a pipe and entering a river environment. Such conditions must be prevented because pipeline leakage or wastewater overflow can increase the risk of environmental pollution. In addition to carrying chemical constituents, geothermal wastewater may also have a high temperature that can disturb aquatic ecosystems.

Yuniarto et al. (2016) reported that the arsenic concentration in the liquid waste of the Ulumbu Geothermal Power Plant was 0.0365 mg/L. This value remains below the total arsenic

quality standard of 0.5 mg/L stipulated in the Regulation of the Minister of Environment Number 08 of 2009. In addition, the arsenic concentration in the Waekokor River before and after wastewater discharge was reported to remain below 0.0002 mg/L. This indicates that, based on the arsenic parameter, wastewater discharge from the Ulumbu Geothermal Power Plant at the time of the study did not significantly increase arsenic concentration in the river (Ministry of Environment, 2009; Yuniarto et al., 2016).

Nevertheless, these findings do not mean that environmental risks can be ignored. The impacts of geothermal wastewater are not determined solely by arsenic, but also by other parameters such as temperature, pH, sulfide, ammonia, mercury, oil and grease, total organic carbon, and wastewater discharge rate. A small wastewater discharge rate may result in greater dilution in the receiving water body, but changes in operating discharge, pipeline damage, sump overflow, or failure of the waste management system may still increase pollution risks.

In addition to the Ulumbu case, other studies have shown that geothermal activities may affect aquatic environments if they are not properly managed. Permana et al. (2015), for example, examined the influence of geothermal activities on fish diversity in the Cikaro River, Bandung Regency. Their study showed that changes in water quality may affect fish composition and distribution because fish are sensitive organisms that respond to environmental changes in aquatic systems. Physical, chemical, and biological factors of water bodies may influence fish diversity and abundance (Permana et al., 2015).

Therefore, water quality monitoring at the Ulumbu Geothermal Power Plant should be carried out regularly at several points: upstream of the discharge point, at the discharge point, and downstream of the discharge point. The monitored parameters should include temperature, pH, arsenic, mercury, dissolved sulfide, ammonia, oil and grease, total organic carbon, and wastewater discharge rate. This monitoring is essential to ensure that plant operations continue to comply with quality standards and do not generate long-term impacts on the Waekokor River.

Impacts of Steam and Non-Condensable Gas Emissions on Air Quality

In addition to liquid waste, geothermal power plant operations may also generate steam waste and non-condensable gas emissions. Non-condensable gases are gases that do not condense under condenser operating conditions. These gases may be carried with geothermal steam from the reservoir and released into the atmosphere through several points, such as atmospheric flash tanks, silencers, cooling towers, and pipeline leaks (Kristmannsdóttir & Ármannsson, 2003).

Non-condensable gases in geothermal systems generally consist of CO_2, H_2S, CH_4, NH_3, nitrogen, and other gases in varying amounts. Among these gases, H_2S is a major concern because it has a strong rotten-egg odor and may cause discomfort as well as health risks when present at high concentrations. At low concentrations, H_2S may cause odor complaints, while at higher concentrations it can affect the respiratory and nervous systems (Kristmannsdóttir & Ármannsson, 2003; WHO, 2017).

Geothermal power plants generally have lower emissions than fossil-fuel power plants. The EIA states that geothermal power plants may release small amounts of sulfur dioxide and carbon dioxide, but their emissions are lower than those of fossil-fuel-based power plants. In addition, geothermal power plants can use scrubbers to remove hydrogen sulfide naturally

present in geothermal reservoirs (EIA, n.d.).

At the Ulumbu Geothermal Power Plant, potential air emissions originate from steam released through the atmospheric flash tank, cooling tower, and possible pipeline leaks. If these gases are not monitored and controlled, they may cause odor problems and reduce air quality around the power plant area. Therefore, the plant operator should regularly monitor H_2S, CO_2, CH_4, NH_3, and other relevant air quality parameters.

Impacts on Soil, Vegetation, and Ecosystems

Geothermal activities may affect not only water and air quality but also soil, vegetation, and surrounding ecosystems. The exploration and development stages of a geothermal field require land clearing for access roads, drilling sites, pipelines, production facilities, and supporting infrastructure. If not properly managed, these activities may cause changes in land cover, erosion, habitat disturbance, and landscape alteration (Glassley, 2015; Shortall et al., 2015).

The extent of ecosystem impact depends on the project location, the area of land cleared, local biodiversity conditions, the technology used, and the effectiveness of environmental management. In areas with high ecological sensitivity, land clearing and infrastructure development must be carried out carefully. Management measures such as limiting work areas, controlling erosion, revegetation, drainage management, and monitoring of flora and fauna are necessary to reduce ecological impacts.

In the context of the Ulumbu Geothermal Power Plant, impacts on soil and vegetation should be assessed in relation to land clearing, construction of power plant facilities, pipeline routes, access roads, and fluid discharge or reinjection systems. If pipeline leaks or wastewater overflows occur, surrounding soils may also be contaminated by geothermal fluids. Therefore, pipeline inspection systems, spill response procedures, and facility maintenance should be important components of environmental management.

Impacts on Public Health

Public health impacts from geothermal power plant operations may occur through several exposure pathways, including exposure to contaminated water, exposure to air containing certain gases, noise, and odor disturbance. In terms of liquid waste, arsenic and mercury are important parameters because both may have toxic effects when exposure occurs at certain concentrations and over long periods.

The WHO (2017) states that long-term arsenic exposure through drinking water and food may cause skin changes, pigmentation, keratosis, vascular disorders, and an increased risk of certain cancers. Therefore, although Yuniarto et al. (2016) reported that arsenic concentrations in the Waekokor River did not increase significantly, regular monitoring remains necessary to ensure that conditions remain safe.

In terms of air quality, H_2S must be carefully considered because it can produce strong odor and cause health problems at high concentrations. Odor complaints from H_2S may reduce the comfort of nearby communities even when concentrations are not necessarily at dangerous levels. Therefore, air quality monitoring and a community complaint mechanism should be provided by the power plant operator.

Environmental Impact Evaluation of the Ulumbu Geothermal Power Plant

Based on the literature review, the environmental impacts of the Ulumbu Geothermal

Power Plant can be grouped into two categories: reported actual impacts and potential impacts that must be anticipated. The reported actual impact identified by Yuniarto et al. (2016) is the discharge of geothermal liquid waste into the Waekokor River. Their measurements showed that the arsenic concentration in liquid waste was 0.0365 mg/L, while the arsenic concentration in river water before and after wastewater discharge remained below 0.0002 mg/L. Based on the arsenic parameter, these values were still below the quality standard established by the Regulation of the Minister of Environment Number 08 of 2009 (Ministry of Environment, 2009; Yuniarto et al., 2016).

However, the potential impacts that need to be anticipated remain broad. These include changes in water temperature, pH alteration, increased sulfide, ammonia, mercury, oil and grease, and emissions of non-condensable gases such as H_2S, CO_2, CH_4, and NH_3. In addition, pipeline leakage, sump overflow, reinjection system failure, and cooling system disturbances may also increase the risk of environmental pollution.

Therefore, environmental impact evaluation of the Ulumbu Geothermal Power Plant should not be limited to a single parameter such as arsenic. A comprehensive evaluation is required by considering water quality, air quality, soil conditions, vegetation, ecosystems, occupational safety, and public health. This integrated approach is necessary to ensure that the Ulumbu Geothermal Power Plant can continue operating as a renewable energy facility without neglecting environmental protection.

Environmental Management Concept for Geothermal Power Plants

Environmental management in geothermal power plant projects must be implemented from the planning stage through construction, operation, and post-operation. During the planning stage, environmental documents such as Environmental Impact Assessment (AMDAL), Environmental Management Plan, Environmental Monitoring Plan, or other required environmental documents must be prepared based on site conditions and potential impacts. During the operation stage, the plant operator must conduct routine environmental management and monitoring in accordance with commitments stated in environmental documents and applicable quality standards.

The main strategy for environmental management in geothermal power plants is the reinjection of brine and condensate into the reservoir. Reinjection functions not only as a waste management measure but also as a method to maintain reservoir pressure and geothermal production sustainability. Through reinjection, the risk of surface water pollution can be reduced because geothermal fluids are not directly discharged into the environment (DiPippo, 2016; Saptadji, 2018).

The second strategy is regular water quality monitoring. At the Ulumbu Geothermal Power Plant, water monitoring should be carried out in the Waekokor River at upstream, discharge, and downstream points. The monitored parameters should follow applicable quality standards, including temperature, pH, dissolved sulfide, ammonia, mercury, arsenic, oil and grease, and total organic carbon (Ministry of Environment, 2009).

The third strategy is air emission control. The plant operator should monitor H_2S, CO_2, CH_4, NH_3, and other relevant air quality parameters. Technologies such as scrubbers may be used to reduce H_2S emissions. In addition, routine pipeline inspection, cooling tower maintenance, and leakage detection systems should be implemented to prevent uncontrolled

gas releases (EIA, n.d.).

The fourth strategy is leakage risk and emergency management. A geothermal power plant must have emergency response procedures to address pipeline leakage, wastewater overflow, reinjection pump failure, or facility damage. These procedures should include reporting systems, area isolation, temporary flow shutdown, spill handling, and environmental recovery.

The fifth strategy is community engagement. Communities surrounding the geothermal power plant should receive adequate information regarding plant operations, potential impacts, environmental management systems, and complaint mechanisms. Community engagement is important to improve transparency, reduce conflict, and accelerate responses to complaints related to odor, water quality changes, or other environmental disturbances.

CONCLUSION

The operation of the Ulumbu Geothermal Power Plant may generate liquid effluents and atmospheric emissions that pose potential environmental risks. Liquid waste streams may originate from geothermal brine, condensate, and process or cooling water associated with electricity generation. Atmospheric emissions may occur through steam venting from atmospheric flash tanks, silencers, cooling towers, and potential pipeline leaks. Depending on the geothermal fluid composition and plant operating conditions, these emissions may contain noncondensable gases (NCGs), including hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), and trace amounts of ammonia (NH_3).

Comprehensive environmental management remains essential because potential pollution risks are not determined solely by arsenic concentrations. Additional wastewater quality parameters, including temperature, pH, dissolved sulfide, ammonia, mercury, oil and grease, total organic carbon, and effluent discharge rates, should be assessed according to their relevance to the wastewater characteristics and applicable environmental standards. Furthermore, atmospheric emissions containing H_2S, CO_2, CH_4, and NH_3 require appropriate monitoring and management to minimize odor disturbances, air quality deterioration, potential health risks to workers and surrounding communities, and greenhouse gas emissions.

Recommended environmental management measures for the Ulumbu Geothermal Power Plant include reinjecting geothermal brine and condensate into the reservoir where technically feasible, conducting routine water quality monitoring in the Waekokor River, monitoring ambient air quality and relevant gas emissions, and implementing regular pipeline inspections and leak detection procedures. Where necessary and technically appropriate, emission control technologies, such as hydrogen sulfide abatement systems or gas scrubbers, should be considered. Environmental management should also be strengthened through compliance with Analisis Mengenai Dampak Lingkungan (AMDAL; Environmental Impact Assessment) requirements, implementation of environmental management and monitoring plans, and active engagement with surrounding communities. These measures could help minimize environmental risks, maintain regulatory compliance, and support the long-term operation of the Ulumbu Geothermal Power Plant as a renewable electricity generation facility while protecting local environmental quality.

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CONFLICT OF INTEREST

The author states that there are no conflicts of interest, whether personal, commercial, or financial, that can affect the implementation and results of this study.

AUTHOR CONTRIBUTION

Akhmad Sofyan, Bambang Yudho Suranta contributed to research design, data collection and processing, result analysis, and article manuscript preparation.

GENERATIVE ARTIFICIAL INTELLIGENCE USAGE STATEMENT

In the process of compiling this article, the author uses generative artificial intelligence (AI) as a tool in language refinement, writing structure, and grammar improvement. The use of AI is carried out on a limited basis and remains under the supervision of the author. All data, analysis, interpretation, and scientific substance in this article have been checked and verified by the author. The author is solely responsible for the accuracy, authenticity, and final content of the manuscript.

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