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Environmental Impact Assessment of Geothermal Power Plant: Analysis Using Life Cycle Assessment (LCA) and Analytical Hierarchy Process (AHP) Methods

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ABSTRACT

This study aims to identify the environmental impacts arising from the electricity generation process at PT. X and to determine alternative mitigation scenarios that can be applied to reduce these environmental impacts. Using the Life Cycle Assessment (LCA) approach, the study successfully identified the cooling tower as the main hotspot in the generation process, with emissions such as CO_2, H_2S, NH_3, and NO_x contributing to global warming potential, acidification potential, eutrophication potential, and human toxicity. Based on the analysis using the Analytical Hierarchy Process (AHP), the most effective mitigation alternative to reduce environmental impacts is the use of high-performance lubricant (HPL) for the fan cooling tower (FCT) system. The use of HPL received the highest priority, with a weight of 46.9% of the total decision, as it can reduce friction and heat, leading to improved energy efficiency and reduced motor power consumption. This research contributes to the development of mitigation strategies that can be applied to achieve a more sustainable, efficient, and environmentally friendly geothermal power plant, while also supporting Indonesia's energy transition.

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INTRODUCTION

Global climate change triggered by increased greenhouse gas (GHG) emissions has become the biggest challenge of the century. The energy sector, especially those based on fossil fuels such as coal, petroleum, and natural gas, is a major contributor to the world's GHG emissions. To contain the rate of global warming and its negative impact on ecosystems and human lives, the transition to renewable energy sources has become a non-negotiable global agenda, including in Indonesia (Choy & Onuma, 2025; Majekolagbe, 2020; Maspul, 2025; Muljono et al., 2025).

The Indonesian government has set an ambitious target to achieve a renewable energy mix of 23% by 2025 and 31% by 2050 through the *Rencana Umum Energi Nasional* (*RUEN*). However, according to the Ministry of Energy and Mineral Resources (2023), Indonesia's renewable energy capacity reached only 12.7% in 2023, indicating a significant gap between targets and realization. The National Energy Status and Outlook states that achievement of the new renewable energy (*NRE*) target is hampered by various factors, including technological limitations, regulatory constraints, and social challenges in the form of public resistance to new energy infrastructure development (Cedeno & Wei, 2024; Onuh et al., 2024; Sen & Ganguly, 2017).

One of the renewable energy sources with great potential in Indonesia is geothermal energy (Suharmanto et al., 2015). Indonesia has geothermal energy reserves of 23.7 GW, which

covers about 40% of the world's total geothermal potential (Darma et al., 2020; Fahmi, 2025; Hossain et al., 2021; Pambudi et al., 2023). The government has targeted the development of geothermal energy at 7.2 GW by 2025 and 17.6 GW by 2050 (*RUEN*, 2017). However, until 2022, the installed capacity had reached only 2,355.4 MW, or around 7.99% of the total national potential (MEMR, 2023), indicating a large gap between potential and realization.

One of the main obstacles in *Pembangkit Listrik Tenaga Panas Bumi* (*PLTP*) development is related to environmental impacts, which remain in the spotlight (Faridah et al., 2024). Some *PLTP* projects face obstacles due to community rejection stemming from concerns about environmental impacts such as gas emissions, noise, land use, and potential disturbances to local ecosystems (Alfian, 2018). Although *PLTP*s are considered cleaner than fossil fuel plants, the process of extracting and utilizing geothermal fluids still produces emissions of gases such as CO_2, H_2S, CH_4, and NH_3, which contribute to global warming, acid rain, and air pollution. A study by Towijaya et al. (2019) states that the average *PLTP* currently produces around 40 kg of CO_2 per MWh, highlighting the need to comprehensively measure indirect emissions across the generation life cycle.

One of the strategic projects in the use of geothermal energy in Indonesia is the *PLTP* in Kamojang, managed by PT. X, one of the pioneers of geothermal development in Indonesia (Pambudi, 2018; SAVIRA, 2023) . Its location on the border of Bandung and Garut Regencies, West Java, makes it one of the main suppliers of clean energy in the Java-Bali region (Fauzia & Makarim, 2024; Meilandari, 2020).

Although PT. X has implemented various environmental practices in general, the potential environmental impacts of its geothermal generation system remain significant—especially related to emissions from geothermal fluids, the use of chemicals in the separation process, and solid and liquid waste management. A life cycle assessment (LCA) of the power generation system at PT. X is an important approach to implement. LCA allows for a thorough analysis of the environmental impacts across the entire life cycle of a power plant. Studies by Zhang et al. (2016) and Frick et al. (2010) have proven the effectiveness of LCA in identifying environmental hotspots in power generation systems, including geothermal technologies.

Identifying environmental hotspots through LCA does not necessarily solve the problem; strategic decision-making is also needed to determine the most appropriate and feasible alternative environmental improvement scenarios. The Analytical Hierarchy Process (AHP) method is a multicriteria decision-making method that allows the assessment of various alternatives based on weighted criteria such as environmental effectiveness, technical feasibility, and cost efficiency. Research by Herva et al. (2011) shows that AHP can assist in systematically determining environmental mitigation programs based on stakeholder participation.

Based on this background, this study aims to measure the environmental impact of the life cycle of the geothermal power generation system at PT. X using the Life Cycle Assessment (LCA) approach and to determine alternative environmental mitigation programs based on the analysis results using the Analytical Hierarchy Process (AHP) method. The results of this research are expected to contribute to the development of more environmentally friendly, sustainable, and community-acceptable PLTPs.

METHOD

This research was conducted at PT. X, a geothermal power plant located in Bandung Regency and Garut Regency, West Java. The focus of the power generation unit is the active generation unit with a total capacity of 235 MW. The research uses a quantitative descriptive approach with the Life Cycle Assessment (LCA) and Analytical Hierarchy Process (AHP) methods. The duration of data collection is carried out for a period of 1 year starting from January to December 2024.

The Life Cycle Assessment (LCA) in this study follows ISO 14040 and 14044 standards with a cradle-to-gate approach, covering the following stages: (1) geothermal fluid extraction and production, (2) fluid transportation and processing, and (3) power generation process. The study did not cover the distribution and decommissioning stages. The environmental impact assessment was carried out using SimaPro software with the ReCiPe 2016 Midpoint (H) V1.06 and CML IA baseline V3.07 method. The impact categories studied included Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity, Ecotoxicity, Photochemical Oxidation, and Abiotic Depletion.

The stages of LCA include: (1) Goal and Scope Definition, which is the definition of the purpose of the study and the limitations of the system with a functional unit in the form of 1 kWh of electricity produced, (2) Life Cycle Inventory (LCI), which is the collection of input data (geothermal fluids, chemicals, water, energy) and output (electricity, emissions, wastewater, solid waste), (3) Life Cycle Impact Assessment (LCIA), namely classification and characterization of impacts using the ReCiPe 2016 and CML-IA methods, and (4) Interpretation, namely hotspot analysis and mitigation recommendations.

Data collection is carried out through: (1) Primary data from operational reports, monitoring data, and direct measurements at PT. X for the January-December 2024 period, (2) Secondary data from the relevant literature, databases (Ecoinvent, ELCD), and previous research. The data collected include: raw material data (steam/steam, HSD, NaOCl), water and electricity usage, emissions to the air (CO_2, H_2S, NH_3, CO, HC, NO_x, SO_2, NO_2), emissions to water (Chloride, Chromium, Copper, Iron, Oils, Phosphate, Zinc, Suspended Solids, BOD, COD, Ammonia), and PLTP production system data obtained through interviews and observations.

After the LCA identifies environmental hotspots, the determination of alternative mitigation scenarios is carried out using the Analytical Hierarchy Process (AHP) method. The AHP is used to prioritize mitigation alternatives based on three main criteria: Environmental Impact (weight 64.5%), Ease of Implementation (weight 26.0%), and Investment & Production Cost (weight 9.5%). Alternative scenarios evaluated include: (1) Use of High Performance Lubricant (HPL) for the Fan Cooling Tower (FCT) system, (2) GeoCities (Cooling Tower Efficiency Software), and (3) Resetting the Tilt Angle of the FCT Blade.

AHP data processing is carried out using Expert Choice software with input from technical experts and stakeholders. The selection of respondents is based on stakeholder analysis to ensure the representation of multistakeholder interests in determining priority weights and allocation of preference scales. The logical consistency of the analysis results was evaluated using the Consistency Ratio (CR) with a CR tolerance limit of < 0.1 to ensure the reliability of the assessment results.

RESULTS AND DISCUSSION

Life Cycle Impact Assessment (LCIA)

Based on the Life Cycle Impact Assessment (LCIA) analysis conducted using SimaPro software, several categories of environmental impacts were identified in the power generation process at PT. X. Assessment using the ReCiPe 2016 Midpoint (H) V1.06 and CML IA baseline V3.07 method. The results of the impact assessment for the scope of the Gate (electricity production process) in the PLTP K2 Unit of PT. X is presented in Table 1.

Table 1. Environmental Impact Assessment on the Gate Scope of the Electricity Production Process of PT. X Unit PLTP K2

No	Impact Categories	Units	Method	Total	% Hotspot
Primary Impact					
1	Global warming potential	kg CO_2 eq/kWh	ReCiPe 2016	1.89E-02	100%
2	Ozone depletion potential	kg CFC_{11} eq/kWh	ReCiPe 2016	0	-
3	Potential for acid rain	kg SO_2 eq/kWh	ReCiPe 2016	3.15E-05	100%
4	Eutrophication potential	kg PO_4^{3-} eq/kWh	CML IA baseline	6.04E-06	93,2%
Secondary Impact					
5	Photochemical oxidation	kg C_2H_4 eq/kWh	CML IA baseline	0	-
6	Human toxicity	kg 1,4-DB eq/kWh	CML IA baseline	2.11E-04	100%

Based on Table 1, the results of the environmental impact assessment show that the Cooling Tower is the main hotspot in the power generation process at PT. X. Primary impacts identified include: (1) Global Warming Potential (GWP) of 1.89E-02 kg CO_2 eq/kWh, with Cooling Towers contributing 100% to this impact, (2) Acidification Potential of 3.15E-05 kg SO_2 eq/kWh, with Cooling Towers also contributing 100%, and (3) Eutrophication Potential of 6.04E-06 kg PO_4^{3-} eq/kWh, with Cooling Towers contributing 93.2% to this impact. The secondary impacts identified include Human Toxicity of 2.11E-04 kg 1.4-DB eq/kWh, with a contribution of 100% from the Cooling Tower.

The main source of emissions from the Cooling Tower is Non-Condensable Gases (NCG) released from geothermal fluids. NCGs contain CO_2, H_2S, NH_3, and CH_4 that are directly released into the atmosphere. The results of this study are consistent with the research by Kristmannsdóttir and Ármannsson (2003) which stated that NCG is the main source of emissions from geothermal power plants. H_2S emissions contribute to acidification potential (acid rain), while NH_3 emissions contribute to eutrophication potential. In addition, CO_2 emissions contribute to the potential for global warming, although the amount is much smaller compared to fossil fuel plants.

The impact of GWP on the scope of the cradle was mainly generated from the drilling process of production wells by 87.23%. In general, the impact of GWP arises due to emissions from the use of fuel or electricity in the drilling process of steam production wells. The emissions that cause the impact of GWP on the cradle scope come from carbon dioxide emissions of 88.96% and methane emissions of 9.88% released into the air. For the potential for ozone depletion, the largest contributor to the cradle scope is generated from the steam transportation process of 52.12%, with methane emissions of 55.21% and nitrogen monoxide emissions of 44.63%. For the potential for acid rain, the largest contributor to the cradle scope

is generated from the drilling process of steam production wells of 96.48%, with sulfur dioxide emissions of 68.84% and nitrogen oxides emissions of 30.08%.

Resulth Analytical Hierarchy Process (AHP)

Based on the results of the LCA hotspot analysis that identified Cooling Towers as the main contributor to environmental impacts, the determination of alternative mitigation scenarios was carried out using the Analytical Hierarchy Process (AHP) method. The hierarchical structure used includes three main criteria: Environmental Impact (64.5%), Ease of Implementation (26.0%), and Investment & Production Costs (9.5%). The three alternative scenarios evaluated are: (1) The use of High-Performance Lubricant (HPL) for the Fan Cooling Tower (FCT) system, (2) GeoCities (Cooling Tower Efficiency Software), and (3) Resetting the Tilt Angle of the FCT Blade. The results of the AHP assessment are presented in Table 2.

Table 2. Results of Weight Assessment of Mitigation Alternatives Using AHP

No	Mitigation Alternatives	Environmental Impact	Ease of Implementation	Total Weight
1	Use of HPL for FCT	43,5%	55,1%	**46,9%**
2	GeoCities (Cooling Tower Efficiency Software)	40,5%	27,3%	36,3%
3	Resetting FCT Blade Tilt Angle	16,0%	17,6%	16,8%

Based on the results of the AHP calculation, the HPL use alternative for FCT received the highest weight at 46.9%, making it the most prioritized mitigation alternative. The use of High Performance Lubricant (HPL) in FCT (Fan Cooling Tower) systems provides a great advantage in reducing friction and heat, which in turn reduces motor power consumption and improves energy efficiency. These results are in line with the research of Mobarak et al. (2014) which showed that the use of high-performance lubricants can reduce friction by up to 25% and extend the life of equipment, which makes it an efficient solution to save energy without requiring a large investment in equipment replacement.

The second alternative considered is GeoCities (Cooling Tower Efficiency Software), which gets a weight of 36.3%. Although more expensive, this alternative is considered to be very effective in early detection of damage and improved energy efficiency in cooling tower systems. The program uses infrared thermography technology to detect damage to the internal parts of the cooling tower, which is very useful for improving the reliability and efficiency of the system in the long run. Despite having higher costs upfront, the program can significantly reduce system maintenance and downtime costs, which makes it a very valuable alternative in the long run, as described in Gharagheizi et al. (2015).

The third alternative, namely the FCT Blade Tilt Angle Resetting, has the lowest weight of 16.8%. While this is a relatively inexpensive and quick solution to implement, its impact on CO_2, H_2S, and NH_3 emission reductions is more limited compared to the other two alternatives. This solution focuses more on direct energy savings without having a major impact on the overall efficiency of the cooling tower system.

The consolidated results showed that the consensus of the AHP for the group was 99.9%, which is very high and showed that the participants agreed on the priority of the criteria and the mitigation alternatives chosen. The Relative Homogeneity of 100% indicates that the assessments between participants are very uniform, with little difference between them. Based

on the results of consolidated decisions and global priorities, the use of HPL for FCT is the best mitigation alternative. GeoCities is also a very relevant option despite being more expensive, as it offers long-term reliability and early detection of damages, which will reduce maintenance costs in the long run.

CONCLUSION

This research successfully identified key environmental impacts of the power generation process at PT. X using Life Cycle Assessment (LCA), pinpointing the Cooling Tower as the major hotspot due to its contributions to Global Warming Potential (1.89×10^{-2} kg CO_2 eq/kWh), Acidification Potential (3.15×10^{-5} kg SO_2 eq/kWh), Eutrophication Potential (6.04×10^{-6} kg PO_4^{3-} eq/kWh), and Human Toxicity (2.11×10^{-4} kg 1,4-DB eq/kWh), primarily driven by non-condensable gas (NCG) emissions (CO_2, H_2S, NH_3, NO_x) from geothermal fluids. The Analytical Hierarchy Process (AHP) analysis determined that using High Performance Lubricant (HPL) for the Fan Cooling Tower (FCT) system is the most effective mitigation alternative, with the highest priority weight of 46.9%, excelling in environmental impact reduction, ease of implementation, and cost efficiency by lowering friction, heat, motor power consumption, and associated CO_2 emissions. Overall, the study advances sustainable, efficient, and environmentally friendly strategies for geothermal power plants. For future research, a detailed cost-benefit analysis of each alternative, pilot project implementations, development of integrated monitoring systems, and expansion of the LCA scope to include decommissioning and distribution stages are recommended.

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