Type of Contribution:
Research Paper
Review Paper
Case Study

COMBUSTION INTERNATIONAL
DOI: 10.51747/coin.v1i1.115

This article contributes to:
SUSTAINABLE DEVELOPMENT GOALS
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Environmental Footprint of Indonesian Geothermal: Emission Profiles, Reinjection, and Induced Seismicity

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Abstract

Energy losses are a significant factor affecting the capacity of pipes as water flow conductors. These losses cause a reduction in the water flow rate within pipes. Various factors contribute to Non-Revenue Water (NRW), including leaky pipe fittings, excessive elbows, pipe branching, and abrupt flow constrictions. A peak NRW of 10.2% was recorded in February 2020, highlighting the need for prompt and efficient leak management to ensure optimal sanitation services. The analysis of varying elbow configurations showed significant differences in water flow rates, although pressure changes were not as notable, with minor variations observed at low elevation points due to low pressure. Elevation also significantly influences water pressure and flow rates. Hence, appropriate pipe installations tailored to varying elevation points are necessary due to the diverse geographical locations of PDAM customers.

Keywords: Elbow variation, tertiary pipes, pressure, water flow, Non-Revenue Water (NRW)

Article Info
Submitted: 2024-10-02
Revised: 2024-12-19
Accepted: 2025-01-25

Publisher
Universitas Panca Marga

1. Introduction

Indonesia's geothermal sector plays a pivotal role in the country's energy transition, offering a low-carbon baseload energy source within the context of its vast geothermal potential, which accounts for approximately 40% of the global reserves [1],[2],[3]. Despite this, the utilization of geothermal energy in Indonesia remains limited, with only about 4.5% of this potential currently harnessed for electricity generation [1],[2]. Recognizing this potential, Indonesia has set ambitious targets to enhance the renewable energy share in its energy mix, aiming for 23% by 2025, as outlined in the National Energy Policy [4][5].

The environmental footprint associated with geothermal energy production necessitates careful consideration. Emissions of hydrogen sulfide (H_2S) and carbon dioxide (CO_2) from geothermal plants raise significant concerns. Conventional geothermal energy production can release CO_2, albeit at lower rates compared to fossil fuels, contributing on average up to 5% by weight [6]. Effective management strategies, including CO_2 reinjection to mitigate emissions, have been proposed [7]. Additionally, managing produced and spent geothermal fluids—especially through reinjection into reservoirs—is crucial for maintaining reservoir pressure and minimizing environmental impacts from improper handling [8].

Another critical aspect is the issue of induced microseismicity, relating to slight seismic events resulting from geothermal energy extraction and fluid reinjection practices. This phenomenon, while often minor, can have implications for local communities and plant operations [4]. As geothermal energy development progresses, a wider range of stakeholders necessitates clearer standardized protocols for monitoring and reporting these environmental and operational impacts.

Current literature reveals a fragmented understanding of the quantitative profiles of emissions and water management practices across Indonesia's geothermal fields [9]. Research efforts often concentrate on localized studies rather than producing integrated insights that could be generalized across the sector. There exists a clear gap for robust, Indonesia-specific, and quantitatively comparable data regarding emissions, fluid management practices, and microseismic patterns. Addressing this gap is essential for enhancing operational efficiency and ensuring that geothermal energy remains a sustainable option in Indonesia's energy portfolio [10].

Future studies should aim to compile and normalize emission profiles, document water management and reinjection practices in geothermal power generation, and characterize microseismic patterns linked to geothermal operations. Utilizing the Driver-Pressure-State-Impact-Response (DPSIR) framework will synthesize these findings, ultimately allowing for the development of comparable indicators that can inform policy decisions and operational strategies within Indonesia's geothermal sector.

2. Theoretical Framework

In operationalizing the DPSIR framework, the geothermal energy sector delineates its complex interrelations through five primary components: Drivers, Pressures, State, Impacts, and Responses, as seen in **Figure 1**.

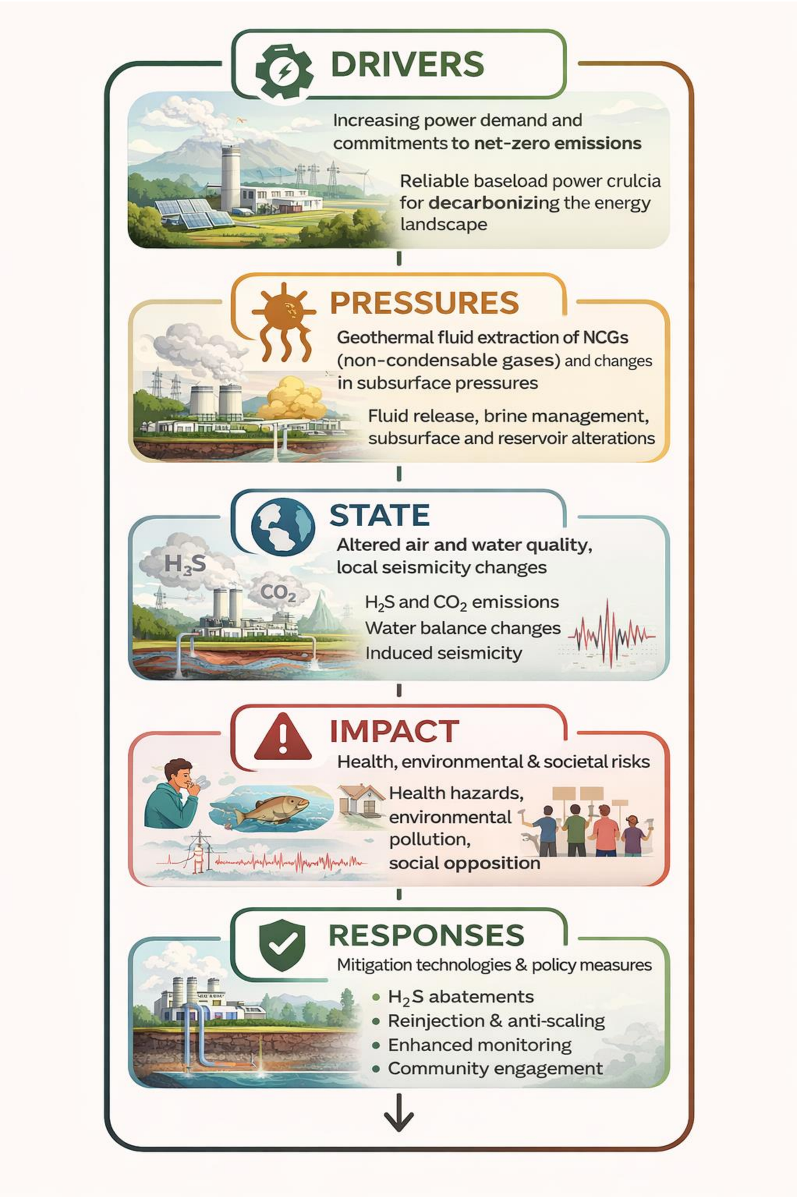

Figure 1. Schematic diagram represents the DPSIR (Drivers, Pressures, State, Impacts, and Responses) framework applied to the geothermal energy sector

2.1 Drivers

Drivers in the geothermal sector include increasing power demand and commitments to achieving net-zero emissions. As Indonesia advances towards its renewable energy targets, the need for reliable baseload power spurs the development of geothermal energy resources, which are recognized as crucial to decarbonizing the energy landscape [11]. The shift to a low-carbon economy underscores the strategic importance of geothermal energy, which provides a consistent and sustainable alternative to fossil fuels [12].

2.2 Pressures

These Drivers create significant Pressures on geothermal systems, manifested as fluid production, the release of non-condensable gases (NCGs), management of geothermal brines, and changes in subsurface pore pressures due to extraction practices [13]. The extraction of geothermal fluids, while essential for energy production, directly affects the chemical and thermal equilibrium of the geothermal reservoir, leading to potential environmental challenges [14]. These pressures need to be managed prudently to ensure the sustainability of geothermal resources [15].

2.3 State

The State of the geothermal environment is thus influenced by these pressures. This includes alterations in air quality due to hydrogen sulfide (H_2S) emissions, variations in CO_2 intensity associated with different geothermal plant technologies (e.g., flash vs. binary cycle plants), reservoir dynamics including water balance, and impacts on local seismicity from fluid injection practices [16]. Each of these factors can invoke considerable environmental consequences, necessitating careful monitoring and assessment [17][18].

2.4 Impact

The resulting Impacts of these state changes encompass significant health risks, environmental hazards, and concerns regarding social acceptability, which can lead to community opposition [19]. For instance, H_2S and CO_2 emissions may exacerbate air quality issues, influencing public perception and acceptance of geothermal projects [20].

2.5 Responses

In responding to these dynamics, the geothermal sector employs Responses that include technological innovations and policy measures. Technologies such as advanced H_2S abatement systems, optimized gas extraction methods, and high reinjection ratios with anti-scaling strategies help mitigate emissions and enhance system performance [21]. Moreover, implementing comprehensive seismic monitoring protocols and community engagement strategies can enhance social acceptability and address public concerns about seismic risks [22].

Establishing working propositions further elucidates this framework: enhanced abatement methods combined with minimized air contact effectively reduce H_2S emissions; managed reinjection processes stabilize geothermal reservoirs and minimize induced seismicity; and variations in CO_2 intensity are closely linked to the levels of NCG and the specific plant technology deployed [17][23].

3. Methods

To document a transparent and reproducible review design of Indonesia's geothermal sector covering the years 2000 to 2025. This approach ensures rigorous selection criteria and a comprehensive analysis of the identified literature. The literature search will be extensive, employing databases such as Scopus, Web of Science, and Google Scholar, along with key proceedings and technical reports relevant to the field.

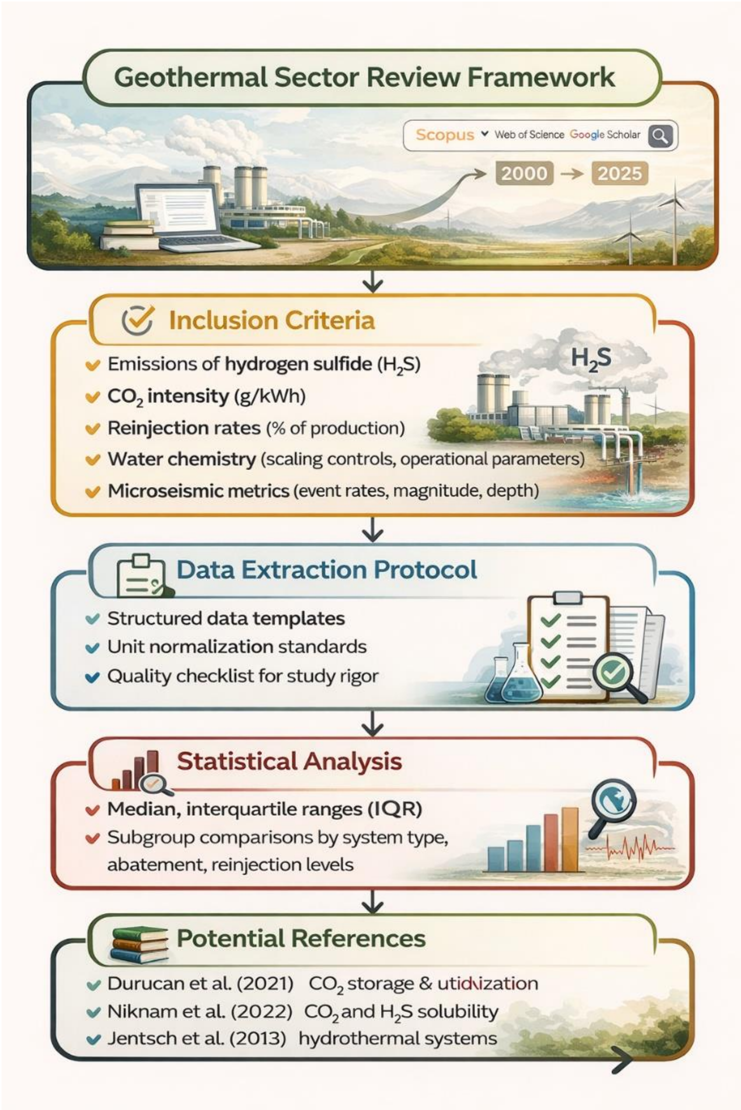

Figure 2. Geothermal Sector Review Framework

3.1 Inclusion Criteria

This review will focus on studies that provide quantitative data on several critical aspects of geothermal energy production, specifically:

- Emissions of hydrogen sulfide (H_2S), reported in terms of both stack and ambient measurements.
- CO_2 intensity, quantified in grams of CO_2 emitted per kilowatt-hour (g/kWh).
- Reinjection rates, expressed as a percentage of production volume.
- Water chemistry, specifically regarding scaling controls and operational parameters.
- Microseismic metrics, including event rates, magnitude distributions, and depths of seismic events.

These criteria align with current research needs and regulatory frameworks that emphasize the monitoring of environmental impacts associated with geothermal energy production, as seen in **Figure 2**.

3.2 Data Extraction Protocol

Utilizing structured extraction templates, data will be collected adhering to unit normalization standards, such as establishing reference conditions for gas emissions. This will ensure comparability across studies and enhance the accuracy of the aggregated data. A quality checklist will be applied to assess the robustness of the included studies. Parameters will include considerations for instrument calibration, sampling frequency, and the uncertainty associated with measurement techniques.

3.3 Statistical Analysis

The analysis will involve descriptive statistics, reporting metrics such as median values and interquartile ranges (IQR) for the collected data. To assess variability across different conditions, subgroup comparisons will be executed, focusing on factors such as plant type (e.g., flash vs. binary systems), abatement status (presence or absence of emission control technologies), and classifications of reinjection rates (high vs. low reinjection proportions).

Exploratory meta-regression analysis will be conducted where appropriate, enabling an investigation into the potential influences of various factors on the observed emissions and other measured variables. Heterogeneity within the data will guide the application of robust statistical techniques to draw reliable conclusions.

3.4 Potential References

To substantiate the review and further refine the selection of studies, the following references are considered relevant:

- Reference Durucan et al. [24]: Durucan et al. discuss a CO_2 storage and utilization project that emphasizes the importance of measuring and monitoring CO_2 emissions associated with geothermal power production, thus providing key insights into the reinjection of CO_2 specific to geothermal systems.
- Reference Niknam et al. [25]: Niknam et al. present a solubility model of CO_2 and H_2S in water relevant to geothermal operations, addressing relevant chemical interactions and processes during geothermal fluid management that contribute to CO_2 intensity considerations.
- Reference Jentsch et al. [26]: Jentsch et al. provide insights into the correlation of volcanic CO_2 emissions with reinjection rates and the dynamics of hydrothermal systems, which can inform the metrics of microseismicity and emissions in the geothermal context.

4. Results

This analysis synthesizes data from various geothermal plants across Indonesia, adhering to a thematic and organized structure. The results will be presented using normalized indicators to facilitate comparisons between different geothermal fields.

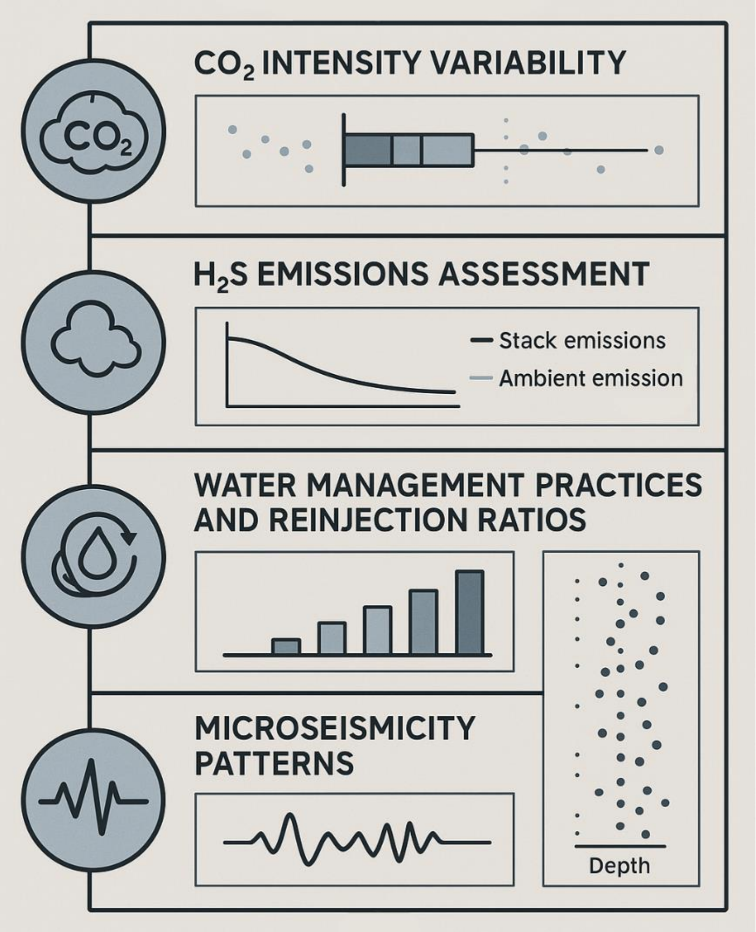

Figure 3. Schematic diagram illustrates the Results of the synthesis of data from various geothermal plants

4.1 CO_2 Intensity Variability

We begin by reporting the ranges and medians of CO_2 intensity across Indonesian geothermal plants. The data reveals significant variability, indicative of differing non-condensable gas (NCG) content, condenser performance, gas-handling strategies, and cycle types (e.g., flash vs. binary systems) [27]. One notable finding is that plants with integrated gas extraction and enhanced condenser performance exhibited lower CO_2 emissions, highlighting the importance of optimizing these operational parameters.

4.2 H_2S Emissions Assessment

Next, we synthesize data on H_2S emissions at stack and ambient levels, distinguishing between sources such as cooling towers and fugitive emissions. This distinction is critical, as retrofitting systems with H_2S abatement technologies has demonstrably reduced measured emissions [28]. In many cases, operational adjustments—such as enhancing gas scrubbing and implementing better air contact controls—have led to significant reductions in ambient H_2S concentrations, thus increasing plant compliance with environmental standards.

4.3 Water Management Practices and Reinjection Ratios

Following the assessment of emissions, we compile data on water management practices, notably looking at reinjection ratios and their relationship to silica scaling control techniques. Various methodologies—including seeded precipitation, the application of chemical anti-scalants, and thermal/pH controls—affect plant availability and operational efficiency [29][30]. A higher reinjection ratio correlates positively with stable reservoir pressure and reduced scaling, thus enhancing long-term plant performance and availability.

4.4 Microseismicity Patterns

The final section discusses microseismicity patterns in relation to injection and production schedules. This analysis includes typical magnitudes, event rates, and depth distributions of seismic events, as well as their proximity to geological structures [31]. The findings indicate that careful scheduling of production and injection is instrumental in reducing seismic activity. Many plants report stable seismicity profiles when water reinjection is precisely controlled, signifying a direct link between operational practices and microseismic risk management.

5. Discussion

The discussion centers on the technical drivers that underpin the observed indicators of geothermal energy systems in Indonesia, specifically focusing on CO_2 intensity, H_2S emissions, fluid management, and microseismicity.

5.1 CO_2 Intensity in Binary Systems

Binary systems are increasingly recognized for their superior efficiency in minimizing CO_2 intensity compared to traditional flash systems. This performance can be attributed to the ability of binary plants to operate at lower temperatures without venting non-condensable gases (NCGs) into the atmosphere. The closed-loop system in binary configurations allows for better management of gas emissions through efficient heat exchange processes [32]. Studies indicate that these systems can achieve CO_2 emissions that are significantly lower than those from flash systems, often due to enhanced condenser performance and optimized gas-handling strategies [33].

5.2 Mitigating H_2S Emissions

To curtail H_2S emissions, strategies that minimize fluid-air contact are critical. Implementing advanced abatement technologies—such as chemical scrubbing and thermal oxidation—can dramatically reduce H_2S levels. The use of chemical treatments effectively mitigates H_2S in geothermal fluid streams before they can escape into the atmosphere [34]. Moreover, retrofitting existing plants with such technologies has shown to reduce ambient H_2S levels significantly, thus enhancing compliance with environmental regulations [35]. Incorporating comprehensive monitoring protocols ensures transparency and reevaluation of operational practices, thereby preemptively addressing potential emissions.

5.3 Reinjection Practices and Reservoir Management

High yet carefully engineered reinjection rates are crucial for stabilizing reservoir pressures while preventing scaling bottlenecks. Proper reinjection strategies utilize thermal and chemical balancing techniques to manage silica scaling and enhance the long-term viability of geothermal reservoirs [35]. This systematic approach not only extends the operational lifespan of geothermal plants but also ensures reliable output, thus making geothermal a sustainable energy source. Effective scaling control strategies include using anti-scalants and implementing thermal/pH control measures, which collectively enhance plant availability and mitigate maintenance downtime.

5.4 Induced Microseismicity Management

Microseismicity generally remains low in magnitude and can be effectively managed through informed site selection, targeted well siting, and satisfactory pressure management regimes. Continuous monitoring techniques, including traffic-light protocols, enable operators to quickly identify and respond to seismic events, thereby mitigating risks. The integration of real-time data analytics tools can enhance decision-making processes concerning operational adjustments in response to microseismic events [36].

5.5 Policy and Operational Guidance

Based on these technical insights, several policy and operational guidelines are recommended:

1. Standardized Reporting Protocols: Establishing comprehensive, standardized reporting frameworks will facilitate the collection and comparison of data across geothermal facilities. This system can streamline regulatory compliance and enhance stakeholder confidence [37].
2. Performance-Based Reinjection Guidance: Policies should define performance-based guidelines for reinjection rates in accordance with best practices. Adjustments should be based on specific site conditions to ensure that operational frameworks are sustainable and efficient.
3. Mandatory Abatement Technologies: Where H_2S emissions exceed set thresholds, mandatory implementation of abatement systems should be enforced. By fostering a regulatory environment that prioritizes emissions

reduction through technology, Indonesia can align with global standards for sustainable energy production [38].

4. Traffic-Light Seismic Protocols: Traffic-light seismic monitoring protocols should be mandated, enabling real-time management of seismic activities. These protocols will inform operational restrictions as needed, preventing unaddressed seismic issues and promoting sustainability [36].

5.5 Limitations and Future Directions

Despite the promising findings, several limitations must be acknowledged. Data heterogeneity across studies can introduce variability in results, complicating comparative analyses. Additionally, access constraints to certain geothermal sites may inhibit comprehensive evaluations, while potential publication bias might exclude critical insights from lesser-known projects [39].

Priorities for future research should focus on life cycle assessments (LCA) to holistically evaluate environmental impacts, alongside integrated geophysical and geochemical monitoring. Enhanced collaboration among stakeholders in the geothermal sector will foster data sharing and enable a more comprehensive understanding of resource management and environmental impacts.

6. Conclusion

Indonesia's geothermal sector holds significant potential to contribute to the country’s low-carbon energy transition. Despite having 40% of the world's geothermal reserves, only a small portion is currently utilized. To meet renewable energy targets, effective management of CO_2 emissions, H_2S emissions, water management, and microseismicity is crucial. The findings highlight the importance of enhanced gas extraction, optimized condenser performance, and advanced abatement technologies to mitigate environmental impacts and improve operational efficiency. Standardized data reporting and seismic monitoring protocols, alongside mandatory abatement technologies, are essential for ensuring sustainable growth. Future research should focus on integrated data collection and collaboration among stakeholders to further optimize geothermal resource management and minimize environmental risks.

Acknowledgement

The authors would like to express their sincere gratitude to the Center of Sustainable Engineering and Economic Research Innovation (SENSEI) for their invaluable support in the completion of this study. The center’s dedication to advancing sustainable engineering practices and fostering innovation in economic research has provided a conducive environment for the successful execution of this work.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding - No funding information from the authors.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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