Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Regionalized LCA of Geothermal Power: Dataset Gaps and Development Needs in Indonesia and New Zealand

Gloria Gladis Sondakh, Bart van Campen and John O'Sullivan
The University of Auckland, New Zealand
sondakh.gloria.gladis@auckland.ac.nz

Keywords: Life Cycle Assessment, Environmental Impact Assessment, Geothermal Data Quality, Emission Inventories, Sustainable Geothermal Development

INTRODUCTION

Geothermal life cycle assessment (LCA) has expanded significantly over the past decade, yet most datasets and methodological frameworks remain centered on European contexts and high-enthalpy electricity systems, with limited representation of Asia–Pacific regions (Basosi et al., 2020; Karlsdóttir et al., 2020; Kjeld et al., 2022).

Indonesia and New Zealand are both global geothermal leaders, each exceeding 1 gigawatt (GW) of installed capacity. Indonesia has rapidly expanded geothermal development in recent years, whereas New Zealand has built upon a long history of geothermal power generation dating back to the commissioning of the Wairakei plant in the 1950s. Despite these differences, both countries face similar challenges in applying LCA due to incomplete datasets and limited regional representativeness (Parisi et al., 2020).

The primary aim of this paper is therefore to identify the methodological and data-related gaps that constrain geothermal LCAs in Indonesia and New Zealand and to propose a pathway for enhancing their regional applicability. Building on a review of existing datasets and current methodological practices, this study emphasizes the need for **a structured**, transparent, and regionally grounded approach to inventory development **that complements** existing geothermal LCA guidelines while reflecting the distinctive characteristics of geothermal systems in each country.

1 METHODOLOGY

A structured review was conducted of geothermal LCA datasets within the ecoinvent v3.10 ecoQuery database and relevant peer-reviewed studies. The analysis focused on identifying the completeness, geographical representativeness, and technological relevance of datasets related to geothermal power generation in Indonesia and New Zealand.

Each dataset was mapped against the modular structure proposed in the GeoENVI (2020) guidelines, covering upstream, core, and downstream life-cycle stages, to determine which stages were well represented and which remained incomplete. Particular attention was given to the availability of inventories for construction, operation, and decommissioning.

In parallel, existing LCA studies and technical reports from both countries were examined to assess how publicly available inventories align with actual geothermal practices, including resource characteristics, plant configurations, and emission profiles. The review also included emergent applications, such as direct-use, mineral extraction, and CO_2 reinjection. This qualitative comparative approach made it possible to pinpoint critical data gaps and inconsistencies that limit the regional applicability of current LCA datasets.

2 FINDINGS AND CHALLENGES

2.1 Database Representation

The implementation of LCA is fundamentally dependent on the availability, quality, and geographical representativeness of life cycle inventory (LCI) datasets. Methodological definitions of system boundaries can only be translated into quantitative models when corresponding datasets exist to describe material inputs, energy flows, infrastructure requirements, and emissions associated with each life-cycle stage. In the absence of adequate inventories, defined modules cannot be fully operationalised, resulting in partial system coverage or reliance on proxy data.

Evidence from the ecoinvent ecoQuery database, as summarised in Table 1, indicates that geothermal datasets for Indonesia and New Zealand remain limited in scope and regional specificity. A substantial proportion of available entries are adapted from Swiss activities, reflecting background assumptions that do not necessarily correspond to local geological conditions, drilling depths, reservoir characteristics, construction practices, plant configurations, or operational parameters. As a result, current database representations do not comprehensively reflect context-specific geothermal systems in these regions. Existing datasets therefore function primarily as provisional approximations pending the development of dedicated, region-specific inventories for geothermal power plant construction and operation.

Table 1. Overview of geothermal datasets available for Indonesia and New Zealand in the ecoinvent database

Dataset	Information	Indonesia	New Zealand
geothermal power plant, 5.5MWe (geothermal power plant construction)	Construction of a geothermal power plant, including both surface facilities and subsurface infrastructure with a total capacity of 5.5 MWe, covering all materials and components required for plant construction.	Not available	Available
electricity, high voltage (electricity production, deep geothermal)	Generation of electrical energy measured in kWh. When electricity is supplied through the market mix, transmission infrastructure, as well as country-specific transmission and transformation losses for medium- and low-voltage networks, are included. Applicable for voltages above 24 kV.	Available	Available
deep well, drilled, for geothermal power (deep well drilling, for deep geothermal power)	Drilling of one meter of borehole for deep geothermal power generation. The modeled well reaches a depth of 5,000 m, with onshore drilling performed by a 6.75 MWe rig and a 10-inch top-hole diameter. The process excludes waste treatment activities.	Available	Available

2.2 Implementation of Current LCA Framework

The GeoENVI (2020) guidelines, initially developed in Europe, provide a harmonized structure for geothermal environmental assessment, dividing the life cycle into upstream, core, and downstream modules. The upstream

module includes material and energy inputs typically represented using secondary datasets, while the core module captures site- and technology-specific processes based on primary data. The core module comprises construction, operation and maintenance, and end-of-life stages. Construction includes wells, pipelines, and plant infrastructure; operation covers fluid extraction, stimulation, equipment replacement, scaling control, and emissions; and end-of-life involves well abandonment and waste treatment. The downstream module relates to energy distribution, which is excluded from standard system boundaries to preserve comparability.

The practical implementation of this modular structure is closely linked to the availability and completeness of supporting LCI datasets. Each module requires distinct data inputs, ranging from background datasets for material and energy production to foreground, site-specific inventories for drilling, plant operation, and emissions. Where geothermal-specific datasets are limited, certain modules cannot be comprehensively represented.

In practice, however, the implementation of this guideline remains inconsistent, as many studies apply these modules only partially. The end-of-life stage is frequently omitted from the geothermal power plant LCAs, with most analyses focusing primarily on construction and operation. This omission overlooks the significant challenges associated with decommissioning, a phase that involves managing large volumes of materials and components requiring proper treatment and disposal, as well as substantial related costs.

2.3 Expansion Beyond Conventional Power Systems

While national differences influence the availability and quality of geothermal inventory data, a broader limitation in the literature concerns the insufficient representation of direct-use and non-power applications within existing LCA datasets. As geothermal deployment expands beyond electricity generation to include district heating, balneology, greenhouse cultivation, aquaculture, mineral recovery, and CO_2 management, many of these applications remain inadequately parameterised in life-cycle models (Sondakh et al., 2025).

Mineral extraction from geothermal brines introduces additional unit processes related to chemical treatment, material inputs, and residue management, resulting in multi-output systems where environmental burdens must be allocated between energy and recovered materials. However, harmonised methodological guidance for allocation in geothermal co-production systems remains limited, and these additional processes expand the modelling requirements beyond conventional geothermal power configurations.

Similarly, CO_2 reinjection in flash systems modifies operational configurations by incorporating gas capture, compression, and reinjection infrastructure, thereby affecting energy demand and material requirements that should be explicitly represented within the operational stage. These developments introduce additional technical subsystems and product flows that extend conventional modelling structures and require more comprehensive inventory data, including parameters related to fluid chemistry, gas handling, and waste streams, to ensure consistent representation within geothermal LCA frameworks.

2.4 Field-Level Technical Variability

Geothermal systems are fundamentally field-dependent. Reservoir temperature, fluid composition, well productivity, plant design, and operational management vary substantially between sites, including within the same country. These parameters determine drilling requirements, material intensity, emission profiles, and auxiliary energy demand, thereby shaping life-cycle inventories and associated environmental impacts.

In Indonesia, geothermal development is largely associated with high-temperature volcanic reservoirs coupled with flash or double-flash technologies. Such systems typically require deep wells and intensive drilling programs. Reservoir fluids often contain elevated concentrations of non-condensable gases, particularly CO_2 and H_2S, which directly contribute to operational emissions and influence global warming and acidification results. In addition, many fields are located in remote or mountainous areas, where extensive road construction and well-pad preparation increase construction-related material inputs.

In New Zealand, long-operating systems such as Wairakei and Kawerau exhibit evolving plant configurations that integrate flash and binary technologies. Operational strategies, including reinjection, gas abatement, and make-up well drilling, differ between fields and over time. While reinjection may reduce direct atmospheric emissions, it increases electricity demand for pumping and gas management. Mature reservoirs may also experience pressure decline and scaling, leading to additional maintenance and drilling requirements that affect life-cycle performance over extended operating periods.

2.5 Data Accessibility and Institutional Context

The extent to which these field-level variations can be incorporated into LCA modelling depends on data accessibility and institutional context. In Indonesia, operational data are often constrained by commercial confidentiality across multiple private developers, limiting detailed inventory representation. In contrast, New Zealand operates within a regulatory framework characterised by established monitoring systems and greater transparency, enabling more consistent and site-specific data availability. Consequently, differences in institutional settings influence the extent to which field-specific characteristics can be accurately reflected in geothermal LCA studies.

Although harmonised geothermal LCA guidelines provide a structured methodological basis, incomplete regional inventories and limited field-calibrated data constrain their practical implementation in Indonesia and New Zealand. Partial modular coverage, expanding system configurations, and field-dependent variability reduce confidence in cross-regional and cross-technology comparisons. Strengthening country-level inventory development is therefore essential to improve the reliability and contextual relevance of geothermal LCA modelling.

3 RECOMMENDATIONS

Advancing geothermal LCA practice requires systematic strengthening of regional inventory development and institutional coordination.

Country-calibrated geothermal inventories should be developed in alignment with ISO 14040/14044 data quality requirements, with explicit documentation of technological, geographical, and temporal representativeness. Key parameters such as drilling depth, well success rates, material intensity, plant configuration, non-condensable gas composition, reinjection strategies, and auxiliary energy demand should be transparently reported. Structured data templates aligned with modular system boundaries would improve traceability and reduce reliance on non-representative proxy datasets.

Inventory coverage should extend beyond conventional electricity generation to incorporate direct-use systems, cascade utilisation, mineral extraction, and CO_2 reinjection. These configurations introduce additional infrastructure, chemical processing stages, and multifunctional outputs that require transparent allocation procedures or system expansion approaches to maintain methodological consistency.

Coordinated collaboration among operators, regulators, researchers, and database maintainers is essential to harmonise data collection and reporting practices. Alignment with existing regulatory monitoring systems can facilitate systematic inventory compilation while addressing confidentiality constraints. Regional pilot inventories can support iterative refinement of data structures, assess completeness, and test methodological assumptions prior to wider database integration.

Long-term data governance mechanisms and capacity-building initiatives are necessary to sustain inventory development and ensure compatibility with international LCA databases. Strengthened regional datasets will reduce modelling uncertainty, enhance comparability, and improve the reliability of LCA as a decision-support tool for sustainable geothermal development. Although this study focuses on Indonesia and New Zealand, the approach provides a structured template applicable to other geothermal regions.

Acknowledgements

The authors acknowledge the Geothermal Institute at the University of Auckland and the Manaaki New Zealand Scholarship for their financial and institutional support of the PhD research underpinning this study.

REFERENCES

Basosi, R., Bonciani, R., Frosali, D., Manfrida, G., Parisi, M. L., & Sansone, F: Life Cycle Analysis of a Geothermal Power Plant: Comparison of the Environmental Performance with Other Renewable Energy Systems, *Sustainability*, *12*(7), (2020), 2786.

GeoENVI: First version of Harmonized Guidelines to perform environmental assessment for geothermal systems based on LCA and non LCA impact indicators: LCA Guidelines for Geothermal Installations, (2020).

Karlsdottir, M. R., Heinonen, J., Palsson, H., & Palsson, O. P: Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization, *Geothermics*, *84*, (2020), 101727.

Kjeld, A., Bjarnadottir, H. J., & Olafsdottir, R: Life cycle assessment of the Theistareykir geothermal power plant in Iceland. *Geothermics*, *105*, (2022), 102530.

Parisi, M. L., Douziech, M., Tosti, L., Pérez-López, P., Mendecka, B., Ulgiati, S., Fiaschi, D., Manfrida, G., & Blanc, I: Definition of LCA guidelines in the geothermal sector to enhance result comparability, Energies, 13(14), (2020), 3534.

Sondakh, G. G: Life Cycle Assessment of the Geothermal Power Plant in the Patuha Geothermal Field, Indonesia, Master of Science Thesis, Reykjavik University, (2022).

Sondakh, G. G., Van Campen, B., & O'Sullivan, J: Preliminary investigation on the suitable scope of geothermal life cycle assessment, Proceedings 47th New Zealand Geothermal Workshop, The University of Auckland, (2025).