Preliminary Investigation on the Suitable Scope of Geothermal Life Cycle Assessment

Gloria Gladis Sondakh[1], Bart van Campen[1], and John O'Sullivan[1]

[1]University of Auckland, 70 Symonds Street, Auckland, 1010, New Zealand

sondakh.gloria.gladis@auckland.ac.nz, b.vancampen@auckland.ac.nz, jp.osullivan@auckland.ac.nz

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ABSTRACT

Life Cycle Assessment (LCA) stands as a critical tool for evaluating the environmental performance of geothermal energy systems, comparing to alternative energy generation and providing information for improvement. However, the geothermal industry does not have a standardized approach to LCA scope and other definitions, resulting in inconsistent methodologies and limited comparability across studies. These inconsistencies pose a challenge for practitioners, regulators, and researchers seeking reliable environmental data.

This paper presents a preliminary investigation into the challenges of defining suitable LCA scope, as well as environmental dimensions for geothermal applications. A literature review of geothermal LCA studies and methodological guidelines highlights variations in system boundaries, data availability, and technology-specific assumptions. To address these gaps, we propose a framework for engaging geothermal stakeholders through targeted surveys and expert consultations, integrating practical perspectives on scope relevance.

As part of an ongoing PhD program, this study seeks to identify critical gaps and outline research pathways that can advance the harmonization of LCA practice in the geothermal industry. The ultimate objective is to build a more consistent and robust foundation for assessing the environmental performance of geothermal energy across technologies and contexts.

1. INTRODUCTION

Geothermal energy represents a sustainable and low-emission resource with strategic applications across the energy sector. It provides dependable baseload electricity generation and supports direct-use applications in heating, cooling, and industrial processes, contributing to energy security and decarbonization goals. As the energy transition accelerates, assessing the full environmental performance of geothermal technologies becomes essential. LCA has emerged as a key methodology to quantify environmental impacts across the life cycle of energy systems, from resource extraction to end-of-life, in line with ISO 14040:2006 (International Organization for Standardization, 2006).

Despite well-established LCA standards (ISO 14040 and 14044), the geothermal sector has yet to achieve a consensus on a consistent methodological approach to defining the scope of such assessments. Differences in the selection of system boundaries, functional units, and impact categories frequently arise between studies, even for similar technologies (Frick et al., 2010). This variability hinders the comparability of results and undermines the credibility of LCA findings for stakeholders and policymakers.

This research, conducted as the scoping phase of the PhD program in Engineering Science at the University of Auckland, aims to identify critical gaps and define future research directions in understanding the environmental impacts of geothermal energy, while contributing to the development of an open-access, community-driven guideline that provides a foundation for harmonized, consistent, and robust LCA practices across the geothermal industry.

The following sections outline the main stages of the scoping phase of this PhD research: a preliminary literature review to establish the current state of knowledge, a discussion with an initial research gap analysis to identify areas requiring further investigation, and a planned stakeholder consultation to integrate practical perspectives and ensure relevance to the geothermal community.

2. LITERATURE REVIEW

According to ISO 14040, an LCA follows four key stages: goal and scope definition, inventory analysis, impact assessment, and interpretation. These stages have guided a growing body of research on geothermal energy over the past two decades. Such studies vary considerably in focus and are often grouped into three main dimensions: type of energy output, reservoir characteristics, and conversion technology. Most research focuses on electricity generation, although some studies extend to combined heat and power (CHP) applications. Regarding reservoir characteristics, LCAs have addressed both conventional hydrothermal systems and unconventional resources like Hot Dry Rock (HDR) and Enhanced Geothermal Systems (EGS). In terms of technology, analyses typically examine flash steam (single or double flash) and binary cycle systems using Organic Rankine Cycles (Marchand et al., 2015).

2.1 Scope

When defining the scope of an LCA, it is necessary to establish system boundaries. These boundaries significantly affect the LCA results, as they specify which unit processes will be included in the quantification of environmental impacts (Hauschild et al., 2018). The geothermal LCA literature is largely shaped by two primary scope approaches:

- Cradle-to-grave: A comprehensive scope that encompasses raw material extraction, exploration, infrastructure construction, operation and maintenance (O & M), and end-of-life.
- Cradle-to-gate: A more limited approach that excludes downstream processes such as decommissioning. This is often adopted when data is scarce or when the goal is early-stage comparison between design options, although it risks underestimating total impacts.

While system boundaries for geothermal LCAs are not universally standardized, this study adopts the framework established by ESMAP (2012), which delineates geothermal development into five key stages: exploration, drilling, testing, construction, and operation and maintenance (O&M). To enhance comprehensiveness and ensure alignment with ISO 14040 principles, the framework is extended in this research to incorporate the end-of-life stage, as decommissioning and site restoration may contribute significant environmental impacts (Table 1).

2.2 Impact Assessment

Life Cycle Impact Assessment (LCIA) is the LCA phase in which environmental impact scores are calculated. In practical applications, this phase is largely automated, requiring the practitioner to select an LCIA method and adjust a limited number of parameters within LCA software. Among the 12 studies reviewed, environmental impacts were consistently assessed, yet discussion was primarily restricted to climate change, expressed as global warming potential (GWP). Other impact categories were calculated but received little to no discussion, raising important methodological and interpretative questions regarding the prioritization of environmental impacts and the extent to which overlooked categories might inform more comprehensive mitigation strategies.

Table 2 provides an overview of literature highlighting the diverse methodologies and environmental impacts assessed in geothermal LCA studies of binary and flash systems. Common exclusions are often justified by factors such as the absence of standardized boundary definitions, limited data availability, assumptions of negligible environmental impact, or a targeted focus on specific environmental hotspots. A wide range of LCIA methods have been applied in practice, as summarized in Table 2, each differing in their underlying approach, mathematical formulation, and resulting outcomes. While contemporary methods such as ReCiPe, ILCD, CML, and IMPACT 2002+ have gradually converged in certain structural aspects, they still produce varying results. Comparative analyses show consistency for categories such as climate change and ozone depletion, but greater variation for ozone formation, particulate matter, ecotoxicity, and water consumption (Rybaczewska-Błażejowska & Jezierski, 2024).

3. DISCUSSION AND INITIAL RESEARCH GAPS

This paper presents a first review of literature and exposes important gaps and questions in scope definitions within geothermal LCA that significantly hinder the comparability, reliability, and practical application of existing results.

3.1 Goal and Scope Definition

The literature review revealed a persistent challenge in defining system boundaries for geothermal LCA, arising from the gap between the ideal of a comprehensive cradle-to-grave assessment and the reality of data scarcity. For instance, studies often exclude end-of-life phases like material recycling due to insufficient data. To address this, a tiered approach is proposed, where the scope is flexibly defined based on the assessment's objective. A foundational tier could use a cradle-to-gate scope for early-stage design comparisons, while a more advanced tier would adopt a cradle-to-grave scope for detailed regulatory or policy assessments. The selection of system boundaries is therefore shaped by the specific needs and priorities of stakeholders.

3.2 Expanding the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA)

Research on geothermal LCA has largely concentrated on GHG emissions, with comparatively little attention given to other key environmental impacts such as land use, water consumption, and toxicity. This narrow focus leads to an incomplete evaluation of the overall environmental impacts of geothermal energy utilization. To address this gap, the framework should broaden the LCI to capture a wider range of inputs and outputs. Consistent with best practice, this should be based on process-specific foreground data collected directly from technology developers or service operators to ensure accuracy and representativeness.

Another important aspect of LCIA is the weighting of environmental impacts. While climate change has often been the primary focus, other categories such as water consumption, land use, and toxicity also play a critical role. Although many of the studies summarised in Table 2 report multiple impact categories, the crucial question is which of these are most relevant for industry, regulators, and operators. Careful attention to impact weighting is therefore essential for developing a comprehensive and realistic understanding of geothermal energy's environmental performance, especially in comparison to alternative energy projects. To move beyond the limitations of a narrow focus, assessments require a methodological framework capable of capturing a broad range of impacts in a consistent and transparent manner. The ReCiPe2016 method provides such a framework by defining 18 midpoint categories, enabling practitioners to evaluate environmental burdens more holistically. Its strength lies not only in this broad coverage but also in its global applicability, making it suitable for consistent and comparable assessments of geothermal energy across diverse regions and technologies. By offering results that are both comprehensive and comparable, ReCiPe2016 also supports stakeholders in identifying the most relevant impact categories to guide decision-making (Huijbregts et al., 2017).

3.3 Other Potential Research Gaps

Additional gaps have been identified in diverse geothermal applications, including the cascade use of low- and medium-enthalpy resources for district heating and cooling, greenhouses, drying processes, balneology, aquaculture, and other utilizations. Furthermore, co-production of minerals and emerging technologies, such as CO_2 injection, should also be incorporated into LCA studies to capture their full environmental implications. Addressing these broader aspects will provide a more comprehensive and realistic understanding of geothermal energy's environmental performance. Taken together, these considerations highlight the complexity and multifunctional nature of geothermal LCA.

In addition, assumptions regarding system lifetimes also play a critical role in shaping LCA outcomes. Most existing geothermal LCAs assume an operational lifetime of 25–30 years; however, geothermal projects commonly remain productive for much longer, often exceeding 50 years. For example, the Wairakei power plant in New Zealand has operated continuously for 65 years and is projected to remain in service for at least another 25 years. Such discrepancies between assumed and actual lifetimes may have a significant influence on the assessment of environmental impacts.

Table 1: Geothermal LCA system boundaries adapted from literature

Author(s)	Country	Power Plant Technology	System Boundary					
			E	D	T	C	O&M	EoL
Sondakh (2022)	Indonesia	Single Flash		■		■	■	
Kjeld et al. (2022)	Iceland	Single Flash				■	■	■
Basosi et al. (2020)	Italy	No information		■		■	■	■
Tosti et al. (2020)	Italy	Flash		■		■	■	■
Karlsdottir et al. (2020)	Iceland	Double Flash				■	■	
Marchand et al. (2015)	Guadeloupe	Single Flash		■		■	■	■
Lacirignola & Blanc (2013)	Central Europe	Binary		■		■	■	■
Gerber & Maréchal (2012)	Switzerland	*EGS*	■	■	■	■	■	■
Sullivan et al. (2010)	United States	Binary and Flash		■		■		
Frick et al. (2010)	Germany	Binary	■	■		■	■	■
Rule et al. (2009)	New Zealand	Double Flash		■		■	■	■
Hondo (2005)	Japan	Double Flash				■	■	

*E: Exploration, D: Drilling, T: Testing, C: Construction, O&M: Operation and Maintenance, EoL: End-of-Life

Table 2: Comparative analysis of impact methodology and environmental impacts reported in geothermal LCA literature

Representative Studies	Impact Methodologies Applied	Key Environmental Impacts Considered
Sondakh (2022) Basosi et al. (2020)	ReCiPe2016	Climate change, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, water consumption
Basosi et al. (2020) Tosti et al. (2020)	ILCD Midpoint v1.0.9	Climate change, acidification potential, freshwater ecotoxicity, freshwater eutrophication, human toxicity (cancer effects), human toxicity (non-cancer effects), ionizing radiation human health effect, land use, marine eutrophication, mineral-fossil and renewable resource depletion, ozone depletion, particulate matter, photochemical ozone formation, terrestrial eutrophication, water resource depletion, land use
Karlstottir et al. (2020) Kjeld et al. (2022) Marchand et al. (2015)	CML (various versions)	Climate change, depletion of abiotic resources, acidification, eutrophication, stratospheric ozone depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photo-oxidant formation, terrestrial eutrophication
Kjeld et al. (2022) Marchand et al. (2015) Gerber & Maréchal (2012)	IPCC GWP	Climate change (Global warming potential)
Karlstottir et al. (2020) Marchand et al. (2015) Lacingrola & Blanc (2013) Gerber & Maréchal (2012) Frick et al. (2010) Sullivan et al. (2010) Rule et al. (2009)	Other methods (USEtox, IMPACT 2002+, CED, Ecological Scarcity2006, Ecoindicator99, EUTREND)	Global warming, acidification, eutrophication, human health, ecosystem quality, climate change, resources, seismicity risk, ecotoxicity, human toxicity (cancer), human toxicity (no cancer), water consumption, non-renewable (fossil), non-renewable (nuclear), non-renewable (biomass), renewable (biomass), renewable (wind, solar, geothermal), renewable (water)

3.4 Usefulness of LCA to Stakeholders and Mitigation

LCA has proven particularly valuable in identifying mitigation strategies that are directly relevant to both operators and policymakers. For instance, Marchand et al. (2015) recommended alternative cooling systems, such as cooling towers or air-dry condensers, to reduce environmental impacts and improve sustainability in geothermal operations. Similarly, Karlsdottir et al. (2020) emphasized substituting diesel-fueled drills with electric drills for the drilling of additional wells during plant operation, thereby lowering emissions and reliance on fossil fuels. Beyond these operational improvements, Karlsdottir et al. (2020) also highlighted more systemic solutions, such as the reinjection of CO_2 through the CarbFix method and the reinjection of H_2S via the SulFix method developed at Hellisheiði, both of which substantially reduced greenhouse gas emissions, acidification, and toxicity impacts. By systematically assessing environmental burdens and pointing to tangible solutions, LCA not only demonstrates where impacts occur but also provides actionable guidance for stakeholders to implement targeted mitigation measures, thereby supporting more sustainable and responsible decision-making.

4. NEED FOR INTEGRATING STAKEHOLDER INPUT TOWARD HARMONIZED GEOTHERMAL LCA (NEXT STEP)

As part of a PhD study aimed at strengthening the methodological foundation of geothermal LCA, the effectiveness of this work depends on the integration of input from relevant stakeholders. Such engagement is essential to identify priorities, address practical limitations, and shape an assessment framework capable of capturing the full spectrum of environmental impacts associated with geothermal energy.

To support this objective, a structured expert survey is being developed to gather insights from academics, industry professionals, policymakers, and engineers. The consultation will focus on three central themes:

- Data and Scope Definition: Evaluate the availability and reliability of data across life cycle stages and geothermal technologies, while identifying critical gaps and incorporating expert perspectives on criteria for defining an LCA scope that balances methodological rigor with practical constraints. As part of this study, the implications of extended geothermal power plant lifetimes are also examined in relation to environmental performance.
- Environmental Impact Coverage: Explore which environmental impacts are typically included in geothermal LCAs, their relative importance, and which aspects can realistically be addressed.
- Pathways to Standardization: Identify major challenges in defining, conducting, and interpreting geothermal LCAs, and evaluate the necessity, feasibility, and mechanisms for developing harmonized scope definition practices.

Key questions guiding this process include:

a. From the perspective of different stakeholders, what data gaps and uncertainties most influence the scope, quality, and reliability of geothermal LCAs?
b. Which environmental impact categories do stakeholders consider most relevant and should be prioritized in geothermal LCAs, and how should these categories be adapted for the cascade use of low- and medium-enthalpy resources, co-production minerals, and CO2 reinjection?
c. In many geothermal LCAs, the operational lifetime of a power plant is assumed to be 25–30 years, whereas in practice plants operate for over 50 years. How significant do stakeholders consider this difference to be in influencing the overall environmental impacts reported in an LCA?
d. What criteria do stakeholders believe should form the basis of a harmonized, context-sensitive framework to ensure consistency across geothermal LCA studies?
e. Which mitigation strategies and environmental management plans are currently implemented or proposed, according to different stakeholders, to address the identified environmental impacts?

Through this consultation, the study will generate evidence that complements existing literature, highlight overlooked practical challenges, and establish a foundation for frameworks that are both methodologically robust and context sensitive. These outcomes will directly inform the next stages of the PhD research while contributing to improved practice and decision-making in the geothermal industry.

5. CONCLUSION

The research sets the foundation for advancing LCA in geothermal energy by outlining the development of a framework that is both scientifically sound and adaptable. Grounded in a comprehensive literature review and supported by collaboration with researchers, practitioners, and policymakers, the framework is being shaped as part of the ongoing PhD study and will continue to evolve through further consultation and analysis. It is designed to accommodate diverse geothermal applications, technological variations, and regional contexts while maintaining consistency and transparency. By improving the reliability of assessments, the framework enhances the value of geothermal LCA as a basis for evidence-based decision-making in policy, investment, and industry. Furthermore, it reinforces the role of LCA as a trusted tool for guiding the effective integration of geothermal energy within low-carbon energy systems, while ensuring that methodological progress remains informed by continuous engagement with the academic, industrial, and policy communities. Looking ahead, the PhD aims to contribute to the international harmonization of geothermal LCA practices, ensuring comparability and transparency across studies.

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