

New Carbon Economy: Geothermal Emissions Management and Utilization in Aotearoa New Zealand, with Te Ao Māori Perspectives

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Keywords: decarbonization, greenhouse gas emissions (GHG), non-condensable gases (NCG), indigenous geothermal, Māori, emissions management strategies, New Zealand

ABSTRACT

The introduction of New Zealand's Emissions Trading Scheme (ETS) in 2008, and its extension to geothermal operations in 2010, has driven significant innovation in emissions management, with annual costs to operators around NZ\$50M. Historically, non-condensable gases (NCGs) were often released to the atmosphere during power generation. However decarbonisation pressures, including ETS costs, have prompted geothermal operators to adopt new strategies for greenhouse gas abatement. ReInjection of NCGs is now standard practice at many sites to close the emissions loop, but full reinjection is not feasible for all fields due to geological limitations and uncertain long-term impacts on production. Industries such as packaging, food and beverage, agriculture, and manufacturing rely on carbon dioxide—the most abundant NCG—create opportunities for commercial utilisation alongside mitigation.

Māori are central to New Zealand's geothermal sector, holding significant ownership of high-temperature resources, especially in the Taupo Volcanic Zone. Māori trusts and organisations are equity partners in major geothermal projects and actively shape development, investment, and operational strategies, guided by tikanga (customs) and kaitiakitanga (guardianship). As New Zealand advances CO₂ management and decarbonisation, Māori will be key decision makers, with constitutional rights under the Treaty of Waitangi ensuring their consultation and recognition in resource management policy. This paper examines current and future approaches to geothermal emissions utilisation, with a focus on commercial, environmental, mātauranga Māori (Indigenous knowledge), and Te Ao Māori (Māori world views) considerations.

1. INTRODUCTION

In geothermal power operations, non-condensable gases (NCG) are brought to the surface dissolved in / with the geothermal fluids (Figure 1). The inability of NCGs to condense (i.e., be turned into a liquid) by the cooling which occurs in geothermal power stations at the surface means NCGs are most often released to atmosphere during the power generation process. However, decarbonization drivers for addressing climate change means NCG abatement and emissions management strategies are a high priority for geothermal operators. Whilst reinjection of NCGs into geothermal reservoirs (Figure 1) has recently increased, it is likely that a combination of abatement strategies (including potential commercial use of waste gases) will be needed to address the NCG emissions issue in its entirety.

Due to its dominance (i.e. ca. 95% of geothermal gases), CO₂ is the primary focus for greenhouse gas management. Methane is a secondary focus because, despite being emitted at lower rates (typically <1.5% of geothermal gases), it is a highly potent greenhouse gas. Note: hydrogen sulfide gas and ammonia gas (<0.5%) are not greenhouse gases but must also be managed during geothermal operations because they are toxic and corrosive and can pose risks to human health and industrial operations.

1.1. Drivers for Change

Geothermal energy provides a means to decarbonize high-emission industries by providing stable, renewable heat and electricity, often replacing fossil fuel sources. However, while geothermal energy is a low-carbon energy source, geothermal plants release greenhouse gases that are naturally present in the Earth's crust and travel to the surface with the geothermal fluids.

Drivers for reducing emissions include:

1. Public and societal pressure for cleaner energy production, which influences policy and the development of more sustainable projects.
2. Investment funds and financial institutions are increasingly using environmental, social, and governance metrics to guide funding decisions. This makes low-emission and carbon-negative projects more attractive and provides better access to capital.
3. Carbon pricing regulations and mechanisms (introduced by governments) increases the operational costs for any remaining greenhouse gas (GHG) emissions, encouraging investment in emission reduction technologies.

Non-condensable gas emissions pose environmental and economic challenges for geothermal operations as their emissions are closely regulated. New Zealand legislation requires that both CO₂ and methane are measured and reported as one CO₂-equivalent number (CO₂e). The introduction in 2008 of the New Zealand emissions trading scheme (ETS) and its applicability to geothermal operations in 2010 (MFE, 2009), has been a key driver for change and innovation in emissions management within the New Zealand geothermal sector.

The New Zealand model taxes emissions similar to other jurisdictions, where carbon taxation follows trading mechanisms and other cap-and-trade type initiatives. In recent years, the price has fluctuated around an average of NZ\$50 per ton—so 500,000 tons of CO₂e has a cost to the New Zealand geothermal industry of about \$25M per year.

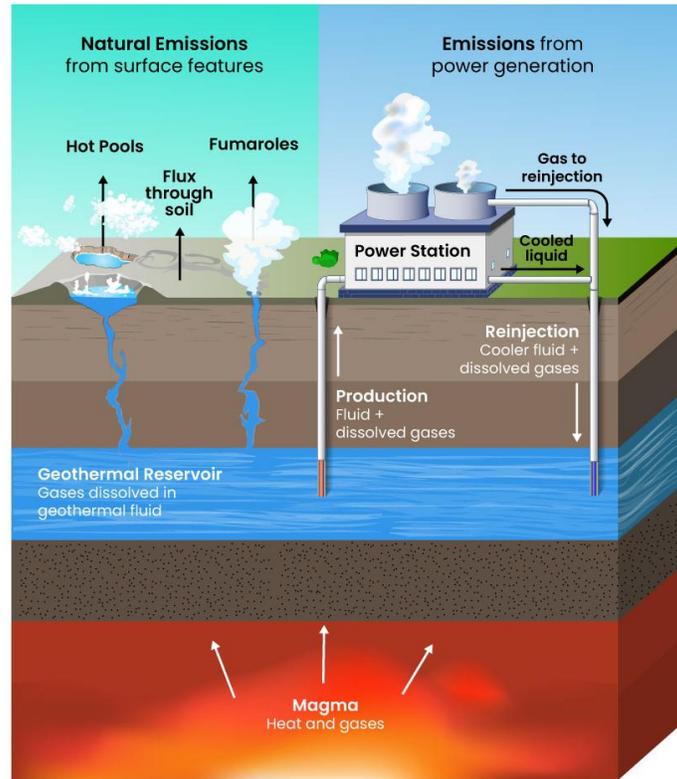


Figure 1. Schematic of a geothermal reservoir and gas emissions.

2. TE AO MĀORI PERSPECTIVES

Māori are central to New Zealand’s geothermal sector, holding significant ownership of high-temperature resources, especially in the Taupo Volcanic Zone (central North Island). As New Zealand advances CO₂ management and decarbonisation, Māori will be key decision makers, with constitutional rights under the Treaty of Waitangi ensuring their consultation and recognition in resource management policy (Lovell *et al.*, 2025). There are a variety of bespoke commercial arrangements between private companies, public companies, community trusts and Māori organizations that own and operate large geothermal power stations and industrial scale direct use facilities in Aotearoa New Zealand. These groups are partnering to operate power stations, supply geothermal fluids and heat for direct use application, and additionally are exploring innovative opportunities, including CO₂ production facilities, food production systems, novel food products, sustainable fuels and more.

Increasingly mātauranga Māori (Māori indigenous knowledge) is being consulted, aligned with and/or brought into conversation with science to support advancement of geothermal projects. Te Ao Māori is a worldview or framework that emphasizes the harmony between people, nature, and spirituality. It embodies respect for the land (whenua), waterways (wai), and all living beings as interconnected parts of a greater whole. This holistic approach promotes sustainability, community and resilience.

For Māori engaging in geothermal projects, land (above and below ground) is key. The well-being of the whenua (land), in particular the reservoir, but also the surface features, air quality and surrounding environments, is intertwined with the well-being of its people. This means that geothermal development must work with land/resources owners, and use a holistic approach that includes economic, environmental, social, and cultural considerations. Choices about greenhouse gas reinjection, venting or utilization are part of that holistic assessment, alongside effects on visible surface features, wāhi tapu (sacred sites) and local livelihoods.

Te Ao Māori focus is on the underground geothermal reservoir (which has been there a long time and will be there for a long time in the future), not the surface infrastructure (which is temporary). The reservoir is a taonga (treasure), and for some perhaps, may be viewed as an ancestor, and thus the most important thing is the continued health of the reservoir. Decisions about emissions management options, such as reinjection, venting or utilization, are therefore considered in terms of their effects on the reservoir and the wider system for mokopuna (descendants) who will inherit these relationships, not just short-term operational efficiency.

The guiding principle of kaitiakitanga is about responsibility to care for the environment. Exercising kaitiakitanga (guardianship) is a long-term commitment that can also mean securing an asset base, seeking commercial outcomes, developing resources, controlled

exploitation, stimulating community development, and managing change. Kaitiakitanga strongly aligns with geothermal reservoir management necessary for long-term (30+ years) sustainable commercial operation, the decarbonization of industrial sectors, and catalyzing economic development and employment opportunities. From a Te Ao Māori perspective, decisions about reinjection, venting and CO₂ utilization are part of exercising kaitiakitanga over the reservoir and associated surface features: good practice aims to reduce net emissions while maintaining reservoir health and respecting cultural values.

Māori participation in geothermal projects requires strong collaborations to ensure inclusive and informed decision making. This means ensuring mana whenua (those who hold tribal rights and authority over territory) decide whether, how, and under what conditions geothermal resources on their whenua are developed at all, and to set their own climate and emissions ambitions for those projects. Ideally, Māori are leading geothermal development projects, driving investment and ventures that align with community goals. In practice, this may involve Māori-led or co-led governance structures, kaupapa Māori (i.e. Māori approach) decision-making processes, and a willingness to trade off some short-term revenue in favor of long-term environmental and cultural outcomes.

3. NCG MANAGEMENT VIA INJECTION

Not all non-condensable gases are vented to the atmosphere during geothermal electricity generation. Geothermal reinjection involves pumping used geothermal fluids back into the underground reservoir. This is undertaken routinely, to manage produced fluids, sustain the geothermal reservoir and prevent land subsidence. In some plants, a significant amount (up to ~20%) of non-condensable gases remain dissolved in the geothermal fluid and are reinjected (called “passive reinjection”). In certain plant designs and geothermal fields, pressure can be maintained high enough throughout the system that all gases remain dissolved, resulting in no gas emissions.

Non-condensable gases can also be reinjected actively, by modifying the plant to dissolve the non-condensable gases into the geothermal fluid in the reinjection line (or at depth in a reinjection well via tubing). Such emissions mitigation through “active reinjection” of non-condensable gases with the expended fluids is increasingly becoming standard practice at many locations to close the emissions loop. This method has been used in Iceland, Turkey and the USA (Carmichael & Zarrouk, 2023). In this way, greenhouse gases spend a few minutes above ground, contained within the pipelines and the plant, before being returned underground.

Across the entire New Zealand geothermal industry, emissions used to exceed half a million tons each year, but that number has been steadily declining as the geothermal reservoirs themselves have degassed to a lower concentration of CO₂ (McLean *et al.*, 2024). Non-condensable gas reinjection projects have been in progress in New Zealand starting in 2021 and continuing until present day (McLean *et al.*, 2024). This has so far been achieved at three geothermal power stations – Ngāwhā, Te Huka and Ngā Tamariki (Ruiz, *et al.*, 2021; McLean *et al.*, 2024; Ghafar *et al.*, 2022). Ngāwhā power station is an example of a zero-carbon operation. The team successfully reduced emissions from the power plant equivalent to 128,000 tons of CO₂e in 2021 to zero by 2023, using 100% reinjection (Cariaga, 2023, McLean *et al.*, 2024). It is a binary plant, which meant that all the gases were still confined within the pipes, making it easier to design a system for reinjecting them back into the brine.

3.1. NCG Injection Strategies

This section briefly overviews considerations for developing a NCG injection strategy.

3.1.1 Engineering Approach and Process Design

The development of an NCG injection strategy begins with a survey of available fluid streams to support gas dissolution and reinjection, assessment of gas breakout pressures (the specific pressure at which dissolved gases within a geothermal fluid begin to come out of solution and form a separate gas phase), and evaluation of pipeline infrastructure for pressure and flow adequacy. Injectate streams with existing operating pressures above gas break out pressure are preferred since they will minimize additional infrastructure requirements. These criteria guide selection of optimal injection points and identify necessary plant upgrades for effective gas dissolution and transport, such as the use of gas compressors. In many cases, 100% NCG injection may not be technically feasible due to existing infrastructure constraints or expected reservoir behavior, and pursuing a lower NCG injection rate may be prudent.

Modelling of the resultant fluid after gas is reinjected yields predictions for pH, scaling risk and oxide layer stability. Corrosion and scaling monitoring on system start up is also required to ensure scaling and corrosion effects are identified and managed appropriately. Where possible, consideration should be made early in the strategy with respect to limiting extended piping of pure NCG streams around the power plant and steam field. Pipelines transporting non-condensable gases under high pressure and over longer distances pose a risk of larger impact zones if a containment failure occurs, due to the volume of gas that could be released. Assessing and managing the risk to personnel and the environment is an essential step.

3.1.2 Reservoir Modeling and Monitoring

Reservoir modeling is an important tool for predicting the behavior of injected NCGs, particularly in understanding the risk of gas returns to the subsurface production areas. For many established facilities implementing NCG injection, a robust reservoir model may already exist, backed by geological, reservoir and tracer test data. In most cases these are not typically calibrated to model CO₂ or gas movement through a reservoir, but they do convey an over-arching view of the established fluid flows and pressures. Regular sampling is advised to track gas returns and adapt NCG injection strategies in response to observed reservoir and well performance responses.

3.1.3 Infrastructure and Operational Flexibility

Operational flexibility is essential for effective NCG injection management. Systems should be capable of adjusting injection rates in response to changes in incoming fluid chemistry, reservoir conditions, plant performance and seasonal factors. This adaptability should be factored into the development of business strategies and in setting realistic expectations for NCG reinjection projects.

3.1.4 Health, Safety, and Environmental Risk Management

Engineering and procedural controls, such as interlocks, appropriate venting points, predefined shutdown sequences and purging procedures are necessary to control the risks associated with NCG injection systems.

The pipework carrying NCG gases (included in dissolved form) present notable health and safety hazards due to the potential release of harmful gases such as hydrogen sulfide (H₂S) and carbon dioxide (CO₂). Accurately modelling gas dispersion is essential for evaluating concentration levels and the affected area during an NCG injection system containment breach. The extent of hazardous gas exposure downwind from a containment failure is primarily determined by hydrogen sulfide rather than carbon dioxide in New Zealand geothermal fields. This may differ in international geothermal fields that have lower H₂S concentrations.

3.1.5 Regulatory and Compliance Framework

Regulatory compliance and Emissions Trading Scheme (ETS) requirements shape NCG management strategies in New Zealand. Most operators have resource consents (i.e. permits) to emit their full NCG stream, with injection mainly encouraged to lower ETS costs. Plants have been configured to be able to switch between NCG injection and emission as needed for operations and safety, allowing quick atmospheric release of NCGs when addressing equipment troubleshooting or repairs. Newer consented power plants are beginning to incorporate NCG reinjection conditions into their consents. Accommodations for adaptability is vital to a sound geothermal regulatory framework, balancing injection, environmental impact, and safety.

3.1.6 Alternative Uses and Future Directions

If complete reinjection of NCGs is not feasible, if the reservoir does not respond favorably to injection, or if there are viable commercial uses for NCGs, then it is essential to consider alternative or complementary direct utilization options.

4. COMMERCIAL ALTERNATIVES FOR NCG MANAGEMENT

This section outlines several avenues of NCG abatement in addition to reinjection, including gas capture and re-use into non-geothermal commercial applications (Figure 2), with a focus on CO₂. Carbon dioxide, the most abundant NCG, is an essential processing gas in the modern world. CO₂ is used across a wide range of industries, including food production and processing, packaging, medical and industrial applications. In New Zealand, CO₂ prices have seen dramatic increases (e.g., from <\$1/kg to over \$4/kg in some instances) arising from a combination of increased demand combined with reduced domestic supply, due to shutdowns of major local sources and supply chain disruptions. High import costs, due to shipping and overseas production, as well as the ETS adding costs to imported CO₂.

Geothermal CO₂ is a potential opportunity to create new revenue streams and support the development of low-carbon products and services, as well as displacing more emissions-intensive production methods and the need to produce CO₂ through traditional means.

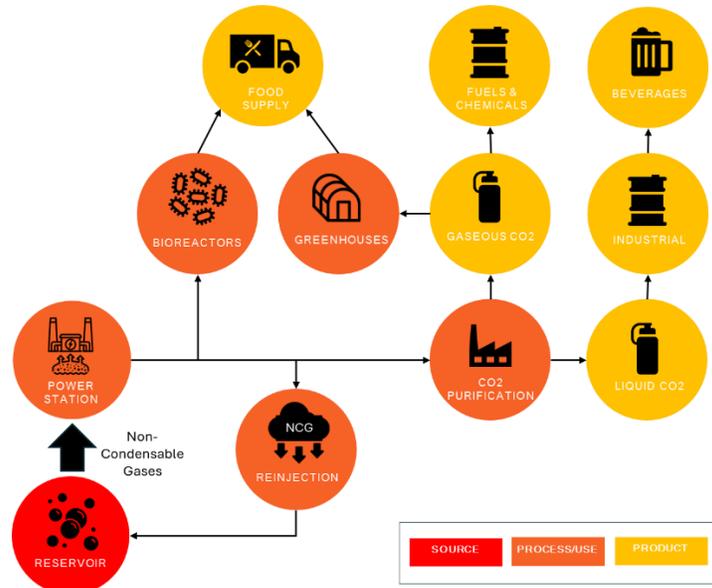


Figure 2: Potential commercial avenues of greenhouse gas emissions abatement, in addition to reinjection.

4.1. CO₂ Production Facilities

There is the possibility of purifying and selling CO₂ from the geothermal NCG stream to a wholesaler or a direct user. This could reduce emissions, generate revenue, and provide a financial benefit from the avoided emissions taxation costs (where they exist). Liquid CO₂ is used in a variety of applications, including beverage carbonation, refrigeration, packaging, and fermentation. Gaseous CO₂ is used in a variety of applications, including packaging, fermentation, and animal stunning. An industrial user of gas would likely require specific levels of purification (adapted from CO₂ Meter, 2019):

- Medical-grade CO₂ should be at least 99.5% pure and free of impurities, such as hydrocarbons, oxygen, and water.
- Food-grade CO₂ should be at least 99.9% pure and free of impurities, such as heavy metals, pesticides, and microbiological contaminants.
- Industrial-grade CO₂ should be at least 99% pure and free of impurities that could contaminate the product or process.

To meet the requirements of the food and beverage industry, the CO₂ would need to undergo purification and then be transported in liquid tanks or as bottled gas to customer/consumer markets (Brownsort, 2019). By capturing, purifying and selling/using CO₂ from geothermal plants, new industries and supply vectors can be formed. Direct collaboration with a new or established local industry is also possible. This approach offers several advantages, including enhanced certainty of supply volume and transport efficiencies (by piping directly) that can lead to competitive pricing. Moreover, partnering with an industrial entity near a geothermal site means access for the industry partner to renewable electricity, low-grade heat, fresh water, minerals, industrial-zoned land, and perhaps existing permits. There could be synergies with other local industries, such as in the New Zealand example at Kawerau or Wairakei/Tauhara where forestry offers a suitable feedstock for fuels production amongst other industrial outputs (McClintock *et al.*, 2020; Stephenson and Goodwin, 2019).

4.2. Fuel & Chemical Production

Many efforts are being made globally to leverage CO₂ in the production of chemicals and fuels production (Grim *et al.*, 2022). Advantages of this pathway are that it aids in mitigating overall greenhouse gas emissions by displacing more emissions-intensive production methods. Also, it promotes local production, reducing reliance on other countries and creates jobs for communities typically in need of employment opportunities.

Some of the most common applications of CO₂ use in chemical and fuel production include:

- *Methanol*: A versatile chemical that can be used in a variety of applications, including as a fuel, a solvent, and as a raw material for other chemicals. Methanol can be produced from CO₂ by reacting it with hydrogen in the presence of a catalyst.
- *Urea*: A fertilizer that is used to improve crop yields. Urea can be produced from CO₂ by reacting it with ammonia.
- *Polycarbonates*: A type of plastic used in a variety of applications, including food packaging, electronics and construction. Polycarbonates can be produced from CO₂ by reacting it with epoxides.
- *Fuels*: CO₂ can be used to produce a range of fuels, including synthetic gasoline, diesel and jet fuel. These fuels can be produced by reacting CO₂ with hydrogen in the presence of a catalyst. Geothermal could potentially provide CO₂ through both NCG capture and direct-air capture (DAC) on-site, making for a circular fuel system.

4.3. Food Production Systems

For horticulture, supplementation of CO₂ is a common practice in greenhouses. This is necessary because atmospheric CO₂ levels are typically low, and plants within closed greenhouse systems can rapidly deplete the available CO₂. By augmenting CO₂ levels, growers can enhance both the yield and quality of their crops (Nederhoff, 2022). Utilizing all the CO₂ from one power plant could support tens of hectares of glasshouse infrastructure by following the standard convention that 150 kg/Ha/hour of CO₂ is an optimal supply rate for closed greenhouse growing conditions (Nederhoff, 2022). For example, a 20-hectare glasshouse would require ~32,000 tons/annum of CO₂ to supplement growing, which would consume a significant portion of the ~37,578 tons/CO₂ per annum emitted at the Nga Tamariki power station (McClean & Richardson, 2021).

A 'Geothermal Food System' is being explored in New Zealand to provide a low carbon 'full inputs' indoor growing environment for primary food production. This system has three main components:

- Heat: A geothermally-heated, semi-closed glasshouse or vertical farm
- CO₂: Direct Air Capture (DAC) of carbon dioxide, a key glasshouse input
- Electricity: Modular power generation using geothermal heat

Whilst the above technologies already exist in the commercial/near commercial space, there remains uncertainty on how the systems can best operate together, coupled with geothermal energy, for a glasshouse operation. If this system can be optimised, there is a potential offering of tangible benefits to the horticulture sector and may remove barriers to large scale investment in commercial production facilities.

4.4. Novel Food Products

A New Zealand-based food-product innovation uses native New Zealand extremophilic microorganisms (extremophiles), grown on waste gases from geothermal power plants, to produce a protein-rich animal feedstock that is nutritious and digestible (Mitchellmore *et al.*, 2025). Industrial gases are consumed by a co-culture of two extremophiles (one bacterium and one microalga), working together as a consortium. The bacterium, *Methylococcus* RTK17.1, uses methane for energy and growth, but to do this it requires oxygen, and it also generates carbon dioxide. The microalga (genus *Galdieria*) uses light as its source of energy, assimilates carbon dioxide during growth, and produces oxygen. In this way, each microorganism consumes the metabolic waste products of the other and a mixed biomass is generated. For geothermal power stations, the production of food/feedstocks could transform a cost-incurring waste stream (greenhouse gases) into a valuable asset, and put these emissions to positive use. This project and the Geothermal Food System project are owned by Tauhara North Number 2 Trust, a Māori organisation with over 11,000 owners, descendants and beneficiaries.

4.5. Atmospheric Carbon Removal

As noted by Titus *et al.* (2024), geothermal energy can also be paired with the direct air capture (DAC) of atmospheric CO₂ or bioenergy-based CO₂ removal to facilitate negative emissions, and be used to offset hard-to-abate emissions (agriculture, cement, etc.) and lower the concentration of legacy CO₂ that already exists in the atmosphere. DAC requires electricity and low-grade heat, both of which are readily available at geothermal power plants. Geothermal-based DAC can use reinjected brine as the transport medium (Ratouis *et al.*, 2022) to be stored in the geothermal reservoir either as a mineral (Snæbjörnsdóttir *et al.*, 2018) or in solution (Kaya & Zarrouk, 2017). Geothermal and DAC have been successfully paired in Iceland (Ratouis *et al.*, 2022) at the Orca plant, but there is currently no commercial application of geothermal direct air capture or bioenergy carbon capture and storage in New Zealand (Figure 3).

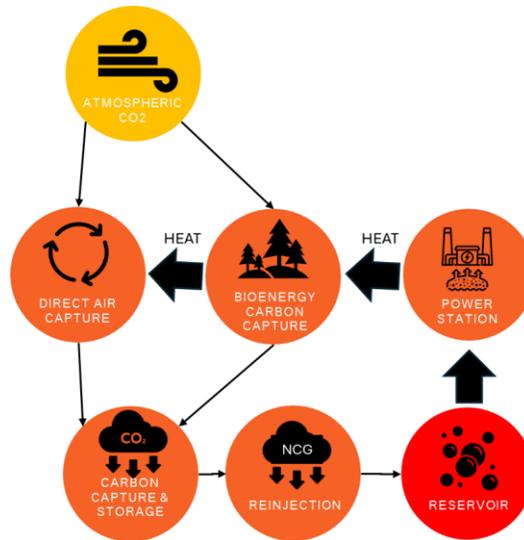


Figure 3: Direct air capture and storage (DACCS) and bioenergy capture and storage (BECCS) could utilize heat from geothermal resources and align with geothermal power station infrastructure.

5. RESEARCHING GEOTHERMAL DECARBONIZATION

Advances in several fields of research are needed to provide solutions to geothermal emissions. These include process modelling, plant design, carbon measurement and accounting, understanding scale and corrosion, reinjection efficacy, financial impacts, regulatory development, understanding the dynamics of CO₂ in a geothermal reservoir, and more (Siratovich, 2024).

Examples of related research currently underway in New Zealand are outlined below.

5.1. Reversing Carbon Emissions in the Geothermal Energy Industry: Template for Emission-Intensive Industries

Geothermal is the focus of the NZ-government funded research program “Reversing Carbon Emissions in the Geothermal Energy Industry: Template for Emission-Intensive Industries” (2022-2027; \$6M; lead: University of Auckland). The multi-institutional team research aims to reduce greenhouse gas (GHG) emissions by creating processes that enable GHG entrapment in New Zealand rock formations, especially CO₂, in solid form (Kaya & Zarrouk, 2022). The research focus is the characterization of geological, geochemical, geophysical, and fluid-dynamic properties to investigate and optimize potential trapping mechanisms and enhance GHG solubility in geothermal wastewater.

5.2. Derisking Carbon Dioxide Removal at Megatonne Scale in Aotearoa

Geothermal CO₂ removal is one of the emerging technologies being examined in the NZ-government funded research program “Derisking Carbon Dioxide Removal at Megatonne Scale in Aotearoa” (2024-2029; \$10M; lead: University of Canterbury). The multi-institutional team aims to investigate different engineered carbon-removal processes, identify the best regions for durable carbon storage, and develop robust environmental monitoring and carbon-accounting frameworks to help Aotearoa New Zealand meet its climate targets. One of the novel technologies being explored is geothermal with bioenergy-based carbon capture and storage (Titus *et al.*, 2024; Titus *et al.*, 2025).

5.3. Towards Cleaner Geothermal: the Geochemistry of CO₂ Reinjection

The New Zealand government funded research project “Towards cleaner geothermal: the geochemistry of CO₂ reinjection” (2024-2027; \$1M, lead: Earth Sciences New Zealand) is studying the effects of long-term CO₂ reinjection, in particular how reinjected CO₂ affects the overall chemistry of the geothermal system and its influence on mineral scale deposition in the deep underground.

5.4. Other

There are also a wide range of related research (geothermal and non-geothermal) including, but not limited to, laboratory experiments for CO₂ mineralization, reactions and interaction with geothermal rocks; carbon capture storage and chemistry; legal and policy dimensions of carbon capture and carbon removal; and more.

6. CONCLUSION

As the world moves away from fossil-fueled industries, the global geothermal industry can further contribute to reducing GHG emissions by reducing its own emissions profile. A significant effort would be required to decarbonize the global geothermal fleet in all locales and circumstances, as the selected abatement pathways will be situation dependent. Whilst binary plants and flash plants with surface condensers have a marginally easier task to inject NCGs, they still face the issue of understanding how much NCG can be safely and sustainably injected back into the subsurface without harming the reservoir or wells. A combination of reinjection and gas off-take at the surface offers opportunities for gases to be utilized or repurposed as an industrial commodity and an enabler to extend the reach and positive impact of geothermal resources. Geothermal operators could also add value through creative use of what has previously been regarded as waste byproduct. Advances in several fields of research as well as an innovation mindset are needed to provide solutions to geothermal emissions, and mātauranga Māori (Māori indigenous knowledge) offers a holistic approach that promotes sustainability, community and resilience to support advancement of geothermal projects.

7. ACKNOWLEDGEMENTS

We acknowledge the funding support from the University of Auckland research project “Reversing Carbon Emissions in the Geothermal Energy Industry: Template for Emission-Intensive Industries” (UOAX2211), funded by the New Zealand Ministry of Business, Innovation and Employment.

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