Reversing Carbon Emissions in Geothermal Energy Production: Te Ara Whakamua

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ABSTRACT

New Zealand is on the path to a low-emissions, climate-resilient future. The NZ parliament approved a bill to make NZ carbon neutral by 2050. These actions demand an accelerated and expanded electrification of our society and economy and aim to achieve 95% renewable generation by 2035. Geothermal energy is technically and economically viable and can provide steady and baseload electricity.

Our research aims to reduce greenhouse gas (GHG) emissions by creating processes enabling GHG entrapment, especially CO_2, in solid form while boosting energy production from geothermal resources. The study requires the characterisation of geological, geochemical, geophysical, and fluid-dynamic properties to investigate and optimise potential trapping mechanisms. To overcome current GHG storage problems, we will present novel techniques to enhance GHG solubility in geothermal wastewater and inject agents into the deep rock to ensure permanent trapping.

1. INTRODUCTION

Carbon capture and underground reinjection have been the focus of researchers around the globe (Altar & Kaya, 2020; Kaya et al., 2018; Kaya & Zarrouk, 2017; Michael et al., 2018; Oudinot et al., 2017; Ratnakar et al., 2020; Zarrouk & Moore, 2007), targeting different deep formations as a common practice to enhance resource recovery (e.g., petroleum, coalbed methane, geothermal). Geothermal reservoirs have been identified as a viable option as they are both GHG's source and storage target.

Geothermal fluid carries several magmatic-originated gases (>90% CO_2 and smaller amounts of H_2S, NH_3, CH_4, and H_2). These gases accumulate inside the power plant condensers. They are mechanically extracted and released into the atmosphere. At the same time, the waste geothermal brines and steam condensates are reinjected back into the geothermal reservoirs. The reinjected brine replenishes the reservoir and helps maintain reservoir pressure to extend the production life of the geothermal system.

The brine offers the opportunity to dissolve and permanently capture the GHG before reinjection. This has been the focus of existing international trials, e.g., Iceland (Gíslason et al. 2018), USA(Richard 1990), Japan (Yanagisawa 2010; Kaieda et al. 2009), Türkiye (Yücetaş, Ergiçay, and Akın 2018), The Philippines (Villena et al. 2005). However, this international knowledge is not directly transferable to NZ due to our unique geological environment and active tectonic setting.

Geothermal power plants are the ideal sites for GHG capture and storage trials because GHGs are already being captured in the steam condensers without mixing with the air (undiluted). The produced geothermal gases are close to the power plant with existing wells and a wealth of exploration data, environmental monitoring data (pre and post-production), and detailed reservoir models. These data can be used to investigate potential gas migration. Our research aims to develop and implement novel concepts for non-ideal rock formations by introducing other materials in reinjected water to promote the desired fluid-rock interaction for permanent storage through mineral entrapment.

2. APPROACH

Our approach builds on the learnings from the decades of research and expertise in geothermal energy (e.g., "Harnessing New Zealand's Geothermal Resources: Hotter and Deeper", funded by FRST, Geothermal Super models, funded by MBIE, Empowering Geothermal Energy, funded by MBIE). The ongoing MBIE project we are part of (Geothermal: The Next Generation) "experimentally" investigates the effectiveness of common NZ rocks for their ability to sequester GHG under strict "laboratory" conditions (no field implementation). Our research is designed to:

a) Develop pioneering methodologies for optimised long-term injection, incorporating chemical (pH) modifications and the addition of ions to reinjected brine to ensure that GHG is permanently trapped in deep rock environments.

b) Apply best engineering practices to capture the gases and dissolve them in geothermal wastewater, with a focus on the GHG extraction system.

c) Select optimum target zones for injecting dissolved gases and setting operating parameters.

d) Design a prototype pumping and reinjection system using the appropriate construction material, and install a pilot capture and storage demonstration to validate our technology. We will explore the application of our technology in at least one existing geothermal development, where we can demonstrate a measurable reduction in GHG emissions from an existing source.

e) Develop a semi-commercial scale extraction plant by determining the optimum operational envelope.

f) Using an existing geothermal power plant, as a demonstration site, our approach will safely and continuously test the disposal of > 90,000 tonnes of CO_2/year, starting from year four of this project.

Our long-term goal will be to dispose of the remaining 468,000 tonnes of CO_2/year currently produced from all other geothermal plants in NZ (McLean et al., 2020). Our vision and the ultimate impact is to extend our technology to dispose of GHG from other emission-intensive sources.

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2.1 Research aims:

a) Develop and test a novel pH modification method for water to increase the dissolution of GHG in geothermal wastewater. We will design a dedicated absorption column with ceramic beads to enhance the dissolution reactions.

b) Design and build a pilot injection system, incorporating different chemical dosing to ensure the permanent mineral entrapment of GHG in a deep rock environment.

c) Build a framework for tailoring the GHG capture technologies specific to different power plant designs.

d) Develop new models for the interaction between different rock and fluid types to ensure applicability across the range of fluid composition and rock formations in NZ and international geothermal fields.

2.2 Science stretch

We will advance know-how in the following areas:

- Incorporation of advanced laboratory validated technology within the surface facility of geothermal power plants and underground GHG entrapment targets.
- Fluid-rock interaction through NZ's first field trial and long-term monitoring of GHG storage, which only basic theoretical knowledge exists. This is through identifying which rock mineralogy best capture CO_2 investigating important unknown binding kinetics and understanding the optimal conditions of the reinjected brine.
- Carrying out this research within the unique NZ geological formations and temperature and pressure conditions will generate new knowledge impacting GHG entrapment technology a commercial adoption.
- Creating a legal and regulatory framework and new derisked opportunities for industry, iwi, and landowners.

Our programme will deliver scientific knowledge and technological know-how to empower Māori Incorporations and Trusts to utilise the environmentally friendly energy potential of Māori-owned lands. This programme centres on a deep-partnering approach with Māori stakeholders, who will not only benefit from the programme, but also play a key role in providing context and knowledge.

The research will incorporate kaitiakitanga perspectives and guidance to support the long-term, sustainable use of geothermal resources. Our approaches will be consistent with Māori data sovereignty, and principles for the implementation of sustainable business management.

Additional science benefits:

- There are also spin-off benefits from this project by extending any proven technology to other conventional emission sources and providing opportunities for commercial consultancy for technology/IP transfer.
- Through this research, we will improve our understanding of deep geological structures such as faults/barriers.
- By stopping the injection of chemical agents, the new technology can be used for well stimulation/permeability enhancement to improve the production of geothermal fluid from damaged wells to commercial levels.

3. DETAILED METHODOLOGY

GHGs naturally occur in geothermal fluid and are commonly concentrated and captured in the condensers of geothermal power plants before being (typically) released into the atmosphere (Figure 1). We will address the fundamental scientific and engineering challenges for reinjecting GHG back into geothermal fields.

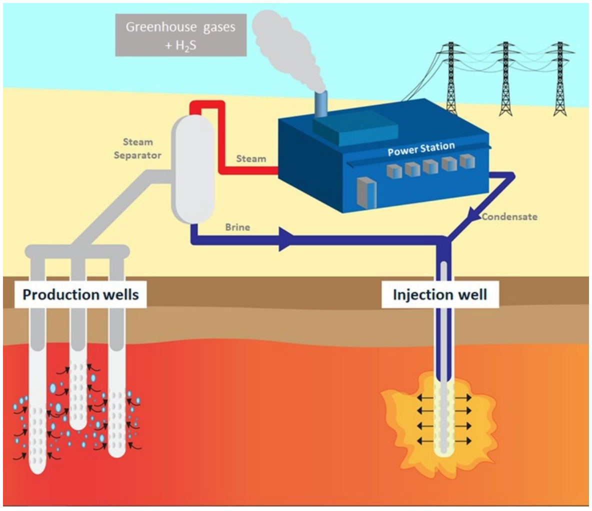

Figure 1. Today's geothermal power station design with the GHG released into the atmosphere

With numerous existing geothermal developments, iwi interests, and proven potential, our research integrates and expands the body of information in geoscientific, gas emission, numerical simulation, and production information already available with experimental research and equipment design. We are addressing critical scientific and commercial challenges that prevent GHG-CS (Greenhouse gas - Carbon capture and storage) programmes in NZ and the world.

The programme is structured into four multidisciplinary themes: Examine, Investigate, Implement and Integrate, and Incorporate.

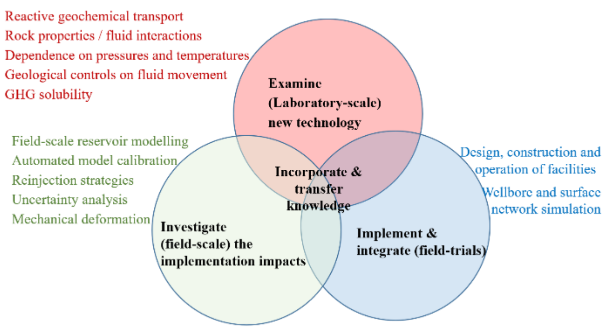

Figure 2. Research methods and their interconnectivity

3.1 Examine: Laboratory-scale investigation of the novel technology.

We will develop and implement a novel pH modification method for reinjected water through experimental testing by adding sodium carbonate (soda ash, baking soda, etc.) to the water. This is to increase the water pH and, hence, increase the solubility (dissolution) of the waste gases (CO_2 and H_2S)

in the reinjected water (Figure 3). Accordingly, this results in a significant reduction in wastewater needed for capturing the GHGs with no reliance on fresh/natural water resources.

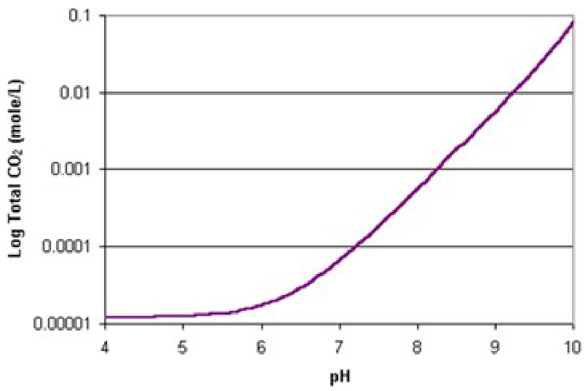

Figure 3. The relation between total dissolved CO_2 in water and the water pH (Farid 2021)

This might appear, at first glance, a straightforward process. However, preliminary work (Altar and Kaya 2020; Castillo Ruiz 2021) indicates that the injection of CO_2 dissolved in water might cause interaction with some of the common geothermal reservoir rock types in NZ, resulting in rock dissolution. This may not be desirable when the aim is to permanently store GHG, since rock dissolution might cause an increase in rock permeability and the possible migration of the waste gases to the ground surface or the nearby production geothermal wells. However, if iron, magnesium and calcium ions are present in the geothermal reservoir rock (e.g. Basalt), they will chemically react with the GHG dissolved in water, forming solid carbonate minerals (Figure 4). To overcome the lack of these minerals in other reservoir rocks (e.g., Greywacke), we will add these readily available ions compounds through a different path; the annulus between the well casing and the dissolved GHG injection tube (Figure 4). This reinjected chemically-modified water mixture will boost the GHG mineral entrapment and ensure permanent storage and safeguard against dissolving reservoir rocks, when it is not desired.

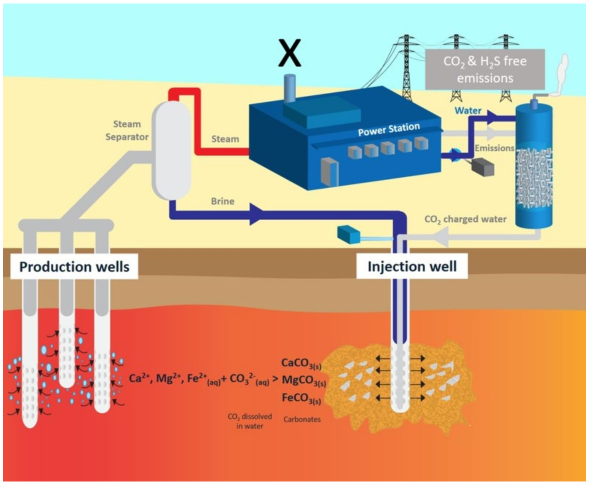

Figure 4. CO_2 injection pilot equipment lay-out, showing the formation of carbonate minerals for a controlled mineral entrapment (not to scale).

We will conduct packed-bed column experiments to ensure optimum pH modification is achieved. We will also test the proportion of ions that we need to add given the rock types and properties of the wastewater.

We will work with our international collaborators on laboratory scale testing (core flooding experiments) our methodology, using sedimentary rock types (non-geothermal) to apply the new controlled mineral entrapment technology. This is to allow the transfer of this technology to other (petroleum, mining, ore processing) industries.

3.2 Investigate: Field-scale implementation impacts

This stage includes numerical reservoir modelling of GHG storage and mineral entrapment:

We propose to develop computational fluid and heat flow/rock-chemical models of geothermal reservoirs in various fields in NZ to explore the differences in their potential for GHG-CS. The input data to the reactive modelling will be obtained from the existing MBIE-funded project (Geothermal: The Next Generation), while a fully-calibrated reservoir model of several established geothermal fields in the Taupō Volcanic Zone (TVZ) will be made available by our industry partners and collaborators.

The numerical models will include the normal flow of fluids (water and GHG) and heat, with detailed surrounding rock properties. These models will be further developed to include full-scale fluid/rock interaction parameters (thermodynamics and kinetics) and will be used to investigate and update GHG's capture and possible migration.

In the early stages of GHG capture and injection field trials, we will work with our industry partners to inject small quantities (about 40 to 50 tonnes) of compressed GHG (gas-phase) without being dissolved in water. The aim is to use the concentrated GHG captured by the power plant facility as a natural and fast-traveling gas tracer (e.g., similar to a dye). This is to study the worst-case scenarios of the impact on the faults and gas migration in the system within 6 to 12 months. Reservoir modelling of these field trials will help refine the reinjection process and allow feedback and coupling with the aboveground gas monitoring network. This work stream will help select the wells suitable for long-term GHG injection for any given site while optimising the long-term injection and monitoring GHG storage. This will be launched while detailing the behaviour of GHG under real reservoir conditions, modelling system sustainability and interactions between rock and fluids, and quantifying the potential of CO_2 sequestration into the different types of reservoirs.

We will select the best wells within the chosen geothermal field that can be used for GHG injection with a minimum chance of GHG breaking through to the ground surface or the nearby geothermal production wells. This work will use existing information provided by our industry partners, including the numerical reservoir model that will be used to run several (best and worst case) modelling scenarios.

3.3 Implement and integrate: field-trials

Designing the GHG capture, pumping and reinjection system, selecting the appropriate construction materials and installation technology. Working with our industry partners, we will be involved in the installation, operation and monitoring of the injection system.

Starting from the existing power-plant design focusing on the GHG gas extraction system, we will investigate the best engineering options to capture the gases and dissolve them in the geothermal wastewater. The water/gas dissolution system will involve further water-cooling and ceramics-packed beds in a vertical absorption column under high (~5 bar) pressure (Figure 4). This will involve:

- A special modification to the reinjection well normally used for brine reinjection to include a long tube to the depth of the water loss zone (Figure 4).
- High-pressure pumps for the two types of geothermal wastewater (brine and condensates).
- A high-pressure gas compressor with the necessary cooling tower to reduce the temperature of the gas and increase the solubility in wastewater.
- A large high-pressure tank/absorption column filled with ceramic-packed beds increases the surface area for the liquid-gas reaction. This is where the novel pH modification technique will be added to increase the solubility of GHG in the geothermal wastewater and to reduce the size of equipment.
- Some of the low solubility geothermal gases in very low concentrations (e.g., hydrogen) will be released into the atmosphere through a small pilot-size flare (the burning of hydrogen in the flare will not produce GHG, but only water vapour) (Figure 4).
- Field testing will be used to validate and improve research on the influence of GHG-rock interactions. Simultaneously, we will quantify the benefits of reservoir pressure support from the injected fluids, leading to a higher generation efficiency.
- Monitoring long-term migration, trap mechanisms and seismicity of the GHG trial via aboveground measuring/monitoring networks.
- Present results of this technology to different new end-users (petroleum, mining, ore processing and other carbon-intense industries) and facilitate commercialisation and IP transfer.

The dissolved fluids will be reinjected under absorption column pressure into the geothermal well through a long tube (Figure 4), taking the fluid all the way to the geothermal well loss zone. Two injection scenarios will be considered: injection of geothermal water condensates only or combined reinjection of water condensates and hot separated water (brine).

3.4 Incorporate - Incorporate and transfer knowledge

An essential part of this project is to integrate the scientific results for the wider community and transfer them to new end-users. We will establish a coordinated strategy, educate and promote enhanced and integrated GHG-CS in NZ's geothermal systems. This step targets three groups of critical stakeholders: Iwi and the wider NZ public, industry and Government.

Policy and regulators:

Working with the central Government, regional authorities (e.g., WRC, BOPRC), and other agencies, we will form "GHG-CS Geothermal Energy Strategy Action Group." This is to help revise regional development policy with allocation guidelines resulting from our new insights concerning NZ's GHG abatement in geothermal systems. Once this technology is adopted, our work will influence engineering, plant, and infrastructure investment and establish underpinning knowledge for the new, high-value technologies and a cleaner environment.

Our GHG-CS Geothermal Energy Strategy Action Group will guide us to set up an "Industry Opportunity Guideline" for industrial GHG-CS both locally and internationally. This is a way to set up resource management regulatory and legal framework standards. A key element of this initiative is establishing an industry/iwi coordinator to focus on and promote engagement, consultation, and commercial opportunities for iwi. GHG-CS Geothermal Energy Strategy Action Group will also advise on international opportunities for implementing and marketing this IP.

Communication of the programme science outputs, industry findings, and guidelines to technical and non-technical audiences will be achieved via a geothermal GHG website. Open access download of publications, case study brochures, hui, visits, and public engagements will create industry-ready information about potential end-users. We aim to identify opportunities and initiatives internationally to learn progress on new industrial applications and promote the utilisation of innovative and novel uses of this technology to allow cleaner (zero-emission) utilisation of geothermally-sourced energy.

4- IMPLEMENTATION PATHWAY(S)

We have developed our programme to support industry aspirations. Our partners will provide technical support and direct involvement in field trials.

Co-design

We developed our programme after several years of ongoing communication and consultation with our local and international collaborators (Figure 5), including Iwi-owned companies, land trusts, international science collaborators, and end-users. The development of a strategy that embraces GHG reinjection feasibility is of particular interest to regional Government, especially in light of the climate emergency declared by the Government in late 2020. We are working closely with Māori throughout our programme (Figure 5), jointly developing our implementation pathway and timeline.

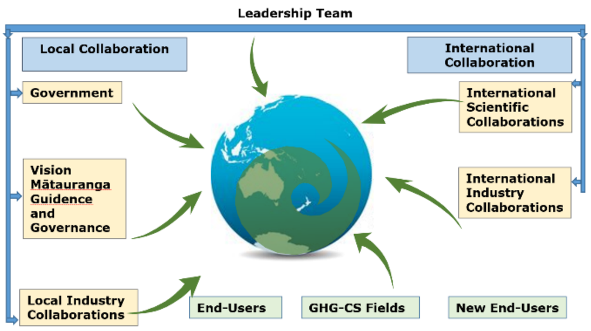

Figure 5. Research programme general structure and implementation partners

With our research and industry collaborators, we will initiate a detailed GHG-CS strategy to guide the sector activities for a 25-year timeframe. It will help to coordinate the promotion of long-term technology implementation, economic development, and jobs anticipated from the development of NZ's GHG-CS projects.

Māori insights into the challenges of geothermal projects resource consents and re-consents through setting policies and legal frameworks will help our programme be treaty-based and achieve more significant well-being outcomes.

1 RESEARCH TEAM

The research programme is going to be led by New Zealand specialists from the University of Auckland (UoA) and GNS Science (GNS). The international science team includes the University of Tulsa, USA, Delft University of Technology, Netherlands, Kyushu University, Japan, Dokuz Eylül University, Türkiye, GZB, Germany, and Italy. The research team has a well-sequenced path of tasks, projects, and milestones to achieve project outcomes. Outcome delivery risk is mitigated by the research team's strong track record, global contacts, institutional support, and long history of collaboration.

Our International industry collaborators will provide international geothermal field data unique to their regions and share their experience from their ongoing GHG injection investigations.

International collaborations with experts for field applications and development of commercial-scale plants will ensure the programme can adaptively manage any relevant advances in geothermal research undertaken offshore. (e.g. lab-scale experiments will be conducted in Germany, on injection and provide data to assess the large scale implementation on sedimentary rocks in Europe. test data will be provided from Kizildere and Umurlu geothermal fields in Türkiye).

The GHG-CS Geothermal Energy Strategy Action Group (Figure 5), which includes some of our international partners, will further drive the programme's focus on ensuring research stretch and next-generation capability development. Together we will identify initiatives, challenges, opportunities and share knowledge on a novel implementation of GHG reinjection and mineral entrapment technology.

2 CONCLUSION

In this project, novel technology will be developed to reduce carbon emissions from geothermal power plants by reinjecting and mineral trapping GHG back to the geothermal reservoirs where they originally came from. This is in line with the New Zealand government's targets of renewable electricity generation by 2035 and net zero emissions by 2050.

While there have been several investigations and projects in New Zealand and overseas to capture and store GHG deep underground, geothermal power developments provide the best opportunity. This is because the geothermal projects typically capture (but release) the GHG and have existing reinjection wells for the return of the GHG back into the deep rock formations.

Our technology is based on controlling the chemical reactions between the reinjected gases and the reservoir rock to convert the waste gases into solid form, which will be permanently stored underground.

Our programme will play an essential role in unlocking the potential of Māori resources. It will underpin research for the development of 'carbon-negative' energy, economic growth, know-how, and job creation while sustaining the environment.

Partnering with New Zealand and the international industry, iwi, and local Government will provide the essential understanding and proven applied implementation of GHG-CS in geothermal systems. Underpinning further advances in GHG disposal and storage from other fixed emission sources.

Once proven, our novel technology can potentially be deployed to other, more intense GHG emission sources (e.g., power production, material processing, industrial-scale forestry, and dairy).

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