NEW ZEALAND'S PATHWAY TO SUPERCRITICAL GEOTHERMAL ENERGY USE: MOVING FORWARD TO EXPLORATION DRILLING

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ABSTRACT

Where is the best location to drill Aotearoa New Zealand's first supercritical geothermal exploratory well? The answer will soon be needed in working to define New Zealand's supercritical geothermal energy opportunity and to advance exploratory supercritical geothermal well drilling.

Early supercritical projects are expected to have long lead times, thus additional research and inquiry should be embarked upon now to ensure future supercritical geothermal developments can align with New Zealand's low carbon economy and energy sector aspirations. Sector-wide roll out of supercritical geothermal operations ideally needs to occur before 2050. Working backwards, pilot and scale up demonstration of supercritical energy production would be needed by about 2040, and thus, the first exploration wells need to be drilled by 2030 or soon after.

This paper outlines preparatory and pre-planning work for drilling a supercritical exploration well. Unknowns include drilling location, well design, drillability, fluid handling, appropriate surface facilities for energy transformation, consenting and more. Traditionally large geothermal operations would have an electricity production focus, but there may be other drivers to undertake the energy transformation, which produce carbon friendly energy. Best practice information for engagement, planning and regulatory framework, and the handling and use of supercritical fluids should be developed as part of determining if supercritical geothermal is a viable industrial energy opportunity for Aotearoa New Zealand. The aim is to advance understanding and knowledge of the nation's supercritical geothermal potential for existing and potential new users of high enthalpy geothermal heat resources.

1. INTRODUCTION

Supercritical geothermal conditions are extensive deep in the Taupō Volcanic Zone (TVZ) above and in proximity to partial melt conditions, offering prospects of high temperature (400 °C – 600 °C), renewable, low-carbon geothermal energy. Whilst supercritical geothermal is not a new idea globally, the conditions have not yet been encountered in geothermal wells drilled for energy production in New Zealand. Hence, early New Zealand supercritical projects are expected to have long lead times, as technical mastery develops the level of understanding sufficient to offer industry-ready, economically feasible solutions.

In order to advance this opportunity for Aotearoa New Zealand, and to ensure supercritical geothermal is considered in the future renewable energy portfolio, research is needed now (even if this opportunity is never fully realised) to match the Government's aspirations and environmental drivers demanding fast solutions in transitioning to low-carbon renewable energy.

This paper explores some of the emerging thinking that is being developed as part of, and alongside, the *Geothermal: The Next Generation* research programme, including:

- Using a strategic approach to realise the Aotearoa New Zealand's supercritical geothermal opportunity
- Geoscience to locate exploratory drilling targets
- Supercritical geothermal exploratory well design
- Consenting for exploratory drilling
- Surface plant for energy transformation
- Innovative energy transformation technologies

2. SUPERCRITICAL GEOTHERMAL: AN OPPORTUNITY FOR AOTEAROA NEW ZEALAND

Why drill deeper and into hotter, possibly even supercritical, geothermal conditions?

As well as generating low-carbon, renewable electricity, geothermal energy is an important enabler of investment in parts of Aotearoa New Zealand's strong and competitive business sectors. Geothermal energy is a contributor to a number of sectors; food and beverage, horticulture, renewable energy, technology and innovation, tourism, and wood processing (Daysh et al., 2020; White & Chambefort, 2016; Climo et al., 2016), supporting regional economic growth and Māori socio-economic development. Realising supercritical geothermal would build on this success offering additional future investment opportunities.

Supercritical conditions may be an opportunity for maintaining and expanding existing geothermal infrastructure in a producing geothermal field, providing an energy refresh, whilst retaining the existing land footprint. Supercritical resources may also present an opportunity for new geothermal ventures beyond the boundaries of currently known geothermal resources.

As well as potential for energy efficiency improvement and more effective industrial heating processes, new industrial processing operations might be established. Current process heat supply from geothermal delivers usable process temperatures up to about 220˚C; what opportunities open up if supply temperatures can be provided above 300˚C?

Supercritical, and conventional, geothermal energy resources could also be an enabler for other low-emission fuel production, such as biomass and green hydrogen, aligning with Aotearoa New Zealand's transition to a low-carbon energy sector and economy. Geothermal energy is being used for green hydrogen production in New Zealand on a pilot scale (Scoop, 2020) and maybe supercritical geothermal could enhance this opportunity for both domestic and international use (MBIE, 2019).

3. A STRATEGIC APPROACH

How do we move Aotearoa New Zealand's supercritical resources from potential to reality?

Large geothermal energy development projects are characterised by significant upfront investment and quite long lead times; the development of a geothermal resource, from exploratory surveys to operational facilities takes from years to a decade or more (Carey, 2015). Significant unknowns to be overcome relating to supercritical geothermal include: resource and drilling locations, applicability of consenting frameworks, well design, drillability (as more ductile rock conditions are encountered), fluid handling, fluid chemistry, deposition and corrosion risks, materials, appropriate surface facilities for energy transformation and more.

A strategic approach is needed that moves New Zealand's supercritical resources from potential to reality, where supercritical becomes technologically business as usual (BAU). A supercritical strategy for Aotearoa New Zealand is being developed (Climo et al, 2020), which seeks to leverage existing knowledge, learn from international collaborators, work closely with priority stakeholders, and explore new ways to reduce risk and accelerate investment. Strategically, there are four critical questions to be addressed:

1. Where are the supercritical geothermal resources?
2. How do we drill in supercritical geothermal conditions?
3. How do we handle and use supercritical geothermal fluids?
4. How do we de-risk and accelerate investment?

Addressing each of these questions requires significant expert activity across science, engineering, finance, planning/regulatory, and societal engagement.

To align hot, deep supercritical geothermal with New Zealand's low carbon economy and energy sector aspirations, sector-wide roll out of supercritical geothermal operations ideally needs to occur before 2050. Working backwards, pilot and scale up demonstration of supercritical energy production would be needed by about 2040, and thus, the first exploration wells need to be drilled by about 2030. This timeline considers that supercritical technology in New Zealand is currently at a low level of readiness (Climo et al., 2020). To reduce the time to achieving earlier deployment, early and greater investment in these work streams is necessary, focusing on the areas that have potential to delay or derail progress. The research and investigations required will need to be undertaken in parallel (Figure 1). Risk sharing and other incentivisation mechanisms might usefully be implemented to assist in attracting investment funding to progress exploratory drilling, and pilot plant and scale up activities.

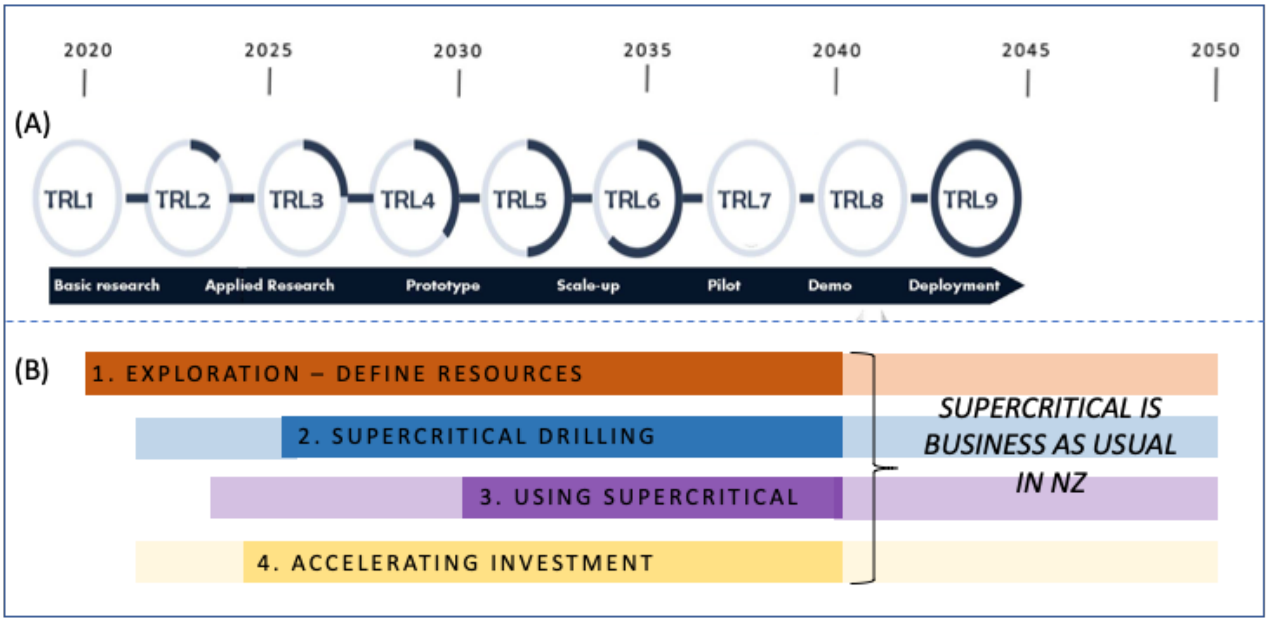

Figure 1: Conceptual timeline for moving Aotearoa New Zealand's supercritical geothermal to business as usual. (A) Technology readiness levels (from EARTO, 2014). (B) Activity timing for the four key questions to be addressed.

4. GEOSCIENCE TO LOCATE EXPLORATORY DRILLING TARGETS

Where are the most promising locations for supercritical exploratory drilling?

Identifying these locations is a focus of the *Geothermal: The Next Generation* (GNG) research programme (Chambefort, 2019), with a goal to deliver exploratory targets for drilling into supercritical conditions in the TVZ.

Aotearoa New Zealand's central North Island hosts more than twenty large geothermal systems, making it one of the few places globally where geothermal development is accessible and technically feasible. The TVZ is the onshore extension of the Kermadec Arc formed by the Australia and Pacific Plate subduction zone (Caratori-Tontini, 2019), which creates a region of thin crust and high heat flow (Bibby et al., 1995). This heat flux is driven by a combination of widespread deep, cooling melt (Hamling 2015; 2016), as well as by shallower magma reservoirs associated with individual volcanoes (Ilsey-Kemp, 2021). These magma systems provide the energy that is contained in rocks at supercritical temperatures (Chambefort et al., 2017; 2019). Theoretically, supercritical geothermal fluids contain significantly more energy than conventional geothermal fluids found at current depths (~3.5 km) and reservoir temperatures (<350°C).

Researchers are using data, modelling and interpretive methods, focusing on depths shallower than 10 km, to test the hypothesis that promising supercritical conditions in the TVZ are found where magmatic derived heat encounters buried fault structures above the ductile crust. Geological, structural, and geophysical data are being re-modelled and interpreted to identify locations of shallower supercritical geothermal conditions. Modelling of thermomechanical and thermochemical processes of heat transfer from magma to the surface is underway, seeking to assist in identifying promising locations with supercritical conditions.

A range of geophysical data along with the application of advanced techniques, some of which are being developed as part of the GNG work streams, are crucial. Existing magneto-telluric (MT) datasets (such as Figure 2) are being re-modelled to fine tune magma and geothermal fluid locations. In parallel, new seismic tomography models are identifying low velocity regions also associated with magma and fluid, providing an important constraint on MT model interpretation. Compilation of aeromagnetic data will be used to locate the depth to Curie Point, indicative of rock temperatures of ~580°C while new gravity models will identify important crustal structures and the depth to basement rocks. Then these complex geophysical models will be tested using numerical simulation to constrain the potential for supercritical fluid conditions in the crust.

This work will likely produce a number of scientifically promising exploratory well locations. The ease with which these, or one of these, sites can then be drilled will depend on a range of factors including: The approvals required under the prevailing regulatory regime, land owner interest in facilitating well drilling, the proximity to infrastructure to support the drilling operation, financing, and then more generally for the longer term, the ability to facilitate a large geothermal development in the general area of the exploratory location.

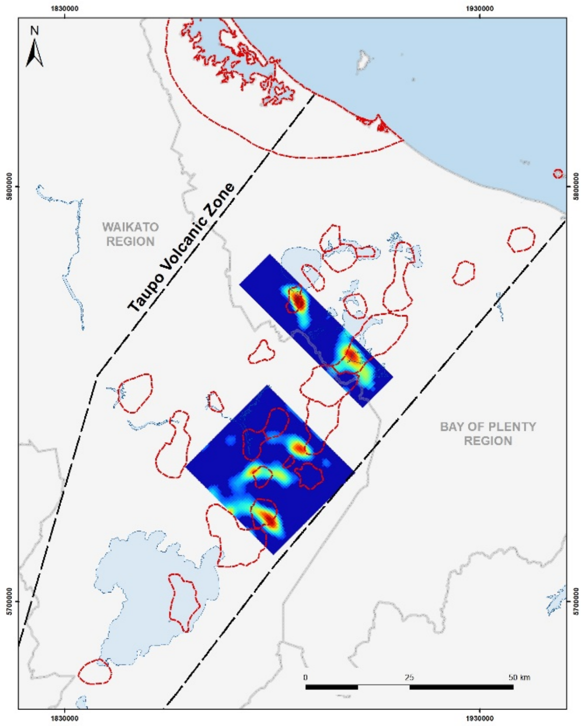

Figure 2: TVZ magnetotelluric inversion models (Heise et al., 2015; Bertrand et al., 2015), sliced at a reduced level of -5000 metres, overlaid on known geothermal fields (dashed red outlines). Within the blue shaded slices, the red areas of shading are the lowest resistivity zones, which are the most altered by geothermal fluids, or partially melted.

5. SUPERCRITICAL GEOTHERMAL EXPLORATORY WELL DESIGN

What underground conditions will drilling likely encounter?

Geothermal well design identifies the required equipment, materials, and drilling procedures to ensure a satisfactory well completion and an acceptable well life. This selection and design process must consider the subsurface conditions likely to be encountered during the drilling process. To advance well design, in parallel with the scientific work described above, two synthetic well prognoses have been developed (Carey et al., 2021), structured to define the conditions expected to be encountered and to be contained by a supercritical geothermal well in the TVZ drilled to 6km.

Geological prognoses and temperature - depth profiles are shown in Figure 3. The locations selected were (i) on the margin of the Rotokawa Geothermal System (SC-2), and (ii) in a location midway between Ohaaki and Ngatamariki (SC-1), some distance from a currently identified geothermal system. The main difference in the prognoses is the expected drilled depth from the surface to the metasedimentary basement rocks; in SC-1 the contact is predicted at 2800 m, whilst in SC-2 it is predicted to be close to a depth of 2000 m. Above the basement metasedimentary rocks is a volcanic stratigraphic pile. Pressure - depth conditions expected are hydrostatic from the surface down to the metasedimentary contact, and probably sub-hydrostatic in the metasedimentary rocks.

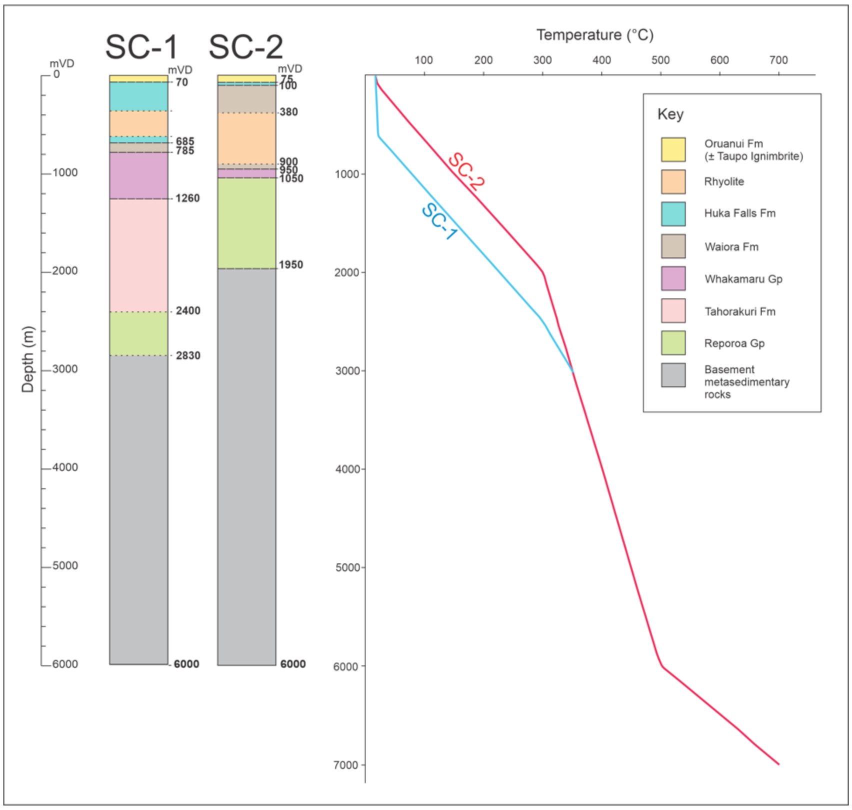

Figure 3: Stratigraphic prognoses and the estimated temperature profiles for SC-1 and SC-2.

Important for well design is to identify what is expected from the well once constructed. Do the wells need to produce fluids under flowing conditions to enable fluid sampling and well testing for fluid and energy production? A slim bore design for characterising downhole conditions is less desirable, because without the capacity to be produced there is an information gap on the ability to flow fluid up from 6 km underground, and an absence fluid chemical characterisation of representative samples that relatively free from the influence of drilling fluids. These data will be important in moving from assessed to actual characteristics of measured geochemical compositions. To collect representative chemical samples, a sufficient period with a well flowing is required to clear drilling fluid related chemical aberrations from the well fluids. This information will be informative in furthering plant design and ultimately business case preparation.

The well designs are anticipated to be challenging regarding materials of construction, to withstand the thermal stresses, pressure and chemistry. The use of high nickel, chrome, molybdenum alloys is being studied and reported in the international literature (Krogh et al 2021). Material selection will be influenced by the anticipated lifetime of the well, as well as the short-term ability to withstand the stresses of well construction and heating. If the well is to have a short life so that it is drilled, flow tested, chemically characterised and then abandoned by being cemented back to surface after testing, the materials of construction might well be different to that of a well drilled to become part of a permanent geothermal production development. To be considered is the realistic material lifetime under the high temperature thermal conditions where creep is reasonably anticipated, and the chemical changes experienced as the fluid state changes from the supercritical phase with reducing pressure and temperature. At the point of phase change, the potential for deposition and corrosion is anticipated to increase rapidly with the rate controlled by the geothermal fluid chemistry.

Also, what of transient conditions when starting and stopping wells? What phase changes will be associated with heating on start-up and cooling on shutdown?

Operational drilling considerations will need to be further investigated in drilling into hotter rock conditions, such as:

- Overall rig capacity capable of constructing the well to the depths required.
- Drillstring hydraulics, drill pipe sizing and appropriate rig pump rates to keep the downhole and surface conditions sufficiently cool in drilling into supercritical conditions at 6 km, while still maintain sufficient flowrates to clear cuttings.
- Selection of drilling fluids to provide adequate performance under the extreme conditions expected.
- Thermal and chemical effects on the drillstring, and on critical drilling tools and equipment whilst drilling.
- What will be required for well control during drilling, and what sort of wellhead will be required for the completed well?
- In progressing the well, is cooling adequate to "strengthen" the near wellbore rock to adequately avoid or adequately delay ductile rocks closing in around the drill pipe above the drilling collars as conditions approach ductile temperatures?
- Being able to effectively cement the casings into the well, avoiding risk of casing buckling and damage from thermal stresses, and achieving zonal isolation using cement.
- Building sufficient redundancy and contingency in the well design such that unfavourable drilling conditions can be managed and overcome without compromising the final useability of the well, and
- What effect lost circulation and internal formation fluid flows will play on the risks and challenges of drilling hot and deep geothermal wells

Once designed, cost estimates will be developed for the drilling operation necessary to complete the well.

6. CONSENTING FOR EXPLORATORY DRILLING

What consents are required for drilling a supercritical exploratory well in the TVZ?

In the *Geothermal: The Next Generation* programme, the planning team have developed a description for a project drilling to depths at which supercritical conditions in the TVZ are anticipated in order to assess the permitting requirements under the operative regulatory regimes in the Waikato and Bay of Plenty Regions and the relevant District Councils (Kissick et al., 2021; 2020). The project description identifies the envelope of requirements for a hypothetical 6 km deep hot geothermal exploratory well drilling and testing operation. This includes construction aspects associated with roading infrastructure, drill site / drill pad and pond construction, the water supply required, 24 hour/seven days per week drilling operation (which could span up to ~80 days), the solids and liquids discharge management, and the drill site accommodation camp. Aspects relating to potential amenity effects are included, as well as aspects associated with post well completion evaluation of the well such as completion testing, heat up, discharge testing for fluid and energy delivery and for fluid geochemistry sampling under flowing well conditions.

An extensive suite of permits would be required for consenting this hypothetical exploratory drilling and testing project.

Also to be assessed, at a high level, is the ease (or otherwise) of developing a large supercritical geothermal project post exploration drilling, under the regulatory regime in areas of different geothermal classification in the TVZ.

Exploratory well investment is likely to be more straight forward if a path to post exploratory development is clear from the outset.

7. SURFACE PLANT & ENERGY TRANSFORMATION

What surface plant is required to handle supercritical fluids?

The assumption is that supercritical or superheated geothermal fluids are produced at the wellhead, thus an important issue to be investigated is how to effectively use the produced fluids.

For a supercritical geothermal surface facility, a secondary heat transfer processing loop is anticipated with heat transferred to either (i) demineralised water to produce supercritical water or superheated steam or (ii) a secondary working fluid (that is not demineralised water).

Phase transition across the critical point, from supercritical to sub-supercritical conditions, will need to be managed in the surface plant, seeking to avoid deposition and corrosion issues. Supercritical geothermal fluid-handling strategies have been discussed in preliminary work for the Iceland Deep Drilling Project (IDDP) (Albertsson et al 2003). Follow up with the IDDP process engineers on the strategies that have subsequently been investigated will provide a basis out of which to consider what might be appropriate in the New Zealand circumstances.

Ultimately, on passing through the geothermal side of the process, the geothermal fluids will be cooled to liquid water, which will then be reinjected back underground. Depending on the processes, chemical control is likely to be needed to delay or prevent mineral deposition as the fluids return to and through the underground formations. On cooling the supercritical geothermal fluids, non-condensable gases will need to be managed to avoid gas blanketing of heat transfer processes. Processes handling and managing the discharge of non-condensable gases will employ applicable industrial gas management practise. This includes the management of any greenhouse gas emissions of methane and carbon dioxide that might emanate from the geothermal fluids.

With heat extracted from the supercritical geothermal fluids, what energy transformation processes need to be employed to use the energy?

Traditionally, high purity supercritical water transformation has been associated with high thermal efficiency coal-fired power stations generating electricity. The first commercial supercritical plant in the world, Philo Unit 6 (120 MW_e), commenced operation in Ohio USA in 1957, running until decommissioned in 1979 (ASME, 2003). The electric power industry has continued to invest in ultra-high purity supercritical water transformation research, development and deployment. Supercritical water-cooled reactors are in development in the nuclear power industry to increase the efficiency of electrical generation by moving from subcritical to supercritical steam power cycles (Kryková et al., 2021). The generation of electricity could reasonably be anticipated from supercritical geothermal fluids provided the water / steam passing through the power turbine from the secondary side of the heat transfer processing loop is appropriately conditioned.

Industrial process heat in New Zealand is often supplied as saturated steam, so if process heat is contemplated as part of a supercritical geothermal development, it will probably be as steam extracted from a saturated stage of a steam turbine. To do otherwise would be a less effective utilisation of the high temperatures that the supercritical heat transfer processing plant has produced. This supply of extracted saturated steam could be at temperatures above the current geothermal supply maximum temperature of about 220°C (Moore, 2011). If the geothermal heat at supercritical temperatures is transferred to a non- water based working fluid in the secondary loop then, depending on the fluid properties, it might be possible to supply heat energy at temperatures greater than 300°C which is into the high temperature process heat category (MBIE, 2018). This would open up new geothermal energy process heat supply options and opportunities.

What opportunities are presented by innovative energy transformation technologies?

A scan of technologies that might be employed that enable green energy to be produced from underground supercritical geothermal conditions without having to produce fluids up a wellbore for processing above ground should form part of the technical inquiry.

And what about hydrogen production? The conventional approach would use electrolysis powered by geothermal electricity. This is the approach being taken by Halcyon Power, a joint venture between Tuaropaki and Obayashi Corporation, on the Mokai Geothermal Field (Scoop, 2020), using polymer electrolyte membrane electrolysis, powered by geothermally-produced electricity (Fuel Cells Bulletin, 2019). Hydrogen technologies are the subject of significant research effort, such as solid oxide electrolysis cells, and what of direct hydrogen production from water using thermochemical processes at temperatures that might to be attainable in supercritical geothermal operations? Hydrogen research is moving at pace, the IEA Hydrogen Technology Collaboration Programme records near 300 billion euros has been mobilised towards project deployment and strategic implementation of hydrogen-based solutions for decarbonization in 2020 (IEA Hydrogen, 2021).

8. SUMMARY

Theoretically, supercritical geothermal fluids contain significantly more energy than conventional geothermal fluids, but realisation of this low-carbon renewable energy opportunity is currently not technically mastered in New Zealand. There are many unknowns to be overcome, across a broad range of aspects; science, engineering, finance, planning/regulatory, and societal license to operate. Given the long lead times for geothermal development projects, and the rapid pace of change in Government aspirations and environmental drivers to decarbonise the economy, research and development effort is needed now to investigate in detail this potential renewable energy opportunity for New Zealand.

A supercritical geothermal strategy for Aotearoa New Zealand is being developed and preparatory and pre-planning work is underway (e.g. geoscience, exploration, well design, regulatory assessment, social engagement) to work towards drilling a deep exploratory well in the next decade. The time is right to determine if and when supercritical geothermal is a viable industrial energy opportunity for New Zealand.

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