NEW ZEALAND'S SUPERCRITICAL OPPORTUNITY: MOVING FROM POTENTIAL RESOURCE TO DEPLOYED TECHNOLOGY

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ABSTRACT

Tapping into deeper supercritical resources to access significant reserves of higher temperature (400 ºC – 600 ºC), sustainable, renewable geothermal energy is not a new idea. Yet, present levels of understanding are insufficient to offer industry-ready solutions for New Zealand.

We are working to develop a New Zealand supercritical heat strategy (2020-2050), looking to accelerate from today's understanding through to early deployment of applicable technologies by 2040. Sector-wide roll-out aims to align with New Zealand's aspirations to be "carbon zero" by 2050. The strategy will build on the scientific understanding of New Zealand's supercritical resources, account for international experiences, and propose work streams to address the technological, legal, regulatory, economic and other challenges to utilisation of supercritical resources.

This paper presents the current state of knowledge on New Zealand's supercritical opportunity and outlines the intended strategic review of barriers and opportunities, working with stakeholders across the New Zealand industry, researchers, business, Māori, and Government. The critical challenge is to go beyond conventional geothermal systems, in search of the scientific, technological, regulatory, market and societal solutions that together, will de-risk and accelerate New Zealand's supercritical exploration and development.

1. NZ'S SUPERCRITICAL OPPORTUNITY

Do supercritical geothermal heat resources (>400 °C) offer significant reserves of sustainable, indigenous earth energy for New Zealand? Massive magma resources at temperatures above 750 ºC support the broader volcanic belt at relatively shallow depths in parts of New Zealand, and this provides the energy that is contained in rocks at supercritical temperatures (Figure 1) (Chambefort et al., 2017). Work streams are being initiated (Chambefort et al., 2019; GNS Science, 2020) to explore the many scientific, technical and societal questions and challenges to be resolved before the supercritical potential can be realised. It is envisaged that the prospects, the technology and governance frameworks will be developed to the point that supercritical earth energy is deployable by 2040. This then gives 10 years for projects to be confirmed, funded, consented and commissioned, and in doing so to position supercritical resources as a significant contributor to New Zealand's Carbon Zero aspirations by 2050.

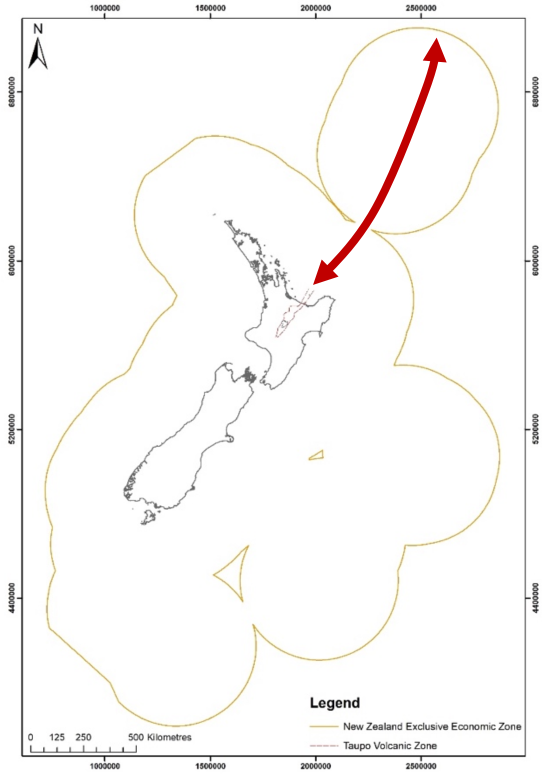

Figure 1: New Zealand's most likely areas for supercritical potential include the Taupo Volcanic Zone, the Kermadec arc offshore to the north (red curve) and Ngawha in northland (not shown on diagram)

This is an ambitious target, considering that supercritical technology in New Zealand is currently at a low level of readiness (Figure 2). This paper outlines the development of a supercritical heat strategy for New Zealand, designed to accelerate and coordinate utilisation of supercritical resources, aligning with the 2050 carbon-zero Government target.

The development of supercritical resources is a global challenge (Reinsch et al., 2017), with supercritical systems being investigated in Italy, Iceland, Japan, Mexico and the USA. International experience is essential to inform New Zealand's supercritical strategy, though not all experience will be directly-translatable to New Zealand's circumstances given the distinctive geological and societal environment.

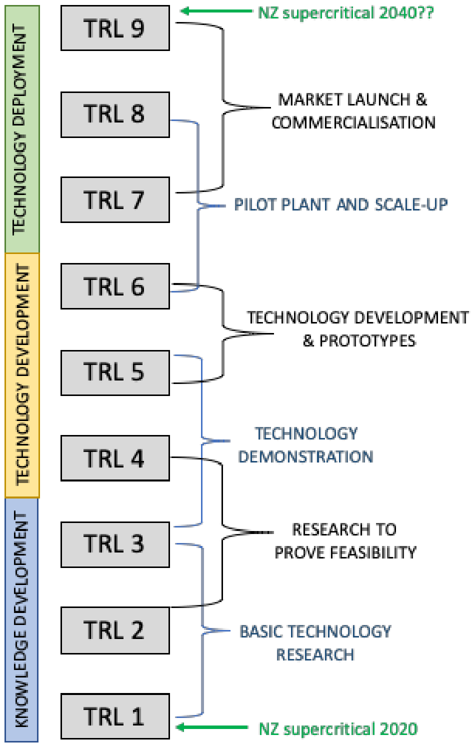

Figure 2: Technology readiness levels (EARTO, 2014)

1.1. New Zealand Government Aspirations & Drivers

The New Zealand Government is committed to accelerating the use of renewable low carbon emission energy. The Climate Change Response (Zero Carbon) Amendment Act 2019 aims to set the framework for New Zealand's transition to a low emissions and climate resilient economy. It supports New Zealand's contribution to the global effort under the Paris Agreement to limit the global average temperature increase to 1.5 °C above pre-industrial levels, and allows New Zealand to prepare for, and adapt to, the effects of climate change.

A large increase in renewable energy use could be enabled by a de-carbonisation of the transport sector, coupled with more development of renewable electricity generation, increasing efficiency in industrial process heat (thus reducing the consumption of fossil fuels) and transitioning industry to lower carbon energy. Renewable energy resources are anticipated to become an increasing component of New Zealand's 2050 "zero carbon" energy portfolio, but the nation has quite some distance to go to achieve this target. Carbon-friendly energy sources, including geothermal, will need to significantly increase their contribution.

1.2. Geothermal Energy Contribution

Geothermal energy is a renewable and reliable long-term energy source, and New Zealand is blessed with abundant geothermal resources. Higher temperature geothermal resources are location-based, as the geothermal fluid containing the heat is not efficiently transportable over long distances (>~30 km; Climo et al., 2017) unless it is converted into an energy form such as electricity, bio-fuel or hydrogen. However geothermal energy can offer significant benefits in cost, carbon footprint and energy security that makes it appealing for industrial and commercial businesses, with an eye to the future, in geothermally-rich regions.

Geothermal energy is currently a sound contributor to the New Zealand energy portfolio. The 2019 data (MBIE, 2019a; 2019b) showed:

- Geothermal energy supplied ~22% of New Zealand's primary energy, that is then converted into an energy form that is consumed (such as electricity or process heat).
- Geothermal energy accounted for 5.5% of all the energy consumed in New Zealand.
- Geothermal generated electricity supplied ~17% of New Zealand's total electricity

In the future, high temperature geothermal resources are capable of providing a greater contribution to electricity generation (supplying energy for electric vehicles) and industrial process heat, as well as commercial and domestic heating.

1.3. Geothermal CO_2 Emissions

For geothermal to play a key role in the zero-carbon energy New Zealand future, the greenhouse gas emissions from conventional resources and supercritical development will need to be appropriately managed. In 2018, geothermal accounted for ca. 2.3% of the greenhouse gas emissions from energy production and use activities (MBIE, 2018a).

Geothermal operations do emit greenhouse gases from the extracted geothermal fluids. The level of CO_2 in the fluid varies significantly between geothermal fields, and monitoring shows emissions decrease over time as geothermal systems de-gas (McLean and Richardson, 2019).

While operational geothermal CO_2-equivalent emissions are higher than wind, hydro or solar energy sources, geothermal emissions are significantly lower than fossil fuel plants (Figure 3). In the last ten years, as New Zealand's geothermal electricity generation increased and fossil-fuel based generation decreased, the overall emissions intensity of the electricity sector approximately halved (McLean and Richardson, 2019).

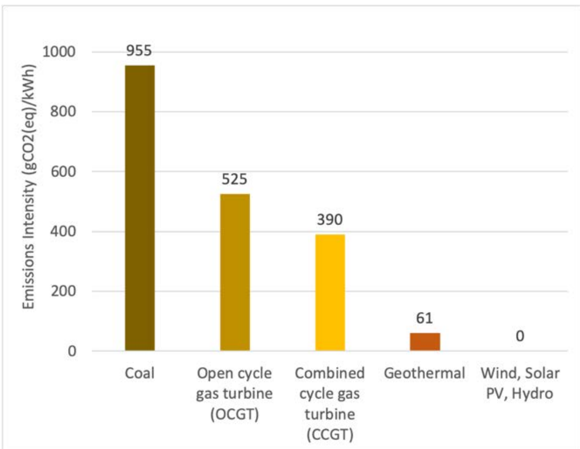

Figure 3: Median of geothermal CO_2-equivalent emissions from 12 geothermal power plants, compared to other types of electricity generation (redrawn from McLean and Richardson, 2019).

In a geothermal operation, non-condensable gases, including CO_2, H_2S and CH_4, are typically released to the atmosphere, however, it is thought that lower emission geothermal operations, possibly zero-emissions, are possible. Carbon reuse is one way to halve the emissions intensity (Carbon Recycling International, 2020) and capture and storage technology is under investigation (Kaya and Zarrouk, 2017). Some of these technologies, or modifications to them, may enable this type of technology to be adopted in New Zealand in the future.

2. GEOTHERMAL GROWTH OPPORTUNITIES

The future challenge for the geothermal sector is to sustainably use geothermal systems to the fullest possible extent including exploring new geothermal possibilities, such as supercritical resources. The following sections examine the growth opportunities for New Zealand's geothermal resources, with a focus on large energy use opportunities i.e. electricity generation and larger industrial heat use.

2.1. Electricity Generation

A low carbon energy future is currently arguably the strongest driver for change in the electricity sector. Geothermal resources currently provide 17% of New Zealand's electricity supply, in a nation that has ca. 80% of its electricity supply coming from renewable sources (MBIE, 2019b) and is seeking to achieve 100% renewable electricity by 2035 in an average hydrological year (ICCC, 2019). There is some scope for further de-carbonisation of electricity supply using geothermal, and there are significant opportunities for renewable electricity to substitute for fossil-fuel usage through electric transport options and heat supply to the industrial sector.

The 2019 assessment of electricity demand and generation scenarios out to 2050 (MBIE, 2019c), examined five different future scenarios. In all instances, new generation capacity is required with electricity demand projected to grow between 18% and 78 % by 2050. The renewables share of electricity generation increases in all scenarios, projected to increase from 82% in 2017 to around 95% by 2050. Total energy sector greenhouse gas emissions fall significantly across all scenarios.

This growth assumed electrification of process heat and the energy required to charge electric vehicles, as well as economic growth of 42% - 132% over the period (noting that this report was published prior to the COVID pandemic). In all scenarios, 2,700 MW of existing generation capacity is retired by 2050, including remaining large coal-fired and baseload gas generation capacity, as they reach the end of their economic lives. To date, as far as can be ascertained, supercritical resources have not been factored into New Zealand's electricity supply projections for the next 30 – 40 years (e.g. Lawless, 2020).

2.2. Process Heat Opportunities

New Zealand's existing direct geothermal use spans sectors including tourism, industrial, horticulture, aquaculture, commercial and residential. While bathing is the most abundant operation, process heat demand is the largest direct use of geothermal energy (Daysh et al., 2020).

There is significant scope for geothermal energy to provide a greater contribution to New Zealand's process heat demand. In 2016, around 55% of New Zealand's process heat demand was supplied by burning fossil fuels, and 4% was supplied by geothermal resources (MBIE, 2018b). Examples of process heat uses and temperature requirements are shown in Table 1.

Geothermal resources can supply heat for new businesses, such as the recently opened Rogue Bore in Taupo, which focuses on geothermal energy for beer brewing. Geothermal energy can also be retrofitted in existing operations to replace fossil fuel supplies. Examples include the changes at Natures Flame in Taupo (using geothermal heat to dry wood fibre for wood pellet manufacturing) and Oji in Kawerau (using geothermal steam for pulp and paper manufacturing) (Climo et al., 2020a).

However, while conventional geothermal resources in the central North Island offer a low-carbon fuel source for a number of New Zealand's industrial process needs, the highest temperature currently supplied from a geothermal resource is to the Miraka milk processing facility at Mokai: at up to 220°C. Supercritical resources are a possible opportunity for geothermal to supply significant quantities of heat energy, but at higher supply temperatures than conventional geothermal energy.

Supercritical prospects are expected to have underground temperatures >374 °C, possibly as hot as 500 °C, at depths down to ~6 km. When extracted, these fluids will reduce in temperature as they move up a well bore. At the surface, available temperatures are still anticipated to be in the 350 °C to 400 °C range, making them suitable for the industrial process requirements for the 'high temperature' MBIE category (refer Table 1).

3. A SUPERCRITICAL STRATEGY FOR NZ

A New Zealand supercritical heat strategy (2020-2050) aims to accelerate from today's limited understanding through to early deployment of applicable technologies by 2040. Sector-wide roll-out aims to align with New Zealand's aspirations to be "Carbon Zero" by 2050.

Table 1: Process heat categories based on temperature (redrawn from MBIE, 2018b)

Category	Process Temperature	Process Heat Use
Low	Less than 100 °C	Water heating, space heating, sanitisation of equipment in the food processing sector.
Medium	Between 100 °C and 300 °C	Industrial processes, drying wood products, drying food products. The highest temperature in food processing is around 200 °C for drying milk powder.
High	Greater than 300 °C	Industrial processes, oil refining, melting metals, chemical manufacturing

A supercritical strategy would provide a coordinated approach to progressing the use of supercritical energy resources through the technology readiness levels. This strategy would embody the principles, shared visions and goals of a range of stakeholders interested in promoting supercritical development, along with ongoing expansion of conventional geothermal energy use, whether it be for electricity generation, direct use or industrial process heat.

A supercritical strategy should be encapsulated in a document that can:

- influence government policies, and national, regional and local efforts
- assist in the implementation of aligned government, industry and iwi strategies (e.g. energy use, renewable energy, low carbon, economic growth, regional development)
- guide future planning, governance structures and regulatory decision making
- bring together various agencies and parties to promote and support the advancement of geothermal technology in New Zealand

A New Zealand supercritical strategy would sit within the existing geothermal strategy framework (Figure 4). Currently in New Zealand, the lowest temperature geothermal energy application is geothermal (ground-source) heat pumps, which can utilise sub-ten degrees celsius ground and water temperatures for efficient space heating and cooling. Growth and advocacy in this arena are driven by the Geothermal Heat Pump Association of New Zealand (GHANZ).

New Zealand's conventional geothermal resources span the temperature range from 30 °C (defined in the Resource Management Act as being geothermal waters) up to working fluid temperatures of ~225 °C. The increased use of geothermal energy for direct use applications is driven by the Geoheat Strategy for Aotearoa NZ (Climo et al., 2017) along with individual geothermal field and plant operators encouraging growth of geothermal direct use, and alongside electricity producers working to increase geothermal electricity generation.

The proposed scope of a New Zealand supercritical strategy (as shown in Figure 4), focusses on the development of supercritical resources for electricity generation, provision of fuels for transportation (hydrogen) and large-scale industrial process heat supply.

3.1. Supercritical Stakeholders

The development of a supercritical strategy for New Zealand will be achieved through engagement and consultation with a wide range of stakeholders (Figure 5, Climo et al., 2020b).

Investors are key to realising the potential of supercritical resource development. Such investors might include (i) those with existing knowledge of geothermal energy developments, such as New Zealand and international geothermal companies, New Zealand government and ahu whenua trusts with geothermal assets; and (ii) new entrants to geothermal projects, such as private investors, Māori trusts and investment entities. For these groups, a supercritical strategy should work to ensure potential investors have confidence in the business cases for future New Zealand supercritical energy developments.

There is also a group of stakeholders expected to have an involvement in supercritical resource regulation. This involvement may stem from a statutory regulatory function (for example, regional council functions established by the Resource Management Act 1991), an interest in sustainable environmental outcomes and resource management, or as a future potential applicant for resource consent or other regulatory approval. This group could include local government (particularly Waikato, Bay of Plenty and Northland Regional Councils), central government (e.g. MBIE, MFE, EPA, Climate Change Commission and EECA), and Māori entities (e.g. Iwi and Hapū entities, Ahu Whenua trusts and economic authorities, Māori Council, Iwi leaders group), electricity generators and/or industrial heat suppliers/users.

A supercritical strategy should also ensure that decision making is underpinned by high quality science. Some nations are progressing deep drilling and supercritical projects and there is much value in collaboration and learning from each other.

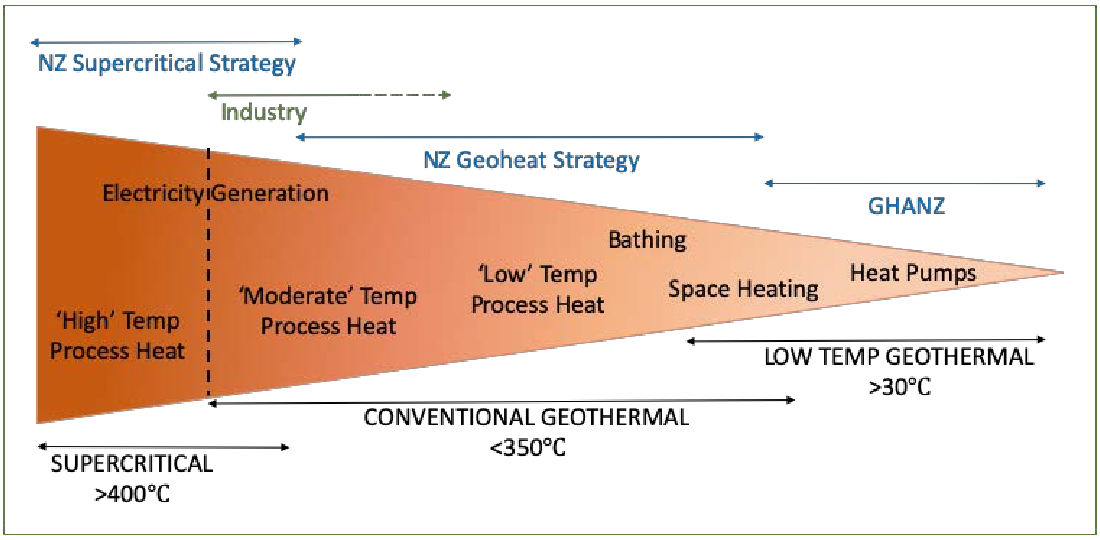

Figure 4: Existing and future strategies in New Zealand's geothermal energy landscape. For New Zealand definitions of low-high temperatures process heat, see Table 1.

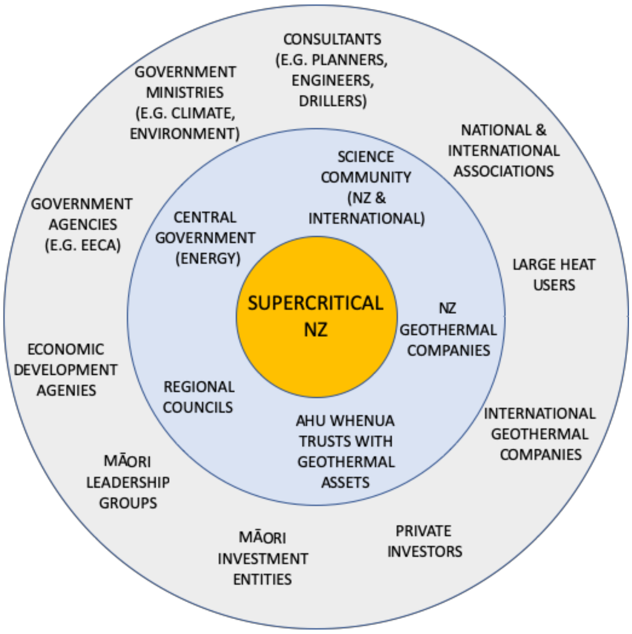

Figure 5: Key stakeholder groups with a potential interest in realising the potential of supercritical resources for New Zealand. Greater engagement activity will occur with groups within the central (blue) circle.

Additionally, and broadly (but not shown in Figure 5), developing and fostering enhanced understanding and awareness in the wider New Zealand public can support social license for ongoing supercritical research and acceptance of science outcomes (short-medium term), and de-risk industry drilling and development programmes (longer term).

4. QUESTIONS, ISSUES AND BARRIERS TO BE RESOLVED TO FACILITATE SUPERCRITICAL DEVELOPMENT

The New Zealand supercritical strategy in development will be built around:

- Stakeholders who need to be involved
- Identifying questions to be answered
- Confirming issues to be resolved
- Overcoming potential barriers to development
- Organising and targeting actions for maximum impact and strategic effect

The following sections outline some of these, noting the material is not exhaustive, rather it is a starting point to open dialogue, and facilitate discussion and engagement.

Today, there are more questions than answers as to what the supercritical future for New Zealand might look like, and a collaborative, consultative processes is essential to develop the most promising pathway for supercritical technology delivery for New Zealand.

4.1. Scientific & Technical Questions

4.1.1. How Big is the Supercritical Opportunity?

- How much energy might usefully be available to New Zealand?
  - Are supercritical resources able to annually supply hundreds of Petajoules? If so, these are game-changer resources for New Zealand. The energy available is expected to have a strong relationship to the depth that can be accessed by drilling and the conditions expected at the drilled depths.
- What sort of permeability is going to be encountered at supercritical depths?
  - At temperatures above supercritical, the rock conditions are approaching, or may even be into, the ductile brittle transition. Does the permeability for energy extraction need to be created? If so, the systems will be much more of an engineered geothermal system.

4.1.2. Reservoir / Resource Complexities

- What will be the effects on nearby or overlying conventional geothermal systems, and the associated power stations and energy production facilities?
- What geochemical conditions are likely to be encountered and what does this mean for mineral deposition, corrosion and gas management, both underground and in the surface plant of a supercritical facility?
- What materials will need to be specified for adequate longevity?
- What downhole tools need to be developed to measure these high temperatures? Current tools available in New Zealand are rated up to ~350 °C and 350 bar, while in Norway SINTEF have developed tools rated to ~450 °C.
- What reservoir engineering methods need to be improved or developed to advance the characterisation of supercritical subsurface resources, including advances in modelling methods?
- What does energy delivery through an individual well look like? An understanding is needed of wellbore flowing stability necessary to maintain a discharge of supercritical fluid to the surface.
- How can stimulation technology be adapted and developed to create supercritical Enhanced Geothermal System (EGS) resources?

4.1.3. Drilling

- What is the capacity of available drilling equipment to drill to 6 km?
- What drilling and engineering complexities are introduced by the higher temperatures and pressures?
- What are the risks of drilling close to magma? What are the implications if drilling intercepts magma? What can we learn and apply from IDDP1 drilling in Krafla that encountered a magma body?
- Can we develop well designs, including with appropriate wellhead componentry, to withstand the temperatures, pressures, depths and fluid chemistry?
- Does the code of practice for deep geothermal wells NZS 2403:2015 need amendment for the

anticipated supercritical conditions? Or do new approaches need to be developed and later developed into standards?
- What are the implications for safety and approval aspects for supercritical resource use? (administered by Work Safe New Zealand)

4.1.4. Surface Plant

- What surface plant design specifications are needed to handle supercritical fluids?
- Should the surface design be based on a closed heat exchanger loop arrangement with gas management, effectively keeping the supercritical fluids all contained whilst extracting the heat for utilisation?

International experience will be drawn on and where possible translated to New Zealand's circumstances. Connections established with the International Partnership for Geothermal Technology (IPGT), IEA Geothermal and other international programmes in, but not limited to, Italy, Iceland, Japan, Switzerland and the USA, offer significant collaborative opportunity to assist New Zealand's supercritical development effort.

4.2. Regulating the Use of Supercritical Resources

How does supercritical resource use fit within the existing resource management framework?

Geothermal development activity in New Zealand is currently managed primarily through the Resource Management Act 1991 (RMA) (Kissick et al., 2020). Through their Regional Policy Statements and Regional Plans, some regional councils have sophisticated and long-standing management regimes in place to manage the actual and potential effects of geothermal development activity. Other aspects around construction and operations are managed under health and safety legislation and regulations administered by Work Safe New Zealand.

Supercritical resources may be so different to conventional resources, however, that the existing regulatory framework is not fit for purpose and may inadvertently hinder future supercritical developments.

Questions for testing and consideration include:

- Are supercritical resources a regional or national-scale resource?
- How should supercritical resource boundaries be defined in Regional Plans? What is the scale of such a boundary, and with what accuracy / confidence can these boundaries practically be determined?
- Do supercritical resources need limits in the amount of energy that can be extracted, or is the scale of the resource so large that it is functionally unlimited?
- If limits are required, how are these to be determined and is an allocation regime required to determine who is granted rights (through resource consents) to develop supercritical resources and to determine how much energy each developer can take?
- Supercritical resources are likely to cross territorial and regional boundaries and extend offshore beyond the limits of the RMA (i.e. 12 nautical mile limit). How should such cross-boundary issues be dealt with?
- Supercritical resources are located at depth with complex connectivity to shallower systems and processes. Exploratory drilling will be expensive and much remains unknown about the characteristics of these resources. In support of a resource consent application to develop a superficial resource project, how could an assessment of environmental effects (as required by the RMA) consider the actual and potential effects of a proposed supercritical development on, for example:
  - Currently defined geothermal reservoirs, shallower groundwater resources, surface geothermal features and existing geothermal users
  - Air, water, soils and human health from chemicals and potential toxicants in supercritical fluids
  - Impacts from reinjection
- Is the existing regulatory framework fit for purpose to provide for supercritical development while managing the effects of its use? If not, what degree of change is necessary? Should a new National Policy Statement or National Environmental Standard be developed?
- Is regulation in advance of supercritical development appropriate? Or does regulation development follow in response to initial exploratory work / early development once more is understood about the resources?
- Conversely, is regulation in advance of supercritical development necessary if the barriers to development under the existing regulatory system are too great?

These and other related questions pose complex considerations to be addressed by New Zealand's regulatory framework.

A further broader question is whether the regulatory approach as a whole needs to change if supercritical resources are capable of annually producing hundreds of petajoules of energy from within New Zealand's Exclusive Economic Zone, both on land and offshore (e.g. Colville and Kermadec ridges, which are anticipated to contain substantial heat energy)? In other words, is the energy source so significant and so wide-spread that a special legislative approach is warranted?

4.3. Market & Investment Opportunities – the Economic Equation

Supercritical geothermal projects are going to require large capital investments, in the range of hundreds of millions to billions of dollars. They will be complex due to resource-specific permitting, construction and commissioning requirements.

Whilst there have been more than 25 deep wells drilled in geothermal fields around the world that have encountered temperatures in excess of 374 °C (Reinsch, 2017), none of these have been or are being used in commercial energy production. There are many unknowns.

Each investment group will have its own tailored and specific criteria to assess investment opportunities. However, there are fundamental questions that investors in supercritical geothermal project are likely to need to address:

- What is the investment opportunity and what are the drivers of that opportunity?
- What does the demand for energy look like for the projected life of the project, and what is the likely supply competition to meet that demand?
- How is timing relevant i.e. is there a benefit in being first?
- Do we have a good understanding of the risks and uncertainty involved?
- What are the outcome scenarios? i.e. what does success or failure look like?
- Is the projected compensation in line with the risk? i.e. what is the appropriate balance of risk and return?
- Can we get more than financial return e.g. increased employment opportunities, security of energy supply?
- How does this investment help, hinder or align with a company's existing portfolio and strategic investment plan?
- What are alternative investment options?
- What are the likely ongoing maintenance and operational costs for the life of the project? Do we understand the longevity of materials and outputs?
- What are the social, community and environmental issues that may arise? How can these be mitigated or appropriately managed?
- Is it ethical?
- Is it sustainable?
- Will we have social license to operate?
- Do we have the capacity and capability required for the ongoing management of the investment? Are the necessary skills and tools readily available to do this?

The first geothermal exploration wells drilled by the New Zealand government in the late 1940s and 1950s (Bolton, 1998) de-risked geothermal energy projects and led to the early phases of the large-scale geothermal energy developments at Wairakei and Kawerau. Similar investment in de-risking supercritical would be likely to catalyse private investment in projects. There maybe be other approaches to de-risking the pilot plant / prototype, TRL6 to TRL 8 readiness level activity (Figure 2), such as establishing a consortia / public-private partnership arrangement to develop a demonstration plant, providing information that can then be used as the basis for modelling the commerciality of supercritical facilities.

5. CONCLUSION

This is a defining time in New Zealand for establishing the nation's plans for a low-carbon energy future. Conventional geothermal resources are a sound contributor to New Zealand's energy portfolio, and their use is likely to increase over the coming decades.

Supercritical geothermal energy may be able to contribute significantly to New Zealand's energy future, and to support New Zealand's Carbon Zero aspirations by 2050. While supercritical geothermal energy is an, as yet, unknown resource, New Zealand is exploring its potential because, if realisable, it is anticipated to be a vast indigenous energy source.

As discussed above, a 2020 – 2050 supercritical strategy is being developed to support progression towards deployment of supercritical energy technologies.

Visit www.geothermalnextgeneration.com to follow the strategy development progress and/or to join in the discussion and get involved.

6. ACKNOWLEDGEMENTS

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