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What is the end use for ultra-hot geothermal energy in Aotearoa New Zealand?

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ABSTRACT

Abundant, proven high-temperature geothermal resources give Aotearoa New Zealand a distinctive advantage in transitioning to a low-carbon energy sector and economy. Geothermal energy has been decarbonising New Zealand's electricity and process heat sectors for over sixty years and has capacity for increased utilisation. Along with expansion of the nation's geothermal electricity generation from conventional geothermal systems (<350°C, ~3.5 km deep) which will see the 170 MWe Tauhara II power plant commissioned in 2023 and others beyond that, what opportunities open if deeper drilling (4-6 km) encounters 400 to 600°C geothermal conditions? Research is underway through the Geothermal: the Next Generation Research programme to evaluate and identify ultra-hot geothermal resources in the Taupō Volcanic Zone (TVZ) that might become the focus of exploratory well drilling, testing and subsequent development activities.

It is proposed that the most likely sector in New Zealand to utilise ultra-hot geothermal is the electricity sector supplying a large user(s) or supplying into the electricity market. Process heat might be a secondary taker of energy from an electricity facility but the process heat industry itself is unlikely to be the primary developer / operator of an ultra-hot geothermal energy supply because of the larger quantities of heat energy that are required for an electricity generation facility and the much smaller amounts utilized by a process heat facility.

Higher temperatures should enable more efficient use of the extracted geothermal energy. The efficiency achieved from an ideal heat engine is computed across a range of temperatures from 150 to 500 °C showing the theoretical efficiency increase as temperature increases.

The paper has been written to encourage dialogue and ideas exchange on end use and the processes that might need to be scoped in seeking to better refine the future utilisation of ultra-hot geothermal energy in New Zealand.

1. INTRODUCTION

Seeking to access hotter geothermal resources deeper in the earth's crust is the focus of activity in a number of nations and programmes. Activity includes the European DEEPEN (Derisking exploration for geothermal plays in magmatic environments) programme, the European MODERATE (Magma Outgassing During Eruptions and Geothermal Exploration) programme, the Clean Air Task Force Superhot Rock work in the USA, the Newberry super-hot EGS work in the USA, the subduction-origin geothermal resource work in Japan (NEDO), the work in Iceland through the Iceland Deep Drilling Project (IDDP) and the Krafla Magma Test Bed (KMT), and the Geothermal: the Next Generation (GNG) programme in New Zealand.

The paper begins exploring what the end use for deep supercritical or ultra-hot geothermal resources in New Zealand might be. It is written to encourage feedback on the thinking that is being undertaken to identify the next best steps to take to progress the utilisation of these very hot geothermal resources in New Zealand.

We include an efficiency analysis to demonstrate that the use of ultra-hot geothermal has the potential to be more efficient than is currently achievable from sub-critical geothermal resources when used for generating electricity (or producing work).

The paper summaries information on forecast outputs that might be expected from 450°C and hotter ultra-hot geothermal wells along with information on geothermal process heat use and electricity generation facilities currently using geothermal energy in New Zealand seeking to provide a context for identifying what industries might use ultra-hot geothermal. Also summarized are aspects of regulatory planning in preparation for exploratory drilling in the Taupō Volcanic Zone (TVZ) with a forward view that the end goal is ultimately being able to have a production use / facility in near proximity. A range of assumptions used in the ultra-hot geothermal thinking are identified, a number of which need to be researched and tested further. Over the period to the end of October 2024 these and other aspects will be worked up into a strategy that is to be prepared as part of the GNG programme.

There is discussion on the types of enterprises that might use ultra-hot geothermal resources. In order to establish probable uses it is necessary to understand the likely fluid state conditions, pressure, temperature, enthalpy, flow, thermal power and exergetic power that might be available at the surface (at the wellhead). The enterprises likely need to operate on a near continuous basis, 24 hours per day, 7 days per week because of the expected high upfront capital required.

These aspects are canvassed later in the paper after the discussion on conversion efficiency in the next section.

2. HEAT TO WORK CYCLE CONVERSION EFFICIENCY

Ultra-hot geothermal utilization producing electricity or work should benefit from increased conversion efficiency as the temperature available to a process increases. This is shown in Figure 1 by the blue line which represents the maximum possible efficiency of any heat engine system producing work operating between specified temperature limits. The theoretical efficiency across a range of temperatures relevant to geothermal wellhead conditions, spanning the range from sub-critical to ultra-hot geothermal conditions, shows the increasing efficiency with increasing temperature.

Using source and sink temperatures the ideal carnot cycle efficiency is calculated using the equation below.

$$\eta = (T_h - T_c) \div T_h$$

η Carnot cycle efficiency (as a decimal, multiply by 100 for a percentage)

T_h Hot source - supply temperature in Kelvin.

T_c Cold sink - reject temperature in Kelvin – taken as 293.15 K.

The efficiency can also be expressed as the ratio of the net work output produced from a gross amount of heat supplied to a process.

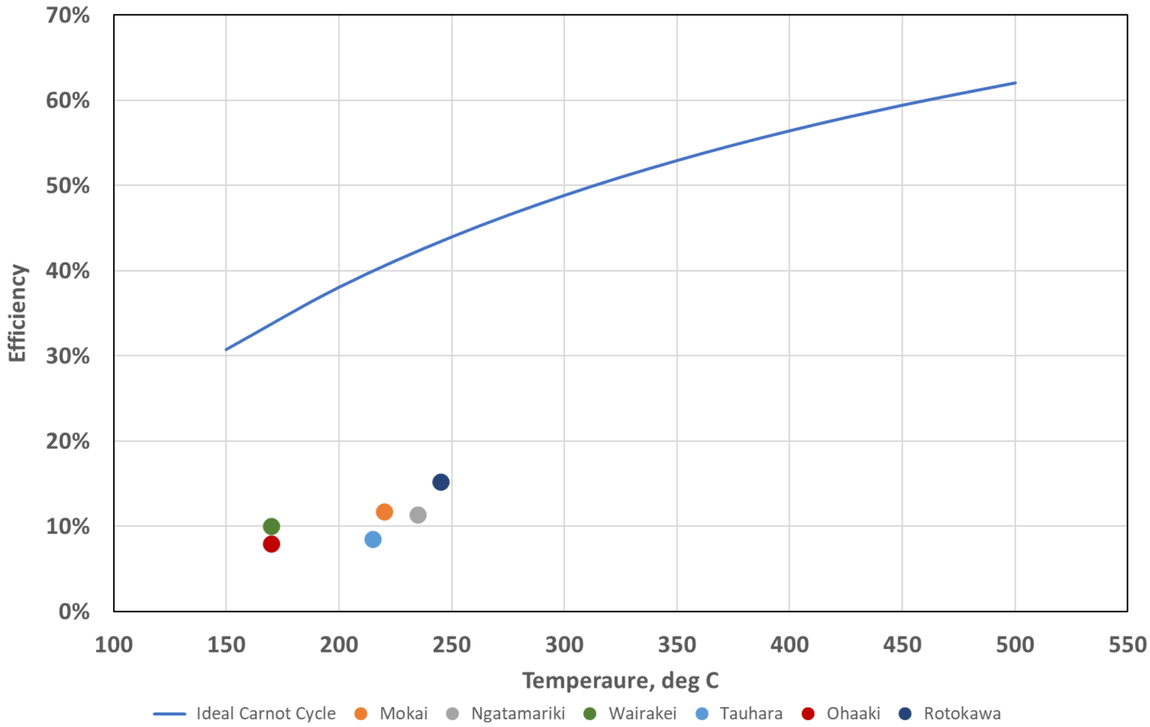

Figure 1 First law of thermodynamic efficiency (%) versus source temperature. The cold sink temperature was taken as 293.15 K in calculating the carnot cycle efficiency (blue line). Dots are the ratio of the net electrical power output divided by the gross geothermal reservoir heat production for several geothermal facilities in the TVZ (plotted against a "nominal" operating wellhead temperature).

For a given amount of geothermal heat supply available to transform into useful work (power) a greater output should be obtained from a hotter supply temperature (ie increasing wellhead temperature) (Fig. 1). Ideal efficiencies (blue line) are unobtainable in any practical geothermal application as is shown by the data from 6 TVZ geothermal facilities plotted as various dots in Figure 1. Zarrouk and Moon (2014) report first law thermal efficiencies of up to a maximum of 18% in their study of 94 geothermal power plants across a range of inlet conditions, producing from geothermal resources with fluid enthalpies spanning the range from compressed water through to steam only.

For a given amount of work the amount of heat supplied and rejected from a process will decrease as the supply temperature increases. This is expected to benefit ultra-hot geothermal facilities in that the size of cooling system should be reduced relative to sub-critical geothermal facilities of the equivalent work (power) output.

3. MODELLED ULTRA-HOT GEOTHERMAL SUPPLY CONDITIONS

Wellbore simulation work by Rivera and Carey (2023) based on average NZ geothermal well productivity indices reports the indicative wellhead conditions along with flow rates, energy and power modelled to be likely available at the wellhead for an individual ultra-hot geothermal well drilled into supercritical conditions of 450 to 600 ^{o}C at a depths of 4500 to 6000m. Table 1 tabulates the range of values from the well bore simulation work.

Exergetic power is the calculation of the theoretical maximum amount of mechanical work that geothermal fluid at various conditions can produce. It is calculated from the mass flow and the fluid properties. This is described in detail in DiPippo (2016) for its application to geothermal facilities and was adopted in the analysis undertaken by Rivera and Carey (2023).

Table 1 – Value range for various parameters computed for an individual ultra-hot geothermal well using average NZ geothermal well productivity indices (PI-2) in the simulation (Rivera and Carey 2023).

Variable	Value Range
Wellhead Pressure	50 to 100 bar
Wellhead temperatures	300 to 450 °C
Enthalpy	2500 to 3200 kJ kg^{-1}
Mass flow rate	10 to 70 kg s^{-1}
Thermal Power	70 to 170 MW_{th}
Exergetic Power	30 to 55 MW_{ex}

4. CURRENT GEOTHERMAL ENERGY END USE INCLUDING SOME RECENT PROJECT ACTIVITY

In this section the geothermal electricity project recently completed at Ngawha, construction activity and further expansion plans at Tauhara are discussed identifying the size and some project metrics, such as fluid and thermal energy requirements in order that these might be compared to what might be produced from a supercritical well(s). Following the section on electricity generation is a section on direct geothermal heat use at Kawerau and Tauhara (Taupō) identifying the scale of the heat supplies to large industrial users. The locations of the various facilities are shown in Figure 2.

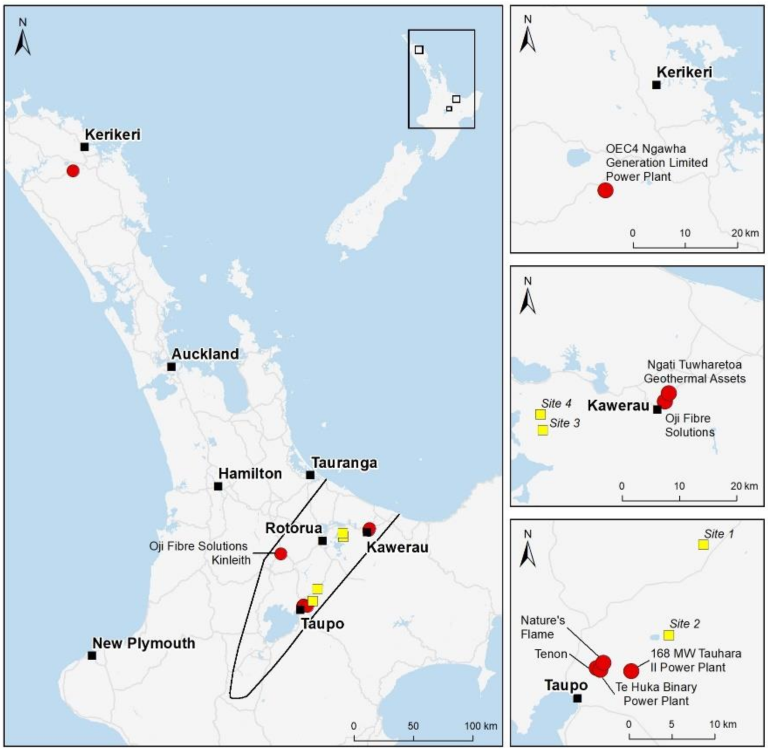

Figure 2 Geothermal electricity facilities at Ngawha, and Tauhara and geothermal heat users at Kawerau and Taupō discussed in the paper marked with a red circle. Location of Oji Fibre Solutions plant at Kinleith and Kawerau. Ultra-hot well sites used in the planning assessment work discussed in the paper marked with a yellow square.

The summary material in the sections below enables a comparison of the size of a geothermal users load relative to the simulated output of an ultra-hot geothermal well tabulated in Table 1.

Recent or Upcoming Geothermal Electricity Generation Developments

Ngawha

Top Energy applied for consents for the OEC4 and OEC5 developments in December 2014 with consents granted in 2016 (Top 2016). An extension to the 2014 application was lodged in 2016 with the consents on this application granted in June 2017. Preparation, well drilling and testing, and the OEC4 power plant construction has been completed, with the plant operational in December 2020 (Top 2021).

The 32 MW_e OEC4 plant draws geothermal energy from three production wells. The fluid quantity consented for OEC4 is 9,400,000 tonnes per year (Carey et al 2020) and the geothermal thermal power delivered to the plant is ~300 MW_{th}. For the discharge of fluid back underground three injection wells were drilled as part of project. The total project cost was reported at NZD178 million (Top 2021).

OEC5 which is expected to follow, is a consented project subject to final approval by the Northland Regional Council (NRC) after a period of several years operation of OEC4. Once NRC approval is given Ngawha Generation Limited can move to taking the financial investment decision to proceed with OEC5.

Tauhara II

Contact Energy applied for consents for Tauhara II in February 2010. Consents were granted in December 2010 including a take consent authorising the take of 213,000 tonnes per day of geothermal fluid. The Consents were exercised soon after grant being used as the authorisation for the fluid supply to the Te Huka Binary Cycle power plant. The Te Huka plant has been operational since May 2010 and is supplied from 3 production wells of which two are online at any one time supporting the facility. In the 2019 calendar year Te Huka produced 190 GWH net from 7.28 M tonnes of fluid (8.04 PJ of heat energy) (Contact 2020). The thermal power requirement of the plant is some 260 MW_{th} and the exergetic power in the fluid supplied was calculated at ~70 MW_{ex}.

Construction of the Tauhara II 170 MWe geothermal development is well underway. The project is expected to be commissioned and fully operational during the second half of 2023 at an estimated cost of NZD818 Million (Contact 2022a). The thermal power requirement of the plant is some 1500 MW_{th}.

Te Huka II - Expansion of Te Huka

Contact Energy has announced it is investing $300m in the Te Huka II geothermal binary cycle power project with an expected capacity of 51MWe, generating 430 gigawatt hours of electricity each year (Contact 2022b). On a pro rata basis using the operational Te Huka plant data, the Te Huka 2 plant will require 3 or 4 geothermal production wells to achieve 51 MWe. The thermal power requirement of the plant is some 500 MW_{th}.

Heat Utilisation

Oji Fibre Solutions - Kawerau

Oji Fibre Solutions is the largest process heat user in New Zealand (Oji 2019) with major facilities at Kinleith and Kawerau. About 20% of the energy supplied to the Oji Kawerau mill is from geothermal energy being both geothermal steam and process steam produced from geothermal steam at the Ngati Tuwharetoa Geothermal Assets clean steam production facility. In 2020 of a total of 7.77 PJ used by the Oji mill, 1.64 PJ was supplied from geothermal energy (Oji 2020). Converting the 1.64 PJ/ annum to average thermal power using 360 days per year as the duration of the supply in any one year identifies a geothermal energy thermal power supply of 53 MW_{th}. Overall the energy supply to the mill is equivalent to some 250 MW, with ~8MW of this being electricity.

Ngati Tuwharetoa Geothermal Assets – Kawerau

Ngati Tuwharetoa Geothermal Assets (NTGA) is the largest supplier of geothermal heat energy for process use in New Zealand. They have supply contracts with a number of industries in Kawerau and with the closure of the Norske Skog Tasman newsprint operation in June 2021 are now supplying ~4 PJ per annum to these industries, which is ~130 MW_{th} when converted to average thermal power over a supply period of 360 days per year.

Tauhara Geothermal process heat supplies - Taupō

Geothermal process heat supplies at an industrial scale have been in operation at Tauhara since 2007. The Tenon sawmill uses about 20MW_{th} of geothermal energy to kiln dry sawn timber. Data for 2018 reported the extraction of 1.7 million tonnes of geothermal fluid (1.75 PJ of energy) from the Tauhara reservoir supplying 482 TJ to Tenon (Contact 2019). In 2019 Nature's Flame installed a 20MWth geothermal supply for drying feedstock for its biofuel pellet production operation.

5. ULTRA-HOT GEOTHERMAL UNDERPINNING REQUIREMENTS

Underground conditions supporting the ultra-hot geothermal are assumed to be at between 450 to 600 °C at depths of between 4500 to 6000 m (Carey et al. 2021; Jolie et al. 2021; Reinsch et al., 2017). Also assumed is that due to the low fluid density of the supercritical fluid, solubility of chemical species is significantly less than for sub-critical geothermal fluids with a liquid component (assuming no increase in magmatic component), that are currently accessed by the geothermal sector in New Zealand (Chambefort and Stefánsson, 2021; Heřmanská et al., 2019).

In order to develop an enterprise utilising ultra-hot geothermal there are a number of requirements needed; these in no particular order are:

1) That suitable land is available at the location of an ultra-hot geothermal resource enabling exploratory activity and later space for a large-scale energy production facility to be established.

2) That regulatory permitting enables exploratory well drilling and testing to be undertaken.

3) That exploratory activities subsequently undertaken are successful and deep geothermal wells accessing ultra-hot conditions (temperatures > 400·°C) can be drilled.

4) That at depth adequate permeability is encountered or created. In the TVZ this will likely be in the metasedimentary formation(s).

5) That self-sustaining flow can be initiated in a well producing fluid to the surface.

6) That pressure change in the deep reservoir with time is small supporting longevity of fluid available for production wells to continue producing.

7) That the geothermal fluid chemistry is such that the change in fluid state moving from supercritical to superheated in the well bore is able to occur without deposition substantially restricting fluid flow in the wellbore.

8) That pilot studies provide confidence in the materials selected for well and surface plant longevity and that corrosion and erosion rates from the well fluids is manageable for operational longevity.

9) That greenhouse gas emissions are captured and reinjected.

10) That regulatory permitting is able to acquire consents that will facilitate a significant energy production development at or near the site.

11) That freshwater can be accessed in quantities adequate for the requirements of the drilling and later for production operations.

12) That a grid connection to the national network or local supply network can be established.

These are all aspects that ultimately will need to be worked through.

The activities of exploratory drilling and pilot studies are an essential part of developing the confidence in using deep geothermal sources. In a geological area such as the TVZ, New Zealand, the unique large volume of deep-seated magmas provide a constant heat source in the mid to shallow crust. With seismic and magnetotelluric evidence of a silicic mush at 6 to 8 km, reaching crust temperatures exceeding 400-450 with a 5-6 km hole is almost guaranteed. This is in contrast to conventional geothermal drilling where well targeting is much more spatially constrained to a geothermal field. As such understanding deep fluid circulation in the TVZ may open the door for new investment outside of the currently operating fields. This is one of the opportunities that targeting hotter temperatures may bring. Without exploratory drilling circumstantial geoscientific evidence will in itself not be sufficient. Once the likely end use is understood then organisations who might fund early-stage exploratory activity might come more clearly into focus.

6. PLANNING ACTIVITIES ASSOCIATED WITH ULTRA-HOT GEOTHERMAL

An overview of the planning requirements pertaining to consenting for exploratory drilling is contained in a report by Kissick et al (2023). The work assesses four TVZ scenario sites for deep exploratory drilling (Fig. 2) with different planning provisions relevant at each of the sites. The consenting requirements at each are similar but with specific site characteristics having implications for the viability of acquiring resource consents. These site specific aspects include land title covenants and encumbrances, reserve status of the land and the geothermal system classification at the particular location. The material in Kissick et al (2023) is summarised in the WGC 2023 proceedings in Kissick et al (2023).

Ultimately private investment is more likely if there is a clear line of sight in a planning sense beyond the exploratory phase that is not overly difficult to navigate in moving to a production operation after successful exploration. Kissick et al (2023) identifies that there are a range of complexities specific to New Zealand to be navigated. At one of the scenario sites a major production development would be very unlikely to be able to be consented because of the land status, at the other three an operation would be expected to be able to be consented but with differing levels of complexity.

Access to freshwater in the quantities required for drilling activities may be a hurdle to navigate. Well drilling is expected to take at least 140 days per well, with water requirements estimated at 600,000 m^3/well at supply rates of up to 6000m^3/day (Kissick et al 2023).

Obtaining consents for exploratory drilling is an activity that will require resourcing over several years with time frames of 4 years or so for a greenfield site. This estimate includes time for consultation and preparation of information for a consent application prior to lodging with the relevant regional and district councils.

7. FACILITIES THAT MIGHT UTILIZE ULTRA-HOT GEOTHERMAL

There are various enterprise types that might pursue an ultra-hot geothermal development, however, the capital profile with the significant upfront establishment investment points to enterprises with near continuous production operations. The operations will typically be 24/7 producing for most of a year. This pushes towards industrial operations, such as processing industries, or electricity generation supplying into the electricity market or to a business that might require large continuous supplies of electricity.

The stand-out sector enterprises are electricity generation or thermal energy supply for large industrial process use.

Table 2 – Simulated output from a supercritical geothermal well (row 1) compared to loads for geothermal heat users (green) and electricity facilities (blue). The number of supercritical wells for the load (column 2) is determined from the thermal power for a thermal load (green shading) and exergetic power for the electricity facilities (blue shading).

Facility	Number of SC wells for load	Thermal Power	Annual Energy	Exergetic Power	Electrical Energy
	#	MW_{th}	PJ	MW_{ex}	GWH / yr
Supercritical Geothermal Well		70 to 170	2.2 to 5.4	30 to 55	-
Tenon Taupō	< 1[1]	~15	~0.5		-
Oji Kawerau	~1[1]	~53	1.7		-
NTGA Kawerau	1 to 2[1]	~130	4		-
Te Huka	1 to 2[2]	255	8.04	~60	190
Ngawha OEC4	1 to 2[2]	300	9	~65	~250
Te Huka II	3 to 5[2]	~550	17	~140	430
Tauhara II	8 to 15[2]	~1600	50	~450	~1400

[1] Number of wells assessed using the thermal power from the simulated supercrictical well (column 3 row 1) and the thermal power for the load (column 3).

[2] Number of wells assessed using the exergetic power from the simulated supercrictical well (column 5 row 1) and the exergetic power for the load (column 5).

Electricity generation clearly fits the profile with ultra-hot geothermal wells modelled as producing exergetic power of upwards of 30 to 55 MW_{ex} with electricity generation operations at a level of 10's to 100's of Megawatts able to be supported from several supercritical geothermal wells as indicated in column 2, Table 2.

The timber industry is less of a fit to the profile because of the smaller load size requirements (Table 2). The largest New Zealand geothermal process heat user uses ~53 MW_{th} of thermal power supplied from geothermal. The total process heat supply at Kawerau is currently about 130 MW_{th}. The two Tauhara businesses using geothermal energy as process heat combined utilise ~40 MW_{th} of thermal power. So for process heat users to be involved in ultra-hot geothermal would likely require a large industrial conglomerate to be established that was interested in supplying the businesses involved with thermal energy on a scale larger than the current Kawerau Industrial cluster. It is unlikely that a major new industrial area outside of Kawerau, Kinleith or Tauhara would be established in the TVZ simply on the basis of discovering a new ultra-hot geothermal energy resource from exploratory activity. The set-up costs of establishing the required infrastructure would push industrial businesses to already established industrial areas where existing planning provisions and supporting infrastructure are in place to support large industrial activity.

A possible thermal use outcome would be that a process heat use establishes downstream of geothermal electricity operation with smaller quantities of thermal power supplied from the electricity enterprise that is using larger quantities of geothermal energy.

Geothermal mineral and critical element extraction has been raised as a possible use. Current understanding is that ultra-hot geothermal fluid the TVZ exploratory programme is targeting is likely less mineralised than that of currently extracted geothermal fluids. As such it is reasonable that interest from minerals sector businesses will currently be at a low level.

The ultimate end use points to electricity generation supplying a large electricity user(s), such as a green hydrogen production business using electrolysis, or into the nation's electricity market.

8. CONCLUDING COMMENTS

There is much activity required to realise production from New Zealand's ultra-hot / supercritical geothermal resources. The pathway involves further geoscientific activity, exploratory well drilling, well testing, pilot plant testing, materials testing, and engineering studies to identify the best energy transformation processes. Collaborative activity will see the New Zealand effort maximising knowledge transfer from the not insubstantial programmes focused on accessing deeper, hotter geothermal resources that are currently underway in a number of nations around the globe.

Engineering activity looking at process design is an important step to enable early cost estimates of electricity generation facilities using supercritical geothermal resources to be developed. The appropriate power cycles need to determined along with fluid handling equipment, particularly to manage entrained or dissolved solids in the supercritical fluid or superheated steam flows. Design pressures and temperatures need to be assessed along with appropriate materials for pressure containment for the wellhead, steamfield and high pressure parts of the power plant facilities. Thicker walled vessels will likely be required to contain the higher pressures than utilised in sub-critical geothermal facilities. Because of the efficiency advantages gained from the higher supply temperatures the power output for a given thermal input will be greater for facilities supplied from supercritical geothermal resources than for the sub-critical geothermal plant currently operating in New Zealand. This should result in a requirement for smaller power plant heat rejection systems for an equivalent plant output. This should be beneficial to the overall costs associated with a steamfield and power plant development.

The most likely sector to utilise ultra-hot geothermal in New Zealand is the electricity sector supplying large electricity consuming businesses or supplying into the nation's electricity market. Process heat might be a secondary taker of energy from an electricity facility but the process industry itself is unlikely to be the primary developer / operator.

Please feel free to communicate with the corresponding author or contact us at www.geothermalnextgeneration.com if you have thoughts or ideas that might embellish ultra-hot geothermal activity in New Zealand and the strategy development.

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