# Superhot Geothermal – A Net Zero window of opportunity for New Zealand?

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## ABSTRACT

The installed geothermal capacity in New Zealand in 2024 is ~1.2 GWe with production of ~8 TWh /yr supplied onto the grid in 2023. The production supporting this generation infrastructure is all produced from wells shallower than 3.5 km depth, but with significant opportunity for additional energy production by accessing deeper resources.

GNS Science, through the MBIE Endeavour Research Programme, Geothermal the Next Generation (GNG), has been considering the deeper opportunity and has developed a Superhot Geothermal Inventory for onshore New Zealand geothermal prospects. Assessment has been undertaken using the United Nations Framework Classification for Resources.

Considering only identifiable resource volumes, outside of any regulatory protected geothermal systems, and within the depth range of 3.5 to 6 km, the inventory identifies that there is a possible additional capacity of up to ~3.5 GWe, producing about 29 TWh /yr.

An electricity market modelling study, prepared by Castalia Ltd (2023) forecast that superhot geothermal power plants could contribute up to an additional capacity of 2 GWe to the New Zealand grid by 2050. This is a consequence of the significant increase in demand, and hence renewable capacity, forecast to be required as New Zealand transitions to Net Zero carbon emissions. Castalia modelled electricity market conditions out to 2050 and assessed the likely commercialisation date for superhot geothermal power plants. Additional capacity of 1.4 to 2 GWe is robust for superhot geothermal power plants producing electricity even at up to double the costs for conventional geothermal.

This is a significant strategic Net Zero opportunity for New Zealand. It should be investigated and evaluated, working towards realising superhot geothermal generation as part of the nation's energy transition.

## 1. INTRODUCTION

### 1.1 Background

Energy policy discussed in recent NZ Government planning documents has focused on solar and wind deployment for electricity generation and has under-appreciated the full potential of baseload geothermal generation. These policy documents include: a proposed update (currently underway) of the National Policy Statement on renewable electricity generation (MoE, 2011), the NZ government's future energy strategy (MBIE, 2023, 2024), and the NZ Climate Change Commission's energy sector modelling (Climate Commission, 2024). In our opinion, geothermal has been under-represented in these plans for future renewable energy sources which aim to meet growing demand from NZ consumers whilst satisfying commitments to meet net zero carbon emissions targets by 2050.

Geothermal has benefits relative to other renewable power generation options that are well recognised. They include reliability, sustainability, efficiency, indigenous energy, security of supply, relatively small surface footprint with opportunities for multiple land uses, and base-load generation, independent of the weather. Superhot geothermal developments will have similar advantages and will likely use even less land for well pads, pipelines and powerplants, than conventional developments because of expected higher average well productivity, more compact and efficient turbines, and reduced cooling system requirements. Newly developed technologies will also enable full reinjection of the non-condensable gas discharges along with the cooled discharge fluids. Hence $CO_2e$ gas emissions to the atmosphere from NZ geothermal power plants (decreasing over time to a weighted average of 57 $gCO_{2e}$/KWh by 2023, (NZGA, 2024)) are not anticipated to be an issue in future superhot geothermal projects.

NZ has benefited from international collaboration through the IEA-Geothermal Technology Collaboration Program in "Deep Roots" (super-critical and superhot) geothermal research and demonstration projects. A summary of these learnings is described in Bromley & Carey (2023).

### 1.2 Inventory

Geothermal - The Next Generation (GNG), is an MBIE funded, Endeavour research project, which has been undertaken by GNS Science between 2019 and March 2025. The efforts included preparation of a preliminary inventory of NZ's superhot geothermal resources (Bromley et al., 2024; www.geothermalnextgeneration.com). The inventory is described in more detail in Section 2. The principal purpose of this task was to assess potential resource availability to inform market analysis and preliminary economic assessment. In order to assess NZ's superhot geothermal potential, the resource inventory uses geophysical data and interpretations, primarily from magneto-telluric 3D models. The assessment applies the project-based United Nations Framework Classification for Resources 2019 update (UNFC, 2022). This classification also incorporates the Supplementary Specifications for application to geothermal energy resources (UNECE, 2019). The UNFC methodology categorises projects that are listed in the inventory, and it reflects on the level of uncertainty that exists prior to drilling at potential project locations. All superhot geothermal projects in New Zealand are currently rated E3, F4, G4 under the UNFC categorisation.

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### 1.3 Economics and investment

As part of the GNG project, a broader market assessment of NZ superhot projects was undertaken by Castalia Ltd (2023) using electricity market modelling that was specifically developed to include superhot geothermal. The results are summarised in Section 3. The challenge for NZ now is how to attract the needed capital and operational expertise, identify opportunities for landowners to collaborate, and align policies for this significant opportunity. We consider the challenge to be faced is analogous to that faced in the 1950's and 1960's, by NZ engineers, scientists, regulators and politicians, who participated in the early years of NZ's conventional geothermal resource exploration and utilisation efforts. Although the uncertainties and commercial risks for superhot geothermal projects remain high at present, history points us towards engaging in a new phase of assertive and bold action to overcome the remaining hurdles and reach the projected renewable energy targets, using superhot geothermal, in a cost-effective, technically robust, and environmentally responsible manner.

## 2. SUPERHOT INVENTORY FOR NEW ZEALAND

### 2.1 Resource assessment

Using available geoscientific and reservoir engineering information, an assessment of New Zealand's supercritical (>374 °C, >220 bara) or superhot (>374 °C, <220 bara) geothermal resources has been undertaken. This assessment targeted the 'deep roots' of known geothermal systems, combined with possible 'hidden' superhot resources, and a preliminary quantification (inventory) was compiled by Bromley et al (2024). These deep resources are predicted to occur at potentially drillable depths of less than 6 km and at temperatures of up to 500°C. The inventory focusses on the Taupō Volcanic Zone (TVZ), and the Northland Region (Ngāwhā).

The resource assessments utilise the 2019 updated UNFC-2009 and its application to geothermal resources using the UNECE-2022 categorisation approach. By way of comparison, a recent application of this assessment methodology has been applied to conventional depth geothermal resources in the Waikato Region of the TVZ (Ussher et al., 2023). The superhot geothermal assessment is based on interpreted deep geophysics data and follows the volumetric approach to quantification of the extraction of heat over a project lifetime (Garg & Combs, 2011), rather than the $MW_e/km^2$ approach in Ussher et al. (2023). The identified resources are subdivided according to locations with respect to their current categorisation under the regional geothermal planning regulations (see Table 1 for other than protected systems and Table 2 for protected systems). Figure 1 shows the locations at 5 km depth of the superhot resources that have been identified so far (based on deep low-resistivity anomalies) from 3D geophysical magneto telluric (MT) models available in the public domain.

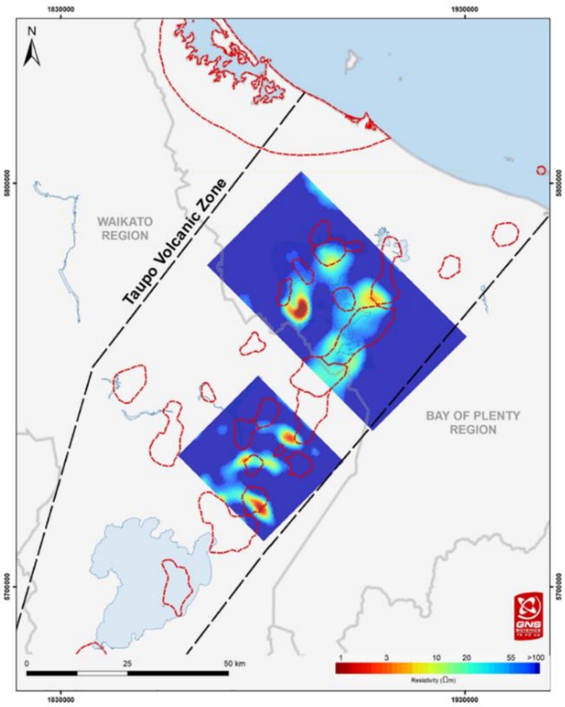



**Figure 1: MT resistivity models at 5 km depth compared to Regional Plan resource boundaries (red lines).**

The assumptions noted in Table 1 are further explained in Bromley et al. (2024) and informed by: Garg & Combs (2011) and Zarrouk & Moon (2014). The MT resistivity anomalies are described in Bertrand et al. (2015, 2022).

A challenge in constructing this superhot inventory was estimating the unknown parameter of superhot reservoir permeability (both for natural state conditions and for development-modified or stimulated conditions). Permeability will govern the potential economic energy deliverability, and extraction sustainability of such resources (Watanabe et al., 2020). It is also challenging to predict the mineral compositions and gas contents of fluid discharges and how these might influence longer term sustainability (Heřmanská et al., 2020, Chambefort and Stefánsson, 2021, Lamy-Chappuis et al., 2022). Analogous fluid properties are inferred from the observed physical and chemical conditions of superhot geothermal fluids that have been encountered in other countries.

**Table 1**. Inventory of probable, 3.5 to 6 km deep, superhot resources in New Zealand (excludes protected systems)

| Systems | Location | Area | Volume | Stored-Heat* | Capacity | Generat-ion |
|---|---|---|---|---|---|---|
| | TVZ | km^2 | km^3 | EJ | MWe | GWhr/yr |
| 1 | Kawerau | 15 | 37.5 | 58 | 412 | 3428 |
| 2 | S Tikitere | | 15.4 | 24 | 169 | 1408 |
| 3 | Haroharo-Tikorangi | | 64.3 | 99 | 706 | 5877 |
| 4 | SW Reporoa | | 23.7 | 36 | 260 | 2166 |
| 5 | W Ohaaki | | 13 | 20 | 143 | 1188 |
| 6 | W Ngatamariki | | 13.6 | 21 | 149 | 1243 |
| 7 | Rotokawa | | 41.1 | 63 | 451 | 3757 |
| 8 | Mokai | 5 | 12.5 | 19 | 137 | 1143 |
| 9 | Wairakei | 5 | 12.5 | 19 | 137 | 1143 |
| 10 | Tauhara | 15 | 37.5 | 58 | 412 | 3428 |
| 11 | Tokaanu | 10 | 25 | 38 | 275 | 2285 |
| | Northland | | | | | |
| 12 | Ngawha | 10 | 25 | 38 | 275 | 2285 |
| | | | | | | |
| Vers. | CB 24-7-24 | TOTAL: | 321 | 493 | 3527 | 29351 |
| *1 | assumes rock: 1.3 specific heat capacity, 2700 density | | | | | |
| *2 | 2.5% heat recovery (4.6% of usable heat >200$^{o}$C), 35 yr life | | | | | |
| | 95% capacity factor, 30% turbine conversion efficiency | | | | | |
| *3 | calculated from deep Central TVZ MT data, (<10 ohm-m) | | | | | |
| *4 | calculated from deep Okataina MT data, (<15 ohm-m ) | | | | | |
| *5 | estimated from geophysics, borehole data & modelling | | | | | |
| *6 | excludes resources under protected geothermal systems | | | | | |
| *7 | default values: 3.5-6 km depths, 375-500 $^{o}$C | | | | | |

**Table 2**. Inventory of probable, 3.5 to 6 km deep, superhot resources in protected New Zealand geothermal systems.

| Systems | Location | Area | Volume | Stored-Heat* | Capacity | Generat-ion |
|---|---|---|---|---|---|---|
| | TVZ | km^2 | km^3 | EJ | MWe | GWhr/yr |
| 1 | SE Rotorua | | 61.1 | 94 | 671 | 5585 |
| 2 | W Waimangu | | 3.7 | 6 | 41 | 338 |
| 3 | E Waiotapu | | 11.9 | 18 | 131 | 1088 |
| 4 | Tongariro | 10 | 25 | 38 | 275 | 2285 |
| | | | | | | |
| Vers. | CB 24-7-24 | TOTAL: | 102 | 156 | 1117 | 9296 |

### 2.2 Modelling

Using supercritical capable codes, large scale mathematical models (e.g. Kissling et al., 2024) and simulations of natural state mass and heat flow through the TVZ have been undertaken (e.g. O'Sullivan et al., 2020). These models provide constraints on likely rock and reservoir properties at the depths of interest. The properties influence the likely productivity and sustainability of superhot fluid resources. Consequently, although insufficient data are currently available to construct robust simulations of individual prospective project resources, representative development scenarios of a typical superhot geothermal prospect can be simulated through economically viable extraction lifetimes. This approach has informed the preliminary inventory assessment. The representative scenarios assume project lifetimes that vary between 35 and 100 years.

### 2.3 Assessment summary

The assessment for a depth range of 3.5 to 6 km identifies that the potential superhot geothermal energy resources suitable for additional power generation are the equivalent of about 4.6 GWe. Future utilisation is predicated on the assumption that technical challenges are overcome. If systems currently protected under existing regulatory planning regimes are excluded, the assessed resource reduces to ~3.5 GWe of installed capacity capable of generating 29 TWh/yr of baseload power. This may be compared with the current geothermal generation capacity from conventional depth reservoirs of ~1.2 GWe (8 TWh/yr in 2023, or 18% of total NZ generation), rising to an anticipated 1.4 GWe of installed capacity by 2030 and possibly 1.7 GWe (12.5 TWh/yr) by 2040 to 2050 (Transpower NZ, 2023).

The geophysical data set of the Taupō Volcanic Zone and Northland is not yet complete. Consequently, the assessment is not fully comprehensive in terms of areal coverage and on that basis is conservative. All these prospects in the New Zealand superhot inventory are at a low confidence level (G4 on the degree of confidence axis from the UNFC assessment) reflecting the current high level of uncertainty, prior to any drilling being undertaken to access superhot geothermal conditions in the 3.5 to 6 km depth interval. As data coverage is extended, models refined, and drilling depths increased, the assessed potential can be updated. The UNFC-2019 classifications (currently E3.2, F4.2, G4.1) will be revised over time, as exploratory drilling and pilot studies are undertaken, enlarging the knowledge-base of specific superhot geothermal projects.

## 3. ECONOMIC MODELLING

### 3.1 Future NZ Electricity Market

To determine the economic value and potential role of superhot geothermal developments in meeting NZ's future power demand, Castalia (2023) undertook a NZ electricity market study. The forecasts in the study consider the NZ Government's climate change commitments regarding use of renewables rather than fossil fuel energy sources. Electricity demand is expected to increase by about 19% by 2037 and 50% by 2050 (based on the NZ Climate Change Commission's 'demonstration path', (Climate Commission, 2023). The main drivers for growth are electrification of transport and industry alongside population and economic expansion. The North Island is forecast to dominate growth in demand (two thirds of the total). The seasonal and daily load duration demand curves are expected to retain the same approximate shape in 2050 as they were in 2023. This affects the relative needs and pricing for baseload and peak generation capacity. The model iteratively calculates the increase in demand distributed across the peak to base load curve for each subsequent year. Wind and solar renewable electricity supplies are de-rated relative to geothermal when calculating a North Island winter-capacity margin to meet demand peaks. That is, large shares of variable renewables will require 'over-building' of capacity to accommodate variations in demand and supply uncertainty. The economic model adopts estimates from the grid operator (Transpower) for the peaking role of 'Variable Renewable Energy' to determine the cheapest option, whilst always providing sufficient capacity.

### 3.2 Cost analysis

Comparative costs, from the model, for different renewable sources of new generation, and battery storage, as a function of capacity factor, are shown in Figure 2. These curves illustrate the cost competitiveness of battery storage and gas-fuelled generation for satisfying short-period peak demand at 10% to 25% capacity factor, but also the cost benefit of building baseload superhot geothermal power plants relative to 'over-built' solar or wind generation for accommodating the full range of capacity factors required to operate the NZ grid. Note that the more expensive battery electric storage capacity would likely substitute for gas peaking if the latter was banned by 2050.

Consequently, the conclusion from the grid capacity modelling is that between 2037 and 2050, about 2 GWe of superhot geothermal capacity would become economic to build (for a 100% renewable scenario, as mandated by the Climate Commission (2023)). A reduced amount of 1.4 GWe would be economic to build for the alternative scenario where some limited fossil-fuel (gas) generation is allowed for meeting demand peaks. The 2 GWe scenario would provide about 16 TWh/yr, approximately 55% of the estimated available superhot resource potential from Table 1 of 29 TWh/yr. This potential amount is in addition to Transpower's prediction of conventional geothermal capacity by 2035 and beyond, which they expect to plateau at 1.7 GWe (12.5 TWh/yr), based on planned and proposed projects (Transpower NZ, 2023). That is, conventional geothermal is expected to grow by about 42% by 2035 compared to the 2024 operating capacity of 1.2 GWe (8 TWhrs/yr in 2023), then remain stable until at least 2050.

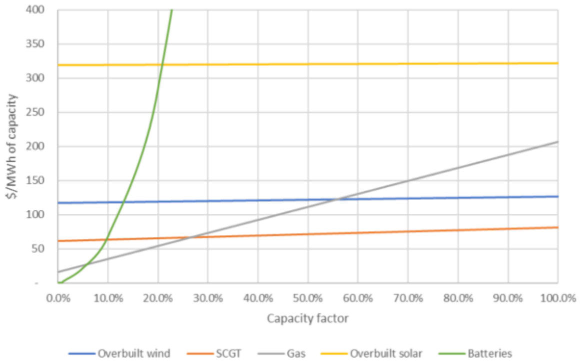



**Figure 2: Comparative cost curves ($/MWh) vs capacity factor (peaking 0-20%, intermediate 20-90%, baseload 90-100%) for different new-build electricity supply/ storage options (from Castalia, 2023); 'overbuilt' means some un-used capacity exists during periods of low demand; (SCGT = superhot geothermal).**

Sensitivity tests on varying the cost of superhot geothermal projects (mostly the capital cost of drilling and surface plant) relative to conventional projects, showed that 2.1 GWe of superhot capacity is economic to build if the cost premium is 0%, 2.0 GWe if the cost premium is +20% (the base case scenario), while 1.9 GWe is still economic even if the cost premium is 100% (i.e., costs double). Similarly, if some gas-fired peaking generation is permitted, the economic capacity drops marginally from 1.4 to 1.3 GWe if the relative cost premium for superhot geothermal increases from 0% to 100%.

### 3.3 Deployment timelines

An ambitious 14-year timeline estimate was prepared by Castalia (2023) for NZ superhot projects to reach maturity and become operational. The timeline was informed by the history of previous energy research timelines and learning rates (Our World in Data, 2022), and assumes all conditions will align and barriers will be overcome. The first 10 years (2023-2033) involves continuing geoscientific, investigatory and engineering research efforts. This is followed by 4 years for design and construction of the first power plant and grid synchronisation in 2037. Parallel to these activities, exploratory drilling consents and approvals are predicted to take 1 year, followed by 5 years of drilling. Once technical issues are resolved, the process of site selection, land acquisition, financial and operational approvals are predicted to take another 2 years, prior to commencing the formal design stage for the first superhot power plant and steam gathering system.

Between 2037 and 2050, for deployment to achieve 2 GWe (16 TWh/yr) of installed superhot capacity, approximately six parallel projects, at about 300 to 400 MWe each, would need to be developed (see Table 1 for the top priority locations). Assuming an average productivity of 40 MWe per well (Rivera & Carey, 2023), one reinjection well per four production wells, and four months to drill each well, this level of new power plant development would require a deep drilling campaign over 10 years (2037 to 2047) using at least two large-capacity drilling rigs.

### 3.4 Direct industrial use and off-grid potential

Castalia (2023) also identified that energy needs for industry, in the form of off-grid power and/or heat at high enthalpy, might also be able to be met from superhot geothermal resources. Direct use of heat for milk processing, timber drying, wood pellet and paper manufacturing in NZ is already an established and economical option for conventional geothermal. These plants typically use steam or two-phase heat exchangers and are often co-located with electricity generation plants. The opportunity to displace some of the 90 PJ/year of industrial energy still sourced from fossil fuels in NZ is appealing. A typical application might be a large central North Island dairy processing factory which could require about 15 PJ/year of energy. Note that dairy factory demand is inversely correlated with electricity prices because dairy milk supply dries up in winter when power demand is high. In terms of revenue generated, the economics of a co-generation project (dairy factory heat and power), using superhot resources, is comparable to that of an electricity-only plant.

## 4. CONCLUSIONS

### 4.1 Resource potential assessment

New Zealand's conventional (sub-critical) installed geothermal capacity is currently ~1.2 GWe generating ~8 TWh/yr in 2023. This is 18% of the total generation of 43 TWh/yr (2023 data), obtained from a total installed capacity of ~10 GWe.

Transpower (the NZ grid operator) estimates that about 16 GWe of total capacity will be required by 2037 as NZ decarbonises its energy use. Castalia Ltd (2023) estimates a 50% increase in demand will occur by 2050. Approximately 1.7 GWe is anticipated by Transpower to be provided by conventional baseload geothermal generation (about 12.5 TWh/yr, or 18% of total demand of 70 TWh/yr, matching the current proportion).

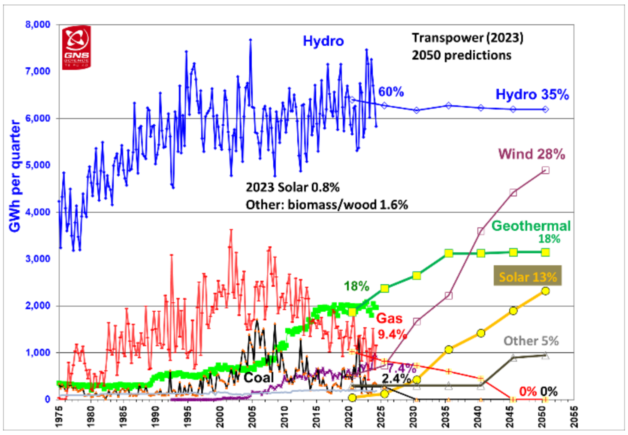
The superhot geothermal resource inventory, for the first time, provides additional potential geothermal capacity for the planners and policy makers to consider. It identifies:

- A total additional capacity of about 4.6 GWe, or 39 TWh/yr for New Zealand.

- After removing the areas that have protected regulatory planning provisions, this reduces the superhot assessment to ~3.5 GWe, or 29 TWh/yr of electricity.

Economic / market studies show that 2 GWe of capacity (15 TWh/yr of generation) would be cost effective to construct between 2037 and 2050 in a fully renewable electricity generation scenario. Alternatively, 1.4 GWe would be cost competitive if some gas peaking electricity generation is still allowed beyond 2037.

Figure 3 shows the historical (1974 to 2024) and projected sources of generation (GWh per quarter) out to 2050. The upper plot illustrates the projections using Transpower's (2023) data which assume total electricity demand growth of 60%, and a maximum installed conventional geothermal capacity of 1.7 GWe (levelling off after 2035), while the lower plot illustrates the projections if superhot geothermal power plants progressively come online between 2037 and 2050. This plot shows the implications of superhot geothermal developments on reducing the reliance for a NZ power grid committed to Net Zero emissions, on large shares of variable renewable energy sources such as wind (reducing from 28% to 18%) and solar (reducing from 13% to 10%) by 2050. The total share of geothermal generation would rise from 18% to about 34% almost matching that of hydro-power generation (35%) by 2050.



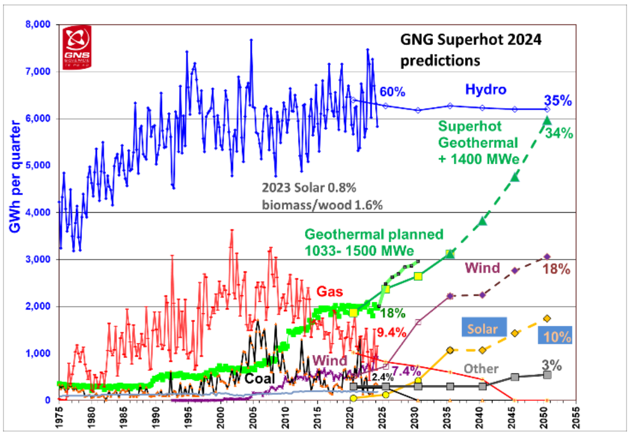




**Figure 3: a) NZ generation mix from 1974 to 2024 with Transpower projections to 2050; b) modified projection using economic superhot geothermal instead of some wind and solar after 2037. (The effect of planned new geothermal projects from 2024 to 2030 are shown as black dots on green).**

Planning the optimal mix of renewable energy sources in the future is complicated. The impact of relatively cheap geothermal power and heat, over time, might increase overall demand by encouraging more switches away from fossil fuel energy sources, hence increasing the need for all renewable options, including wind and solar power. The benefit of adding more baseload geothermal to the future generation mix might reduce the baseload component needed of hydro generation (currently about 60-70% of hydro generation is baseload), and hence allow it to cost-effectively firm up more variable wind and solar, with reduced need for over-built capacity and/or battery storage. But, in the future, this may also require public acceptance of more flexibility than existing consent limits allow for the operation of hydro-dam lake levels and river flows. The variability of water supply due to rainfall changes, combined with the existing strict consent conditions, creates challenges for hydropower plants in responding to the intermittency of wind and solar power, and this will worsen if, as predicted in the Transpower scenario (Figure 3a) wind and solar combined are relied upon for more than 40% of total annual power demand.

### 4.2 Challenges

To facilitate a smooth transition towards the anticipated renewable energy target by 2050, and realise a significant renewable energy opportunity for New Zealand, the challenges are how to attract the needed capital, resource the investigative work, identify opportunities for landowners to collaborate, and align geothermal policies.

This assessment of superhot potential for NZ has identified several engineering and geoscientific challenges and gaps in technology that will require attention and investment. The challenges include:

• Improve communication of the GNG key research findings to sector stakeholders, Māori interests, government agencies, regional councils, potential funding partners, land-owners and infrastructure investors.

• Improve coordination among government and interested private sector parties to mobilise the necessary investment required for exploratory wells and associated scientific research & development.

• Demonstrate long-term energy extraction sustainability is achievable through exploratory wells, flow testing, and improved reservoir modelling.

• Further develop modelling methods to increase confidence in projections of future superhot behaviour and test the hypothesis that the deeper the fluid extraction/reinjection, the smaller the near-surface effect, and hence reducing the need for a pre-cautionary approach regarding deep geothermal resource planning.

• Remove regulatory barriers and re-work regulatory planning frameworks to assist timely development of robust superhot projects across the Taupō Volcanic Zone, Bay of Plenty, Waikato and Northland Regions. A forward-looking sequence from exploratory activity through to superhot power plant permitting will be needed to facilitate funding for exploratory activities (Kissick et al 2024).

• Encourage investment in studies to solve technical challenges such as: well drilling and completion methods; management of scale formation, corrosion, and thermal stress issues; design of efficient and cost-effective turbines, heat-exchangers and surface piping for superhot fluids.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