CASTALIA

Supercritical Geothermal in New Zealand:

Economic opportunity in renewable electricity generation and for off-grid energy

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Table of contents

Appendices

Tables

Figures

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Definitions

CCC	Climate Change Commission
CCUS	Carbon Capture Utilisation and Storage
Enthalpy	The sum of the internal energy and the product of the pressure and volume of a thermodynamic system. In the case of geothermal, it is measured as joule per kilogram (energy per unit mass)
EV	Electric Vehicle
GNS	GNS Science-Te Pū Ao, the Institute of Geological and Nuclear Sciences
HFC	Hydrogen fuel cell
IDDP	Iceland Deep Drilling Project
KMT	Krafla Magma Test Bed
LCGEP	Least-cost general expansion plan
LDC	Load duration curve
MDAG	New Zealand Electricity Authority's Market Design Advisory Group
MW	Megawatt
MWth	Megawatt thermal, typically the input energy required for a power plant using thermal energy
Next Generation	GNS' Geothermal: Next Generation project
NICM	North Island capacity margin
NZGA	New Zealand Geothermal Association
SCGT	Supercritical geothermal
Solar PV	Solar photovoltaic
SOSA	Transpower's security of supply assessment
TVZ	Taupō Volcanic Zone
VRE	Variable renewable energy

Executive summary

GNS Science-Te Pū Ao (GNS) is responsible for researching and developing new applications of technology. It is leading the 'Geothermal: The Next Generation' project. This project will address the geological, geochemical and technological challenges of super-hot geothermal use. The GNS team combines expert geophysicists, geologists, experimental geochemists, modellers and strategic advisors. They are investigating New Zealand's supercritical geothermal conditions and drawing insights from international experiences.

GNS has hired Castalia to evaluate the economic opportunity for supercritical geothermal (SCGT) in New Zealand. SCGT represents an exciting new frontier for renewable energy generation and utilisation. It has unique characteristics that differ from current geothermal energy resources. It has the potential to meet a significant component of New Zealand's renewable energy demand beyond 2037.

The New Zealand Government has an ambitious target for net-zero emissions by 2050, including achieving 100 percent renewable electricity generation (under normal hydrological conditions) by 2030. New Zealand's conventional geothermal generation resources will contribute to additional electricity generation. However, the contribution is not expected to be significant, especially compared to the potential contribution from SCGT. In addition, New Zealand's energy demand is growing, and much of that will be met by electricity in the future. As electric vehicles (EVs) grow as a proportion of the vehicle fleet, industrial and commercial processes and heat uses switch to electricity, demand for grid electricity will grow.

SCGT represents a significant opportunity to meet New Zealand's future energy demands and contribute to climate policy commitments. Until now, government agencies in New Zealand, including the Ministry of Business, Innovation and Employment (MBIE) and the Climate Change Commission (CCC), have not included the potential benefits of SCGT electricity generation or other energy use in their policy analysis and advice.[1]

SCGT is a potential constant, zero-emissions abundant source of energy

SCGT could meet all elements of the energy trilemma and provide abundant low-cost, zero emissions, and reliable electricity for New Zealand. According to GNS' Next Generation experts, SCGT resources could potentially generate 30,000 GWh of energy annually. This abundant underground energy source remains untapped.

SCGT is also spatially efficient. The footprint of a SCGT well field and power plant would be similar to a conventional geothermal plant, which is around 7.5 km^2 of land per TWhr/year. In contrast, solar PV requires around 5x as much land to generate the same energy (not accounting for capacity factor).

Over the last two years, geothermal operators have reduced the relatively minor emissions from conventional geothermal to near-zero by reinjecting greenhouse gases extracted from wells back underground from whence they came. New geothermal projects will be built with

[1] MBIE develops the 2023 Energy Strategy and advises the Government on energy policies, including the 100 percent renewable electricity goal by 2030. CCC formulates carbon budgets and models various electricity generation technologies and energy sources for its governmental advice.

reinjection technology as a core part of the project commissioning. When SCGT is developed, we expect even greater advances in reinjection and emissions-minimisation. SCGT should be treated essentially as a zero-emissions energy source.

SCGT generation could be commissioned as early as 2037

The GNS Geothermal Next Generation team and researchers around the globe are actively working on developing SCGT. It is approximately at level 3 (applied research) of the European technology readiness scale. Bringing SCGT to commercial readiness requires significant effort, investment, and cooperation among multiple parties.

The science of exploring SCGT resources and the potential for harnessing them is progressing steadily. The key barriers to the development of SCGT are around drilling productive wells that have a commercial lifespan, as well as developing the commercial technologies for the SCGT energy transformation processes (such as electricity generation). Additionally, there is a critical challenge in the environmental consenting regime, where Government support will be essential to avoid delays not directly related to resolving genuine environmental issues.

Castalia estimates that the earliest timeframe for SCGT commercialisation is 2037. We based this on estimates of the significant scientific and engineering progress that still needs to be made. We inferred a development timeframe based on the learning curves of other energy technologies, including conventional geothermal (by reviewing the history of geothermal in the Taupo Volcanic Zone), shale gas, and solar PV. We also assumed that the New Zealand Government would support the development of this new energy source by enabling a permissive environmental consenting regime. We also assumed that landowners, many mana whenua, would support the development.

We look forward to discussing the assumptions and findings in this draft report with mana whenua representatives.

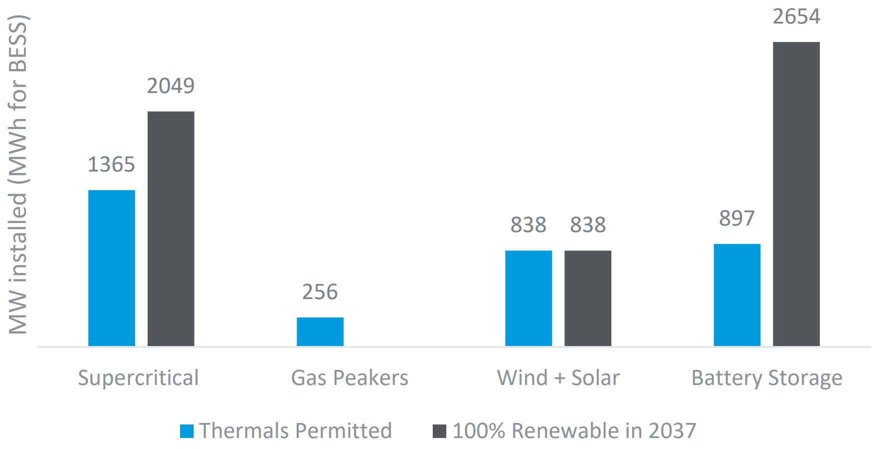
SCGT could provide around 2,000 MW of new electricity generation capacity from 2037 in a zero-emissions scenario

SCGT has the potential to provide a lower-cost pathway to a low- or zero-emissions electricity grid from the late 2030s. Castalia's modelling shows that SCGT could make up a substantial portion of new generation capacity, even when compared to low-marginal cost variable renewable energy sources such as wind and solar generation, particularly after the late 2030s.

Several analyses have assessed New Zealand's future electricity demand and the pathways to achieve it with low- or zero-emissions. However, none of these analyses conducted by Transpower, the Climate Change Commission, MBIE, and other stakeholders has considered the potential of SCGT. As a result, we developed a new modelling approach to estimate the role of SCGT in a future where there is a low-cost variable renewable generation, on-grid storage options, and the potential for a higher carbon price or a ban on fossil fuel generation.

Our modelled results suggest that if and when SCGT is feasible, it could provide around 1,365 MW to 2,050 MW of new capacity, depending on whether gas-fired peaking generation is permitted beyond 2037, as shown in Figure 0.1.

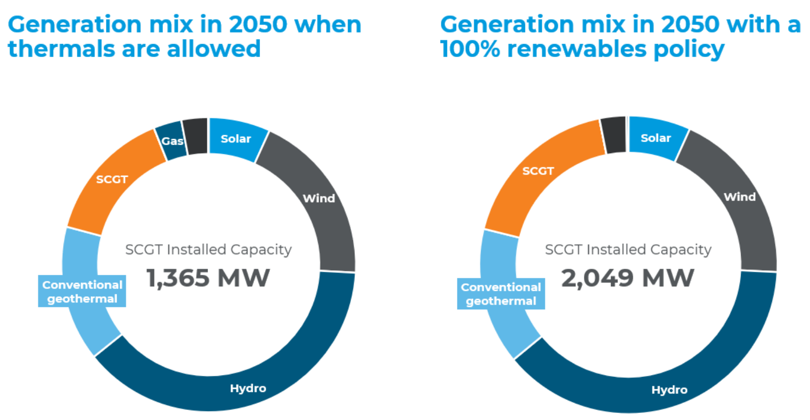
Figure 0.1: Forecast generation built between 2037 and 2050 (base case assumptions)



Source: Castalia generation model

The figure below illustrates that the total generation fleet in 2050 under a thermal permitted scenario and the 100 percent renewable generation scenario will have a significant share of SCGT.

Figure 0.2: Generation mix in 2050 with and without thermals

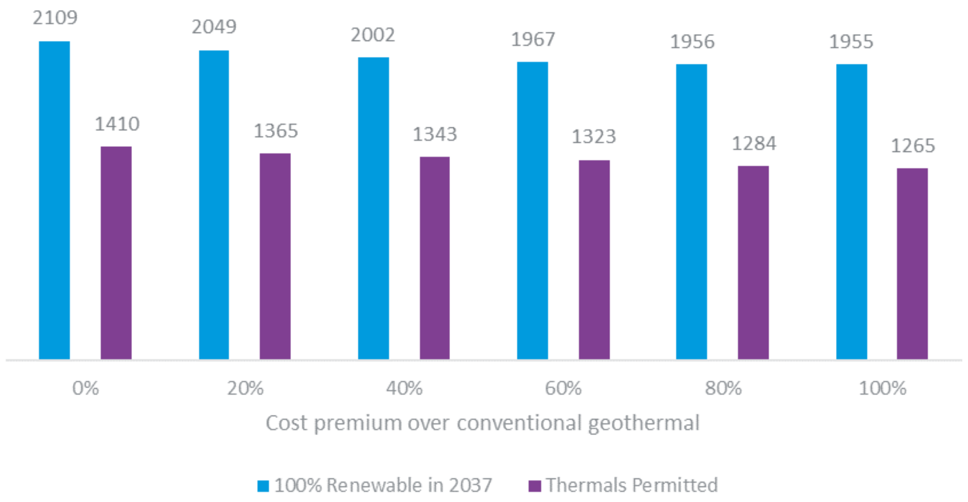


Source: Castalia generation model

The costs to build SCGT generation plants are uncertain and have not yet been estimated for the New Zealand context. The wells will be around twice as deep as the current deepest conventional geothermal wells, with hotter fluids and different chemical characteristics.

Even if costs are double the conventional geothermal costs, very significant SCGT could be built in the 100 percent renewable scenario. At 1.5x the cost of conventional geothermal, demand for SCGT will be robust in the renewable or gas-peaker electricity system scenarios, as illustrated in Figure 0.3.

Figure 0.3: SCGT nameplate capacity at different price points in the gas-peaker and 100 percent renewable scenarios



Source: Castalia generation model

SCGT could also provide energy for other uses in economical ways

SCGT could provide large amounts of heat energy for other uses. Currently, conventional geothermal is used in dairy processing and for processing wood products. We considered two additional uses for SCGT:

- **Building a mega-dairy processing plant to process raw milk into milk powder and other products using SCGT heat**. This could use the complementary seasonality of both dairy processing (spring and summer peak) and electricity generation (winter peak) demand. We estimate that a SCGT plant that combined a curtailable electricity generation plant and a dairy factory that used diverted heat could use up to 26 PJ of energy
- **Using SCGT heat to process plantation wood into pellets,** for example, to fuel the Huntly power station throughout its operational lifespan or to provide renewable fuel for other converted coal boilers, presents an interesting opportunity.

Next steps

Despite the potential benefits of SCGT, government agencies have yet to include it in their analysis. We recommend that GNS proactively initiate discussions with MBIE and CCC to explore how SCGT can contribute to addressing the energy trilemma. The objective of engaging with the government is to highlight the potential advantages of SCGT and encourage investments to enhance its technology readiness. If the ambitious timeline of 2037 is to be reached, significant investment and policy alignment is needed. The Government has granted fast-track consenting for renewable generation, including hydro, solar, and wind, so it could consider similar accommodation for geothermal or SCGT in due course.

1 SCGT is a potential new energy source

Supercritical geothermal (SCGT) represents an exciting new frontier for renewable energy generation and utilisation. It has unique characteristics that differ from current energy resources. We set out our core assumptions about the development of SCGT, including its characteristics, energy outputs, and the timeframe for its development.

1.1 SCGT could provide reliable, low-emissions energy

The characteristics of this SCGT energy source mean it could be a reliable, high-efficiency, and low- emissions form of energy for Aotearoa, New Zealand.

SCGT utilises high underground temperatures and pressures

SCGT energy is sourced from extremely hot rock heated by magma.[2] When pure water exceeds 373 degrees Celsius and 220 bars of pressure, it becomes "supercritical,"[3] making it neither liquid nor gas. In this state, the enthalpy is up to about three times higher than the production enthalpy of the geothermal waters currently extracted from the high-temperature geothermal fields in the Taupō Volcanic Zone. Around the globe, supercritical conditions generally occur at a depth of around 13km. However, the Taupō Volcanic Zone (TVZ) is near shallower magmatic-derived heat sources with SCGT conditions expected to exist as shallow as ~4km.

SCGT has theoretically higher conversion efficiency than conventional geothermal

Using SCGT energy to produce electricity or 'do work' is expected to be more thermodynamically efficient as the available underground temperature increases. Theoretical efficiency calculations from fundamental thermodynamics show that improved efficiency is achieved with higher geothermal resource temperatures. This means the amount of useful energy produced compared to the total energy available should be higher than conventional geothermal.

SCGT is spatially efficient

Geothermal energy facilities, including those expected from SCGT, have a relatively small land footprint compared to solar and wind installations. This means SCGT should have reduced amenity and land impacts relative to some of the other forms of renewable generation. On average, a conventional geothermal power plant, including the infrastructure for electricity generation and the wells to access the geothermal reservoir, requires about 7.5 km^2 of land per TWhr/yr (120 MW consistent generation). This is much less land than most other forms of renewable energy (for example, solar PV at 37 km^2 per TWhr/yr).[4] With careful planning and fewer drilling pads (such as might be expected for a compact SCGT development), the land

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2 Roberts, David. 'Geothermal energy is poised for a big breakout'. Vox. Accessed 21 July 2023. https://www.vox.com/energy-and-environment/2020/10/21/21515461/renewable-energy-geothermal-egs-ags- supercritical

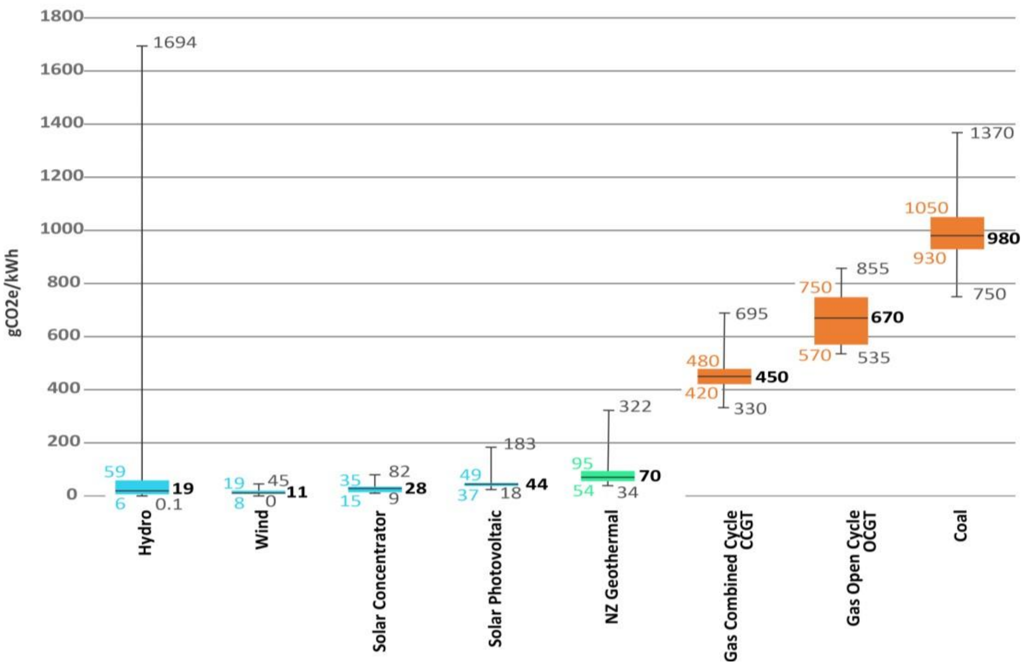
3 The salt content affects the temperature and pressure conditions at which the fluid becomes supercritical and so for sea water at 3.2 percent weight Sodium Chloride the critical point conditions are at a temperature 407 degrees Celsius and 298.5 bars of pressure. (Bischoff and Rosenbauer 1988) //nca2014.globalchange.gov/ (page 258)

footprint can be reduced even further, providing for multiple land-use between pads, such as farming or forestry.

SCGT is a low-carbon energy resource

Even if SCGT power plants emit some carbon dioxide and other GHGs, these are materially lower than fossil fuel energy emissions, and they differ in that they originate from gas emissions naturally passing through the earth's crust. Indeed, a computer simulation of the long-term effect of 100 years of geothermal energy extraction, followed by several hundred years of natural recovery, shows that geothermal energy extraction is actually a net zero operational carbon emission process.[5] During the plant's lifetime, the median lifecycle emissions intensity[6] (accounting for construction and decommissioning emissions) for New Zealand geothermal is 70 gCO2e/kWh (in 2019), while the lowest emitting fossil fuel–gas CCGT–produces over seven times that amount.[7] During operation, geothermal does, however, emit more than renewable power sources such as wind, hydro, and solar. Figure 1.1 shows these differences.

Figure 1.1: Comparison of lifecycle emissions intensity across renewable and fossil fuel energy types



Note: Replotted from Siratovich et al. 2021, by GNS Science. Bold numbers are the median. Box edges are upper and lower quartiles. Whiskers are maximum and minimum.[8]

5 O Sullivan et al 2021, https://doi.org/10.1016/j.renene.2021.05.021

6 Lifecycle analysis models the emissions over the expected lifespan of the plant, including emissions associated with materials and construction, operational emissions, and decommissioning.

7 McLean, K., and Richardson, I. 'Geothermal Greenhouse Gas Emissions in New Zealand in 2020: Lifecycle and operational emissions.' New Zealand Geothermal Association, November 2021.

8 Ibid.

Currently, there are efforts to reduce greenhouse gas emissions from geothermal power generation facilities by returning the gases back underground through injection wells.[9] The New Zealand Geothermal Association (NZGA) is leading this initiative involving various geothermal resource and plant operators. We understand that Ngawha Generation Limited has published material indicating that operational atmospheric emissions from Ngawha facilities have been eliminated. A quarter of the emissions from the Nga Tamariki Geothermal Power Station, as well as all the GHG gases associated with the Te Huka power plant, are currently being sequestered underground.

The atmospheric emissions reduction technology will be continuously improved before implementing it in super-hot geothermal facilities. These advancements are expected to significantly reduce operational greenhouse gas emissions from NZ geothermal facilities, and SCGT power generation will adopt zero operational emissions technology.[10]

Moreover, SCGT plants may have relatively low embedded emissions compared to wind and solar. These embedded emissions are particularly important because manufacturing emissions for imported components are not accounted for in the New Zealand Emissions Trading Scheme. The lifespans of geothermal powerplants tend to be very long—Wairakei is currently in its 65th year of operation—and the materials used tend to be recyclable. This means any emissions created during manufacturing are effectively spread over a longer period. This compares to the 30-year lifespans which can generally be expected from solar PV.[11]

New Zealand is at an early stage of SCGT technology development

SCGT technology is currently at approximately level 3 on the European Technology Readiness Scale (TRL) - the experimental proof-of-concept stage.[12] Appendix A presents this scale in detail. Multiple countries are experimenting with SCGT wells, but it is not yet at the commercially viable stage (TRL stage 9) in any of the nations.

…but international and local progress is promising

Several countries are actively involved in the research, development, and deployment of SCGT projects. Completed projects include GEMex, which explored super-hot geothermal systems in Mexico[13] ; DESCRAMBLE, which extended a well in Italy to 2.8km and over 500-degree Celsius temperatures[14] ; and DEEPEGS, which demonstrated the feasibility of Enhanced Geothermal Systems in delivering renewable energy in Europe.[15]

A number of projects are currently in progress. These include the European DEEPEN (Derisking exploration for geothermal plays in magmatic environments) programme,[16] the European MODERATE (Magma Outgassing During Eruptions and Geothermal Exploration) programme,[17]

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9 Carey, B., and Chambefort, I. 'What is the end use for ultra-hot geothermal energy in Aotearoa New Zealand?' GNS Science, 2023.

10 Ibid.

11 https://www.energy.gov/eere/solar/end-life-management-solar-photovoltaics

12 Personal communication from GNS Science, 12 July 2023.

13 https://wayback.archive-it.org/12090/20190927153900/https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/geothermal/gemex

14 https://www.descramble-h2020.eu/

15 https://deepegs.eu/

16 https://www.or.is/en/about-or/innovation/deepen/

17 https://cordis.europa.eu/project/id/101001065

the Clean Air Task Force Super-hot Rock work[18] and the Newberry super-hot EGS work in the USA[19], the subduction-origin geothermal resource work in Japan (NEDO),[20] the work in Iceland through the Iceland Deep Drilling Project (IDDP)[21] and the Krafla Magma Test Bed (KMT)[22], and GNS' Next Generation programme in New Zealand.[23]

1.2 SCGT could provide up to 30,000 GWh per year in energy output

At the overall national scale, SCGT energy potential in New Zealand is estimated to be large, equivalent to at least three times the current output of conventional geothermal, from early computational assessments by GNS.[24] Conventional geothermal (less than 3.5km depth) has the capacity to grow by 50 percent over the next 8 years, from 8,000 GWhr/yr to 12,000 GWhr/yr. Super-hot geothermal (another name for SCGT in the context of this report), considering the depth interval between 3.5 and 6km depth, could theoretically generate an additional 30,000 GWhr/yr.[25] Appendix B shows the estimated output for the 12 potential locations (excludes protected geothermal system locations as identified in the planning documents of the Waikato and Bay of Plenty Regional Councils) in the TVZ and Northland.

1.2.1 SCGT in electricity generation

A promising end use for SCGT is electricity generation. It could supply energy to large power users or contribute to the electricity market.[26] This is discussed in more detail in Section 3 below. Two technologies for conventional geothermal electricity generation are used in New Zealand:

- **Geothermal steam**: Steam from underground or separated from two-phase geothermal fluid is used directly to drive a turbine generator
- **Binary cycle**: Geothermal fluids heat up a closed-loop organic fluid such as n-pentane, which is expanded through the turbine to generate electricity. The heated organic fluid releases heat to the atmosphere, is condensed, and then gets pumped back to be

18 https://www.catf.us/about/

19 http://www.geothermal-energy.org/pdf/WGC/papers/WGC/2020/31059.pdf

20 https://www.nedo.go.jp/english/news/AA5en_100251.html#:~:text=New%20Energy%20and%20Industrial%20Technology%20Development%20Organization%20%28NEDO%29,with%20great%20potential%20to%20reduce%20greenhouse%20gas%20emissions.

21 https://iddp.is/

22 https://www.kmt.is/

23 https://www.geothermalnextgeneration.com/

24 Personal communication from GNS Science, 16 July 2023.

25 Assuming a 95 percent capacity factor and 30 percent turbine efficiency; This estimate considers depths between 3.5km and 6km, across unprotected systems. It excludes resources underlying protected geothermal systems (Rotorua, Waimangu, Waiotapu, Te Kopia, Orakei Korako, Tongariro). GNS estimates that 30 percent of New Zealand's energy potential is held in these protected systems.

26 Carey, B., and Chambefort, I. 'What is the end use for ultra-hot geothermal energy in Aotearoa New Zealand?' GNS Science, 2023.

reheated in the loop, enabling continuous power generation from energy in the geothermal fluids.[27]

Similar processes are expected to be used for SCGT electricity generation, with some research underway internationally to adjust energy transformation methods to SCGT conditions. It is expected that a secondary cycle, similar in concept to a binary cycle generation system, might be suited for SCGT conditions.

Conventional geothermal resources generate a significant amount of the total electricity generated in New Zealand. In 2022, geothermal power stations generated 18.5 percent of New Zealand's electricity.[28] Recent and upcoming geothermal electricity generation developments include the Ngāwhā OEC5 plant, Tauhara II, Te Huka II, Ngatamariki Unit 5, Kawerau TOPP2, and Taheke Unit 1.

Energy extraction can operate continuously for extended periods

SCGT facilities, in theory, should operate at all hours of the day for 365 days each year. It is, therefore, a reliable and consistent energy source. At a macro-scale, the magmatic heat source is continuously available on a geological timescale, providing an abundant source of heat over the commercial lifetime of a plant.

SCGT can be curtailed…

It may be possible to build a SCGT power plant that can reduce its power output from its maximum. This can be done by a turbine bypass system (in a binary cycle design) or through a well-flow control valve. Both technologies are currently used with conventional geothermal resources. Well-flow control valves have been used to curtail the output from dry-steam geothermal power plants in The Geysers in California and Poihipi in New Zealand.[29] A turbine bypass system is used at the Puna Geothermal Venture in Hawaii.[30] Experts from GNS' Next Generation project suggest that the characteristics of SCGT are such that well flow control valves will work in this case, too.[31] Curtailment is not a feature required for SCGT to contribute to the New Zealand grid, as is discussed in Section 1.3.

…however, it is unlikely to be needed.

In most cases, it makes sense to run geothermal power plants at their full output continuously. The marginal cost of producing geothermal electricity is approximately $0. And though energy can be retained in the reservoir by not drawing from it, the sheer amounts of energy available make this irrelevant. Therefore, so long as electricity prices remain above $0, a generator is better off generating as much as possible.

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27 Kissick, D., Climo, M., and Carey, B. 'An Overview of New Zealand's Geothermal Planning and Regulatory Framework,' Geothermal: The Next Generation, August 2021, available at: https://assets.website-files.com/5ee80754caf15981698cc972/612c72326270bdcf6b0c2639_Regulatory%20Review%20Report%20V1.2%20FINAL.pdf

28 MBIE (2022), New Zealand Energy Statistics, available at: https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/electricity-statistics/; More detailed data is available: https://www.mbie.govt.nz/assets/Data-Files/Energy/nz-energy-quarterly-and-energy-in-nz/electricity.xlsx .

29 Patrick Dobson et al., 'Analysis of Curtailment at The Geysers Geothermal Field, California', *Geothermics* 87 (1 September 2020): 101871, https://doi.org/10.1016/j.geothermics.2020.101871.

30 Josh Nordquist, Tom Buchanan, and Michael Kaleikini, 'Automatic Generation Control and Ancillary Services', *Geothermal Resources Council Transactions* 37 (2013): 761–66.

31 GNS' Next Generation team member Chris Bromley

This is confirmed by the offers made by existing geothermal generators to supply electricity. Almost 90 percent of the megawatt-hours offered by geothermal generators on a representative day during Winter 2023 were priced at less than $0.10/MWh, compared to a prevailing electricity price above $100/MWh.

If geothermal is curtailed in a competitive electricity market, it typically occurs for one of three reasons:

- The electricity price has fallen below zero, and the generator is losing money by supplying power to the grid (for example, The Geysers)
- The electricity generator is being paid to provide ancillary services to the grid (for example, reducing its output to keep the grid's frequency at the desired 50 Hz; Puna Geothermal Venture)
- The electricity generator is limited in the amount of geothermal steam they are permitted to draw over a given day (for example, Poihipi).

None of these three circumstances is likely to apply to SCGT in New Zealand.

Electricity prices are very unlikely to fall below zero in New Zealand. Prices will generally only be near zero in New Zealand if output from generators with a marginal cost of zero (for example, run-of-river hydro, geothermal, and wind) equals or exceeds demand (including the charging of batteries). If this occurs, wind generation is likely to be curtailed, as all modern wind turbines have curtailment capabilities or run-of-river hydro will be allowed to spill. This will ensure that electricity prices do not fall below zero without any adjustment being necessary by geothermal plants.

In other countries, electricity prices sometimes fall below zero. In Germany and the United States, for instance, renewable generators earned production-related subsidies per MWh they produce. Therefore, they keep producing even at negative prices. Such subsidies are not paid in New Zealand, so this will not occur here.

Similarly, SCGT is very unlikely to be used to provide ancillary grid services in New Zealand. Transpower currently pays generators $14 million a year to provide 'over-frequency reserve' and 'frequency keeping services' – i.e., plants that vary their output to keep the grid at 50 Hz.[32] Currently, only 15 MW per island is required for frequency keeping, and most of the frequency management offers are made by hydro plants, which have hundreds of MW of capacity available to offer the services. They will likely continue to be the cheapest method available for frequency management.

Finally, the sheer amount of supercritical resources available means that it is unlikely that local authorities will set binding drawing limits. Even if limits are set, generators can tailor their power station capacities to match them. Poihipi only curtailed its daily production because it had consent to draw enough steam for 45 percent of its nameplate capacity when operated

[32] Transpower. "Frequency Keeping." Accessed August 16, 2023. https://www.transpower.co.nz/system-operator/information-industry/electricity-market-operation/ancillary-services/frequency.

continuously.[33] It is now supplied with steam from Wairakei, making curtailment unnecessary.[34]

If the electricity market is not competitive, a SCGT generator might wish to curtail output to inflate electricity prices artificially. However, such behaviour is unlikely to be acceptable to New Zealand regulators. Therefore, the report and the economic modelling do not consider the curtailment of SCGT.

1.2.2 SCGT in direct heat applications

Direct heat utilisation is another promising SCGT use, with such energy utilisation expected to be in conjunction with a major SCGT production facility such as an electricity generation operation. Geothermal heat is currently used in the tourism, aquaculture, agriculture, and residential sectors. It is used to kiln dry timber, process paper, grow vegetables, process honey, heat aquaculture ponds, heat water, and provide medicinal uses.[35] In Taupo, the Tenon sawmill uses geothermal energy to kiln-dry sawn timber, and Nature's Flame uses it for drying feedstock for its biofuel pellets.[36] At Kawerau, geothermal heat is used to kiln dry timber, manufacture tissue paper, produce pulp, and process milk. Miraka's dairy factory uses geothermal energy at Mokai to process milk.

1.2.3 SCGT in power-to-X uses

SCGT could be used for "power-to-X". This refers to technologies that convert electricity into other forms of energy, energy carriers, or chemicals. This includes processes like electrolysis creating hydrogen from water (power-to-gas), synthesis to create synthetic fuels (power-to-liquid), or processes to generate heat (power-to-heat).

- **Power-to-gas**: SCGT could supply electricity for electrolysis processes, splitting water into hydrogen and oxygen. The hydrogen produced can then be used directly as a fuel, combined with captured CO_2 to create synthetic methane, or used in fuel cells to produce electricity
- **Power-to-liquid**: Similarly, SCGT could supply electricity to power processes that combine hydrogen with CO_2 to create synthetic liquid fuels. These synthetic fuels can be used as a direct replacement for traditional fuels in transport or other sectors, offering a potential pathway to decarbonisation
- **Power-to-ammonia:** Using SCGT electricity to produce hydrogen, which is then combined with nitrogen to produce ammonia. Ammonia is an energy-dense and easily transportable form of energy, and it's also a crucial ingredient in many industrial processes, including fertiliser production.

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[33] Zarrouk, Sadiq J, Michael J O'Sullivan, Adrian E Croucher, and Warren I Mannington. "Optimized Numerical Modeling of Production from the Poihipi Dry Steam Zone: Wairakei Geothermal System." In *Proceedings of Thirty-First Workshop on Geothermal Reservoir Engineering*. Stanford University, 2006. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2006/zarrouk.pdf

[34] Lawless Geo-Consulting. "Future Geothermal Generation Stack." MBIE, March 2020. https://www.mbie.govt.nz/assets/future-geothermal-generation-stack.pdf.

[35] Ibid.

[36] Carey, B., and Chambefort, I. 'What is the end use for ultra-hot geothermal energy in Aotearoa New Zealand?' GNS Science, 2023.

1.2.4 Sources of uncertainty in SCGT output

Many factors potentially affect the SCGT energy output, including land ownership, the Conservation Estate, land encumbrances, and easements, the regulatory planning provisions relating to land that might be considered prospective for SCGT, the depth capability of drilling equipment, availability of fresh water to facilitate the drilling operations and commercially reliable conversion technologies.

SCGT output could be restricted by the location of some resources within the Conservation Estate. Currently, 30 percent of energy potential is held in protected lands, including National Parks.[37] If regulations around these areas change, the energy potential could change, increasing or decreasing, depending on the nature of the regulatory changes.

Achievable drilling depths will get deeper with time, impacting the accessible resource potential. Current SCGT output assessments are based only on the 3.5 to 6km depth range. This range is assumed to represent the maximum drilled depth achievable with technology likely to be available in New Zealand over the next five years. Technology development is expected to increase drilling depths and the energy output potential with time.[38]

Output potential depends on a project's energy conversion efficiency and the on-going reliability of production and injection operations. These are affected by both process and resource factors, including:

- The power plant's size, design, and parasitic loads
- The return of geothermal fluids back into the underground
- The management of the gas content in the geothermal fluid
- The dissolved minerals content amongst a range of factors.[39]

1.3 SCGT is technically dispatchable

If geothermal generation could be made dispatchable, it could supplement variable renewable generation assets like wind and solar. In the modern electricity grid, with an increasing share of low-marginal cost variable renewable generation, traditional concepts of "baseload" and "peak" are becoming less important. Variable renewable energy (wind and solar) is forecast to make up a larger share of New Zealand's electricity generation capacity over time. A key feature of modern electricity systems is no longer the continuous supply of energy (baseload) but rather its dispatchability—the ability to deliver power when needed.

As low marginal cost variable renewable generation is integrated into grids, grid assets that can provide fast response time, high ramp rates, and varying durations of energy storage become valuable characteristics. Under this new energy paradigm, wind and solar generation provided at low cost when available need to be supported by dispatchable assets.

37 Personal communication from GNS Science, 13 July 2023.

38 Ibid.

39 Zarrouk. S. J., and Moon. H. (2014). Efficiency of geothermal power plants: A worldwide review. Elsevier, 51(2014), 142-153. https://doi.org/10.1016/j.geothermics.2013.11.001.

Geothermal dispatchability is technically possible

It will probably be technically feasible to make SCGT curtailable (that is, reduce energy output to the grid from its maximum). SCGT is likely to be similar to dry stream geothermal, where reducing the well-flow to reduce power output is currently an option. In conventional two-phase (water and steam) geothermal, throttling a well can lead to discharge instability. This is possibly not the case with SCGT, where the fluids are expected to be much more like steam/vapour.

The curtailment of dry steam geothermal is a widespread practice. The Geysers power stations in California are regularly curtailed simply by reducing well flow. This is for both economic reasons (the electricity price often falls below $0 in California due to the high penetration of variable renewables and volume-based subsidies) and technical reasons (the Californian system operator pays The Geysers to provide load balancing services).

Similarly, the Poihipi station in the Taupo Volcanic Zone was previously curtailed by reducing production well steam flow to comply with resource consents.

Some binary cycle geothermal can be curtailed. This occurs at the Puna Geothermal Venture in Hawaii because these grid services are particularly valuable to the isolated and small-sized grid on the Big Island of Hawaii.

Curtailing geothermal generation is only economic in exceptional circumstances

However, as noted in Section 1.2.1, curtailing geothermal capability is unlikely on the New Zealand grid due to the near-zero marginal costs of SCGT generation and the grid's stability. SCGT is not expected to provide curtailment services for New Zealand, as other technologies are better suited for this purpose. Hydro operators are contracted to provide frequency response services to the grid, and only 15MW for each of the North and South Islands is required in New Zealand.

Curtailing could make economic sense in specific cases. In Section 3, we discuss when it might be cost-effective, especially when paired with seasonal dairy demand. However, this report and the economic modelling do not consider curtailment a requirement for SCGT.

2 SCGT could be commissioned from 2037

Our basic estimate is that the first SCGT resources can be grid-connected by the beginning of 2045. This assumption is required to forecast the energy market conditions SCGT will encounter. These conditions underlie our estimates of the possible economic value of the resource.

This 22-year timeline, out to 2045, is the **baseline** case, made up of three phases, each of which has been estimated separately:

- **Scientific and technical progress**: 15 years from 2024, including five years of exploratory drilling starting in 2027),
- **Regulatory approvals**: A total of five years, running in parallel with scientific and technical progress and including two years for the approval of exploratory drilling and
- **Design and construction of the first plant**: Six years, starting in 2039.

This timetable necessitates political support and committed investors for the project. Nevertheless, it's achievable: From the decision to initiate exploratory drilling in 1949 in the TVZ to the launch of the world's first wet-steam geothermal power station at Wairakei, it only took nine years.

The timeline may even be faster. More workstreams could be run in parallel. Potential renewable energy benefits may encourage regulators to expedite their processes. Scientific and technical progress may advance as rapidly as during the early stages of traditional geothermal development in New Zealand. Finally, construction times could fall to only slightly above the period required to build a conventional geothermal plant today.

We estimate that, in this **ambitious** case, the time-to-market could be as short as 14 years (i.e., 2037), made up of:

- **Scientific and technical progress**: Nine years from 2024, including five years of exploratory drilling starting in 2025),
- **Regulatory approvals**: A total of two years, running in parallel with scientific and technical progress and
- **Design and construction of the first plant**: Four years, starting in 2034

Figure 2.1: Baseline Timeline for SCGT

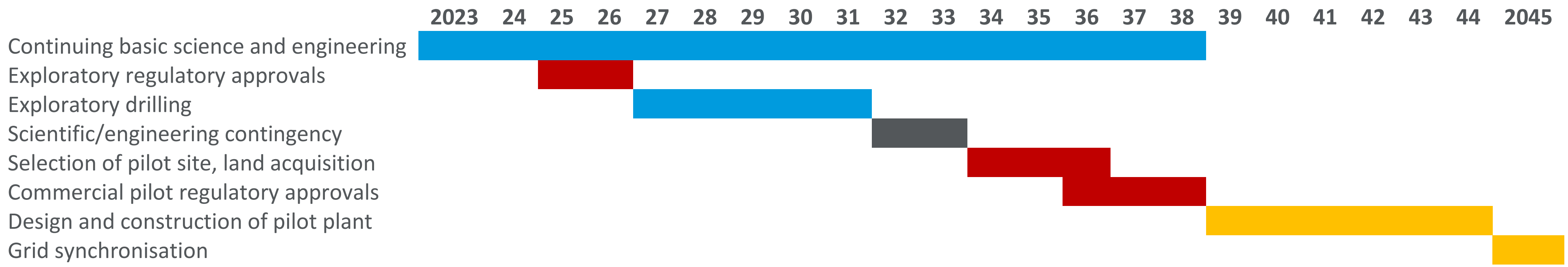
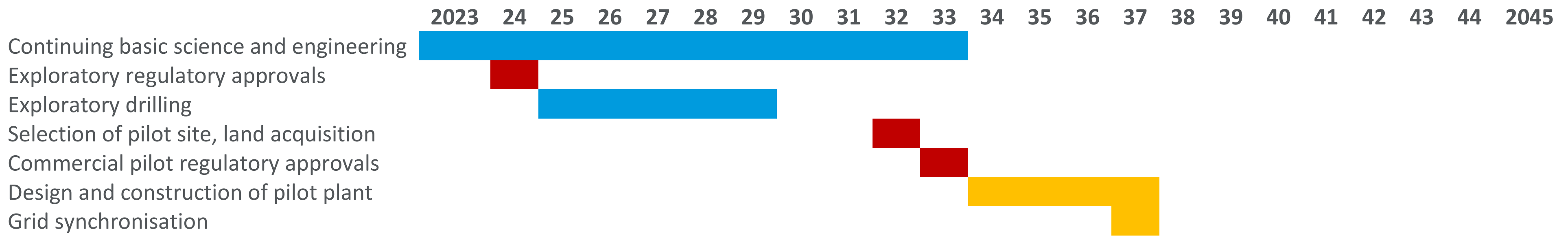


Figure 2.2: Ambitious Timeline for SCGT



2.1 Significant scientific and engineering progress needed over 15 years

SCGT is a new energy production method, and technical progress must be made before it is commercially viable. We assume that this required technical progress will take 15 years from the beginning of serious investment before design can begin on a commercial power plant. This assumption was developed by comparing the technical progress required for SCGT to the development paths followed by other technologies, including early NZ conventional geothermal, shale oil and gas production in the USA, and solar power globally.

Significant progress has already been made overseas and in New Zealand

In 2009, the Iceland Deep Drilling Project (IDDP) successfully extracted super-hot geothermal steam from a relatively shallow depth from the IDDP1 well. The same Icelandic project has also successfully reached depths of 4.6km in the IDDP2 well. A third IDDP well is in the planning phase.

A pilot SCGT well is scheduled to be drilled in Japan in 2024/25.

…but uncertainty remains

GNS' Next Generation project has established that there are three substantial technical challenges to be resolved before SCGT reaches commercial viability:

- Well construction to SCGT depths that enable an adequate commercial well life to be achieved
- The reliable production of the SCGT fluids from depth, including the management of scaling, corrosion, and well-bore thermal stress issues
- The appropriate technology to use for SCGT power generation, including any fluid processing required in any energy transformation process.

There is significant uncertainty about how the behaviour and composition of geothermal fluid at SCGT depths differ from that extracted at conventional depths. There are also differences in the SCGT conditions at depth in the TVZ compared to those in Iceland, Italy, and Japan.

Significant investment will be required before viability is reached

Answering these questions and solving any resulting engineering challenges will require further investment in scientific and engineering efforts.

It will also require drilling exploratory wells to SCGT depths in the TVZ. These exploratory wells will allow scientists to better understand the conditions underground and the composition of the fluids and refine the modelling and assessment estimates relied upon in this report. The GNS' Next Generation project is already well-advanced in identifying sites for such drilling. A report from Traverse Environmental, an environmental planning consultancy, has scenario-tested four sites to identify possible planning requirements.[40]

[40] GNS, Traverse Environmental (2021), An Overview of New Zealand's Geothermal Planning and Regulatory Framework, available at: https://assets.website-files.com/5ee80754caf15981698cc972/612c72326270bdcf6b0c2639_Regulatory%20Review%20Report%20V1.2%20FINAL.pdf

We have assumed that the preparatory design work, the materials procurement and equipment contracts, the exploratory drilling, and the well testing activities will take five years. We understand it took 168 days to drill the 4.5 km IDDP-2 well in Iceland[41] , and the minimum time estimate for a 6km SCGT well in the TVZ is 140 days.

The scientific and technical component is the most uncertain element in the timeline. Technical progress is inherently unpredictable. Nonetheless, geothermal is a proven technology, so the challenges created by deeper depths and the fluid phase change in moving to SCGT conditions are chiefly engineering concerns. GNS' Next Generation project team is confident that, with sufficient resources, including investments, the technical prerequisites for commercial SCGT will be met.

The development of conventional geothermal offers a useful comparison

Conventional geothermal was first developed in the early 20th century. Experiments in Larderello, Italy, began in 1904. The first commercial geothermal power station was operating there by 1916, despite the First World War. This first plant produced 7.5 MW of electricity. Significant damage was done to the plant during the Second World War, but geothermal electricity continues to be generated at the site today (~800 MW).

In 1958, the world's second commercial geothermal power station was commissioned at Wairakei, New Zealand. This was the first 'wet steam' geothermal power station, which generated energy from geothermal fluid in both the liquid and vapour states (two phase).[42] When the second stage was completed in 1963, Wairakei had an installed capacity of 192MW.[43]

As an analogy for SCGT, we have focused on the initial development of the wet-steam geothermal drilling and production at Wairakei. This development was larger and conducted in different conditions compared to the initial Larderello development. It was also an incremental change to the initial dry-steam Larderello development, somewhat analogous to the incremental change anticipated from conventional to SCGT.

The Wairakei project proceeded rapidly. New Zealand officials had occasionally visited Larderello, but the Government only paid serious attention to geothermal potential in New Zealand after 1945. A survey of the TVZ for geothermal potential was then commissioned. Experimental drilling began in 1950. In a year, 15 bores were successfully drilled. In 1953, the Government appointed consultants to advise on the use of the resource for power generation. In 1955, the idea to use some of Wairakei's energy for heavy water distillation for Britain's nuclear power sector was abandoned. The entire project was now to generate electricity. Earlier that year, work had begun on manufacturing the turbo-alternators for the power station, as well as basic civil and structural engineering work on site. In early 1956, the main contractor was employed, and by late 1958, the first stage was generating power. By 1963, the entire project was completed.[44]

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41 http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/37000.pdf

42 Richard S. Bolton, 'The Early History of Wairakei (with Brief Notes on Some Unforeseen Outcomes)', Geothermics 38, no. 1 (March 2009): 11–29, https://doi.org/10.1016/j.geothermics.2008.02.004.

43 New Zealand Geothermal Association, 'Geothermal Electricity Generation Activities Report', 2023, 4, https://www.nzgeothermal.org.nz/downloads/NZGA-Geothermal-Electricity-Generation-activities-report-2023.pdf.

44 Bolton, 'The Early History of Wairakei (with Brief Notes on Some Unforeseen Outcomes)'.

All told, the Wairakei project took 11 years, from the beginning of serious consideration in 1945 to the beginning of construction for the commercial power station in 1956. More than a third of this time was devoted to scientific assessment and surveying of the TVZ. Although SCGT will require some surveying work additional to what has been completed as part of GNS' Next Generation project, the intervening 78 years of geological science conducted in the TVZ will assist in restraining its scope and, in our assessment, will allow it to be completed in less than four years.

The lessons of shale production inspire both caution and optimism

From a negligible amount in the year 2000, natural gas extracted from low permeability shale rock now accounts for three-quarters of total US natural gas production.[45]Shale production operates at much lower temperatures and shallower depths than SCGT. Still, it required significant innovation in extracting fluids from beneath the ground, and we find it useful for comparison.

The key innovations behind modern shale drilling began in the 1970s. Incentivised by the global oil crisis, energy companies and the American government collaborated on a series of R&D programmes to increase US energy reserves. By 1997, the combination of 'massive fracturing' (i.e., the use of larger amounts of water than previously used in fracking techniques) and horizontal drilling allowed producers to cost-effectively tap the huge gas reserves trapped in the Barnett Shale in Texas. Once proven, the methodology quickly spread across the United States.[46]

The shale experience represents an alternative path for scientific and technical progress on SCGT drilling. Whereas conventional geothermal proceeded smoothly from the resource's discovery to its energy exploitation, shale drilling proved fraught. It took 21 years from the first federal government research project focused on shale gas in 1976 and many failed attempts before it was economical to extract shale gas. In the end, it was only a mistake and unsanctioned cross-pollination between competing gas producers that revealed the solution.[47] However, once this discovery was made, it revolutionised the American energy market, providing a plentiful source of domestic energy that is cleaner than coal and economical to extract.

Solar PV shows that rapid energy research progress is possible

Solar photovoltaic (PV) energy experienced slow progress followed by explosive growth. The technology was invented in 1954 at Bell Labs.[48] It received extensive use in the United States' space programme, but almost 50 years after it was invented, the total global installed capacity was only 1GW in 2000.[49] In the succeeding 23 years, however, solar capacity has increased

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[45] Energy Information Administration, 'Natural Gas Gross Withdrawals and Production', 30 June 2023, https://eia.gov/dnav/ng/ng_prod_sum_dc_NUS_mmcf_a.htm.

[46] United States Environmental Protection Agency, 'Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States', 2016, chap. 3; Alex Trembath, 'History of the Shale Gas Revolution', Breakthrough Institute (blog), 14 December 2011, https://thebreakthrough.org/issues/energy/history-of-the-shale-gas-revolution.

[47] Gregory Zuckerman, 'Breakthrough: The Accidental Discovery That Revolutionized American Energy', The Atlantic, 6 November 2013, https://www.theatlantic.com/business/archive/2013/11/breakthrough-the-accidental-discovery-that-revolutionized-american-energy/281193/.

[48] Geoffrey Jones and Loubna Bouamane, '"Power from Sunshine": A Business History of Solar Energy', Working Paper (Harvard Business School, 25 May 2012).

[49] By comparison, conventional geothermal capacity in New Zealand alone currently exceeds 1 GW.

1000-fold.[50] In the ten years from 2010, the levelised cost of energy for solar fell from 42c/kWh to 6c/kWh in 2021 US Dollar terms.[51] By 2020, the International Energy Agency was ready to conclude that, in certain circumstances, "solar PV is now the cheapest source of electricity in history."[52]

Even in the most optimistic scenario, it is unlikely that SCGT will receive the same level of investment that solar PV has enjoyed over the last decade. Nevertheless, this example demonstrates that progress in energy engineering can experience a significant acceleration if government subsidies or market incentives are introduced to support it.

These comparisons lend support to a 15-year R&D window

Our 'best case' estimate for the SCGT R&D period required before commercial design and construction can begin is nine years. This takes the Wairakei baseline of 11 years and subtracts two years due to the reduced need for geothermal surveys. This matches the lag between the first experiments at Larderello and commercial deployment. We have directly adopted this estimate in our ambitious timeline.

Our 'worst case' estimate is 21 years. This is based on the delay between the foundation of the first federal shale project in 1976 and the first commercially viable shale gas production in 1997.

Our 15-year baseline assumption for the SCGT R&D window is the average of these two estimates. As the gap between the estimates demonstrates, this is subject to significant uncertainty. Nonetheless, it is sufficient for use in the economic modelling exercise contained in this report.

2.2 Landowner support and access rights are critical

Exploratory SCGT well-drilling and later development will require support and access rights from landowners and possibly encumbrance holders. Landowners will ultimately need to consent to the location of SCGT wells and major plants. A number of the landowners in the TVZ are Iwi and hapu entities and trusts. As landowners, they have supported or are actively involved commercially in developing and operating conventional geothermal energy facilities. Joint venture arrangements, or agreements with access fees, land rent, and commercial remuneration, will also need to be accounted for as part of the economics of SCGT projects.

2.3 Regulatory approvals and legal issues could take two years with political buy-in

Local and Regional governments will need to grant environmental consents for exploratory wells. This process may be sped up by using consents already issued for conventional geothermal production. Traverse Environmental concluded that gaining consent for the easiest

[50] Our World in Data, 'Installed Solar Energy Capacity', 28 June 2023, https://ourworldindata.org/grapher/installed-solar-pv-capacity.

[51] Our World in Data, 'Levelized Cost of Energy by Technology', 20 October 2022, https://ourworldindata.org/grapher/levelized-cost-of-energy.

[52] International Energy Agency, 'World Energy Outlook 2020', October 2020, 214, https://www.iea.org/reports/world-energy-outlook-2020.

available option would take roughly 18 to 24 months. As such, we have assumed a two-year lag time before exploratory drilling can begin.

Once a viable site is found, the developer will need to acquire resource consents for commercial production and landowner approval. We assume that this would take approximately three years from the beginning of the process to the issuance of the resource consent. This process is assumed to run concurrently with the final three years of scientific and engineering work.

This estimate for regulatory timelines is based on recent industry experience.

Other than depth, commercial SCGT is mostly indistinguishable from conventional geothermal for consenting purposes. Therefore, we adopt the average consenting delay for large conventional geothermal power plants as our baseline. In the past 20 years, four large conventional developments have occurred in New Zealand.[53] A fifth (Tauhara II) has been consented but is not yet complete. These five developments took an average of 10 months to consent from the application. We then increase this baseline by 20 percent to allow for the adjustment of codes of practice that apply to geothermal drilling for use at SCGT depths. We then add 24 months to account for the pre-application process. This 24-month period is a slight increase over that supplied by Traverse Environmental for the most difficult case of exploratory drilling. This results in our assumed midpoint consenting delay of 36 months.

Table 2.1: Recent Consenting Timelines for Large-Scale Conventional Geothermal in New Zealand

Project	Capacity (MW)	Consented by	Applied	Consented	Total delay (days)
Kawerau KGL	100	Waikato RC	Aug 2005	Sep 2006	396
Nga Awa Purua	140	Waikato RC	Jun 2007	Jan 2008	228
Te Mihi	160	Board of Inquiry	Jul 2007	Sep 2008	400
Nga Tamariki	82	Waikato RC	Nov 2009	May 2010	188
Tauhara II	234	Board of Inquiry	Feb 2010	Dec 2010	294

Source: Parliamentary select committee submission, Ministry for the Environment, Mercury Energy publication
RC = Regional Council

These timelines may be delayed by changes in the underlying regulatory framework.

At present, the law governing environmental consenting in New Zealand is the Resource Management Act 1991. This Act is currently being repealed and replaced. Nonetheless, ministers retain the power to 'call-in' projects of national significance and speed-up their consideration of the proposed new Act. Ministers have previously used this power to expedite the consideration of conventional geothermal projects because of their contribution to energy security and renewable energy goals. We believe ministers would be willing to do the same in this case.

Our ambitious timeline case assumes all processes proceed at a pace facilitated by willing party involvement, unimpeded by either process or legal delay or funding constraints. The first

[53] A large development is one where total installed electricity-generating capacity is greater than 50MW.

stages of conventional geothermal energy in New Zealand were regulated through bespoke Geothermal Energy Acts. If the Government agrees that SCGT is a significant opportunity, it could legislate a permissive regime directly.

2.4 Development and construction should take about six years

Our baseline estimate for the post-R&D construction time for the first plant is six years. This is based on the experience of the geothermal sector both at its inception and today.

Today, conventional geothermal power stations can be built within 2 to 4 years from the time resource consent is granted. The five recent large projects in New Zealand have had an average time from consent being granted to commissioning of 5 years and 3 months. After excluding the outlier of Tauhara II, this falls to 3 years and 4 months.[54] This is made up of a 1 year and 1 month pre-construction period and a construction period of 2 years and 3 months.

Table 2.2: Recent Post-Consent Timelines for Large Conventional Geothermal in New Zealand

Project	Capacity (MW)	Consented	Construction began	Commissioned	Time from consent (yrs)	Construction time (yrs)
Kawerau KGL	100	Sep 2006	Jan 2007	Aug 2008	2.00	1.67
Nga Awa Purua	140	Jan 2008	May 2008	May 2010	2.29	2.00
Te Mihi	160	Sep 2008	Feb 2011	May 2014	5.66	3.25
Nga Tamariki	82	May 2010	Jul 2011	Sep 2013	3.31	2.17
Tauhara II	234	Dec 2010	Mar 2021	Dec 2023 (est.)	12.98	2.67

Source: Various news articles

By contrast, the design and construction stage for the first power plant at Wairakei took 5 years, from 1953 to 1958. It required significant innovations, chiefly in drilling into the wet geothermal resources and separating the geothermal liquid from the steam.

The newness of SCGT makes it more comparable to the Wairakei example than today's relatively commoditised construction process for conventional geothermal. For instance, SCGT will require drilling deeper and likely use first-of-its-kind technology. Both add significant uncertainties to construction times.

Therefore, we take the Wairakei example as a baseline timeline estimate. In the broader context, it is difficult to know whether time savings due to innovation and mechanisation since 1953 will be sufficient to offset the time costs associated with the increased regulatory complexity. Thus, as a contingency margin, we have added an additional year (20 percent) to the Wairakei timeline. This results in our 6-year construction estimate.

[54] Contact held off on beginning construction of Tauhara II after consent was granted to ensure the project was economic.

This 6-year estimate seems reasonable in the context of both New Zealand's geothermal construction experience and the wider global energy sector. An 81 percent premium over the recent large conventional geothermal projects seems an adequate allowance for the inherent complexity of a first-of-its-kind SCGT development. In the global energy sector, the average construction time in 2018 for renewables was 1.8 years, and for thermal power generation was 4.1 years.[55] Though SCGT is a renewable resource, its technological properties are more like those of thermal generation. A 50 percent premium similarly appears reasonable.

In our ambitious timetable, however, we have assumed that construction timelines are more in line with modern conventional geothermal. Many of the key components of a SCGT power plant can be found in a combined-cycle gas turbine power station (utilising high-pressure steam boilers) or a conventional geothermal plant. This means some components might be able to be purchased 'off the shelf,' significantly reducing construction time. Whether this is possible depends on the exact nature of the geothermal fluid or conditions found at SCGT depths. Our ambitious timetable assumes it is possible, leading us to a 4-year construction period – an 8-month premium over the average for conventional geothermal.

[55] International Energy Agency, 'Average Power Generation Construction Time (Capacity Weighted), 2010-2018', 14 April 2019, https://www.iea.org/data-and-statistics/charts/average-power-generation-construction-time-capacity-weighted-2010-2018.

3 SCGT could meet significant future electricity demand

If SCGT generation is developed in line with our estimated commissioning date of 2037, it could meet a significant amount of electricity demand in the future. New Zealand's electricity demand is forecast to grow by 19 percent by 2037 and about 50 percent by 2050, and SCGT will play a valuable role in meeting this increased demand.

Existing modelling of New Zealand's power sector has not considered the possibility that significant additional geothermal resources could be added to supply the grid. Therefore, our analysis includes new modelling of the likely build-out of generation capacity to meet future demand in a scenario where SCGT geothermal generation is available from 2037.

Power system planners would normally prepare a least-cost general expansion plan (LCGEP)to determine which form of generation is economical and when it should be added to the grid. Such an exercise is outside the scope of this assignment. However, in modelling a potential role for SCGT, we can mimic a LCGEP by using the binding constraints on the New Zealand electricity system to guide the analysis.

We modelled whether SCGT can meet that additional demand. Our model tests whether SCGT is cost-competitive with the next best combination of generation assets. Variable renewable generation (most likely wind) will be the least cost generation option when it can generate. VRE needs to be firmed when the wind is not blowing or the sun is not shining. Therefore, we compare the cost of firmed VRE to SCGT and other generation options at the security of supply standard set by the system operator.

We find that SCGT is a viable option for energy generation. We analysed two cases:

- In our base case, which retains new and existing thermal generation as an option and assumes that SCGT has capital costs 20 percent higher than conventional geothermal, we expect 1,365 MW to be built between 2037 and 2050.
- If thermal generation is permitted in the 2037-2050 period, SCGT remains the lowest-cost option for a slice of new demand unless its capital costs are more than 100 percent higher than conventional geothermal. If the existing thermal generation is retired in 2037 to align with the availability of SCGT, demand increases to 2,049 MW at a 20 percent cost premium.

3.1 Electricity demand will rise by 19 percent by 2037

New Zealand will require a lot more electricity in the future. By the time SCGT generation can be developed in 2037, New Zealand will require between 14.4 to 17.4 GW in capacity, according to Transpower.[56]

New generation investment will have to be added to the grid at a constant rate to meet increasing demand. Electricity demand will grow with population growth and from more

[56] Transpower (2020), Whakamana i Te Mauri Hiko, available at: https://www.transpower.co.nz/about-us/our-strategy/whakamana-i-te-mauri-hiko-empowering-our-energy-future

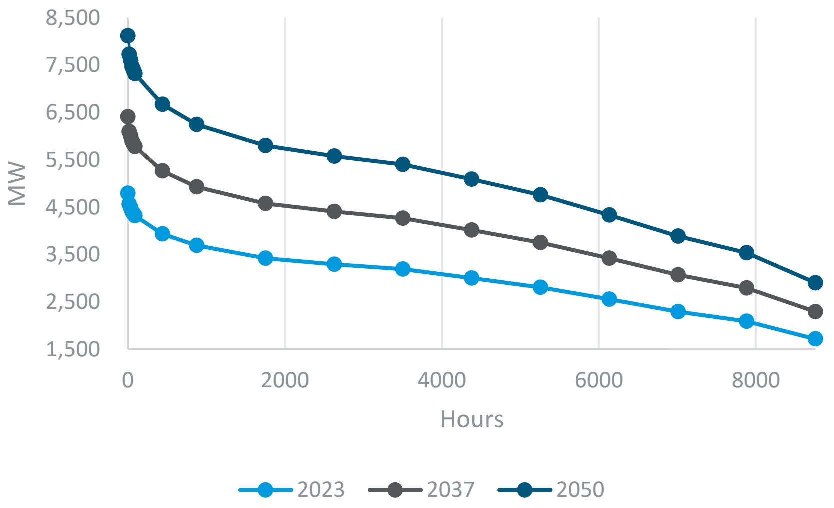
electrification of industrial and commercial process heat and other energy uses. The vehicle fleet will transition to battery-electric vehicles (B-EVs) and, in some cases, hydrogen fuel cell (HFC) vehicles using hydrogen produced from electrolysis. In order to estimate the required demand that SCGT might meet, we estimated a future load duration curve for the North Island.

We use the CCC demonstration path to derive North Island demand

To estimate the electricity demand, we used the CCC analysis, extrapolating it by developing a load duration curve for 2037. This curve is based on the national electricity demand forecast from the CCC's Demonstration Path, along with assumptions regarding future developments.

- This national forecast is converted to a North Island forecast by multiplying it by the share of 2022 national non-Tiwai demand, which came from the North Island. This implies that Tiwai exits at some point between 2023 and 2037. A North Island forecast is used because this is where SCGT will be located and because of the transmission constraints in the model
- This leads to a forecast for average hourly electricity demand in the North Island out to 2050
- This point forecast is then converted to a series of forecast annual load-duration curves in the following way:
  - A North Island LDC is computed using raw Electricity Authority data for the 2022 calendar year. The LDC is highly granular for the top decile of electricity demand. Below this top decile, each decile of electricity demand is computed. Each point on the LDC is then converted to a percentage of average demand.
  - The LDC is assumed to retain the same shape over time. Therefore, forecast LDCs are derived by multiplying the point forecasts of average demand by the mean-standardised 2022 LDC
- Each year's forecast LDC is then subtracted from the previous year's LDC to create a North Island ΔLDC. This is the demand that needs to be met by the new generation.

Figure 3.1: Load Duration Curve for North Island in 2023, 2037 and 2050



3.2 Modelling suggests 1,360 to 2,050 MW SCGT capacity could be built

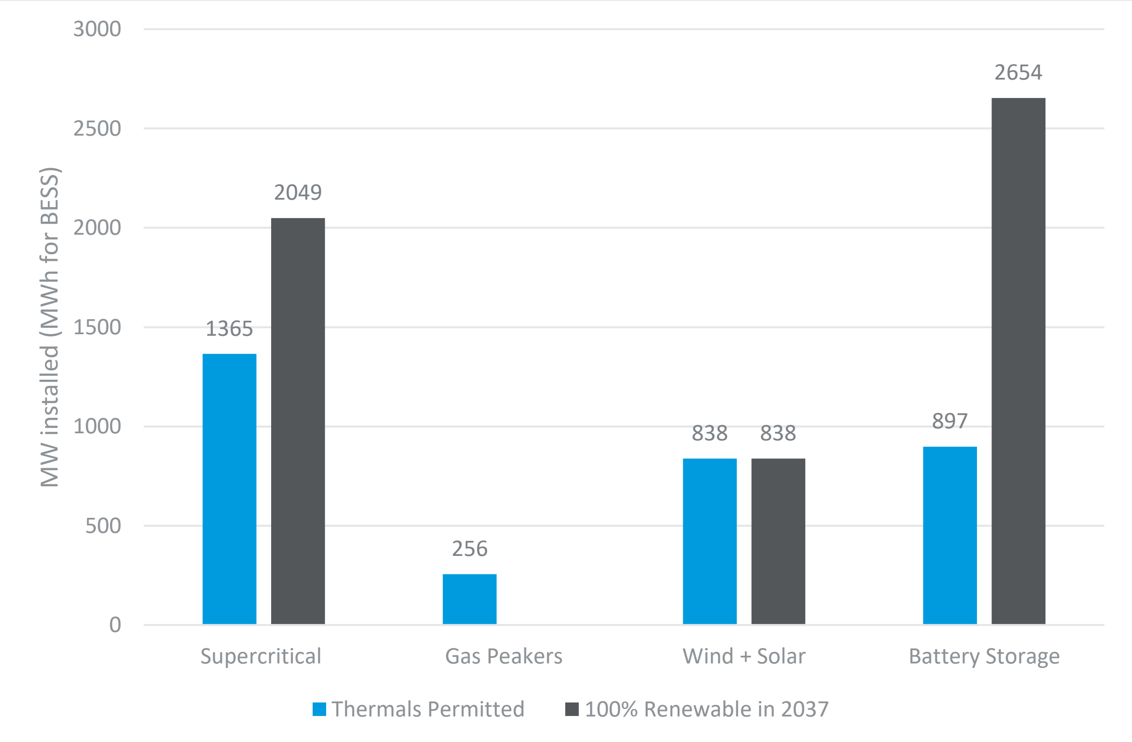
It is expected that SCGT generation will be economically viable when compared to other forms of electricity generation from 2037 to 2050. To determine the likely build-out of SCGT in New Zealand's competitive electricity market, we modelled the competitiveness of different generation types. This modelling was performed considering the system operator constraints and anticipated policy settings that are likely to be in place by the late 2030s.

Overall, our modeling focused on finding cost-effective ways to expand the North Island grid while ensuring it meets the expectations of a reliable electricity supply for New Zealanders. We explored two scenarios:

- **Base case,** where fossil-fuel thermal generation is allowed (with the CCC's Demonstration Path carbon price)
- **100 percent renewable scenario**, where New Zealand achieves 100 percent renewable electricity generation.

Figure 3.2 shows the key results for the new generation built from 2037 in both scenarios.

Figure 3.2: Forecast generation built between 2037 and 2050 (base case assumptions)

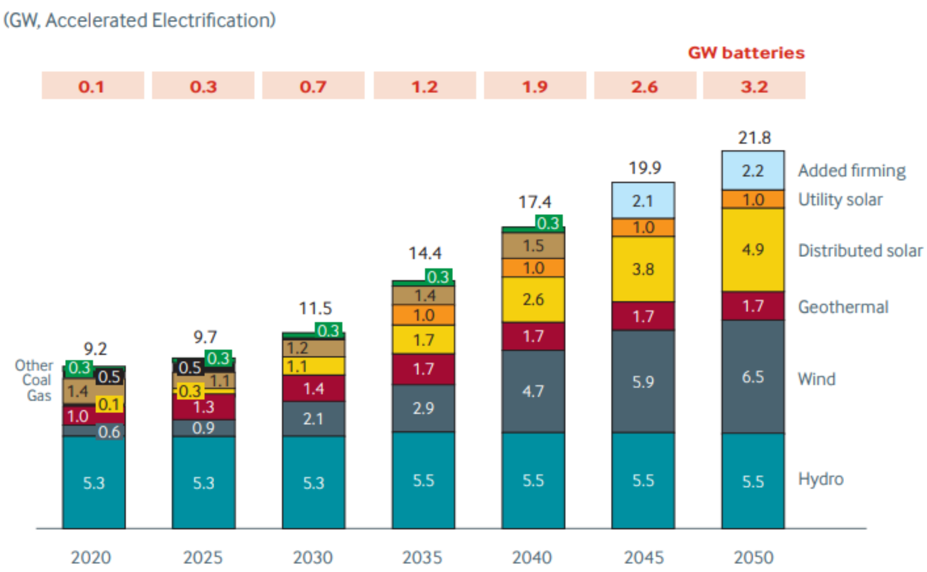


Source: Castalia generation model

We had to develop a new model because SCGT has not been considered by policy makers

Scenarios prepared by the Climate Change Commission (CCC), Interim Climate Change Commission, Transpower, MBIE and other industry commentators only expect already planned conventional geothermal projects to be added to the grid (around 200MW additional geothermal capacity). All assume that most new generation capacity will be from wind and solar, with minor additions to the hydro and geothermal fleet. Gas-fired peaking generation will be added under some scenarios. Battery storage capacity will also be added to firm the variable renewable capacity. Figure 3.3 below shows Transpower's forecast electricity generation capacity to 2050.

Figure 3.3: Transpower's forecast electricity generation capacity by generation type



Source: Transpower (2020), Whakamana i Te Mauri Hiko

The cost-competitiveness of variable renewable generation, constant operation and storage capacity is challenging to estimate. Each has different characteristics, availability factors and fixed and variable costs. Therefore, we had to develop a new model to anticipate the probable expansion of SCGT within New Zealand's competitive electricity market.

Modelling approach adopts system operator's constraints

The model predicts the mix and quantity of generation investment given the costs of different types of generation that would occur from 2037 in a perfectly competitive market. We assume a competitive market would result in the optimal mix of generation types to deliver the required security of supply at the least cost.

We used the system operator's security of supply standards for overall energy security of supply and North Island capacity required to ensure reliable supply as binding constraints. This is logical because SCGT is located on the North Island and most of the new demand will also be on the North Island. Transmission constraints limit the amount of energy that can be transmitted from south to north.

We assume that this standard will be met until 2037. Beyond that point, we analyse the demand growth in the North Island and determine the least-cost generation mix needed to meet this growth while ensuring the continued security of the power supply. We assume this standard is met up till 2037. We then considered the demand growth in each island and determined the least cost generation mix required to meet that growth while ensuring the security of supply. We concentrate on the North Island Capacity Margin (NICM), as this is likely to be the relevant binding security constraint to which North Island SCGT generation can contribute. However, it does also contribute to the winter energy margin.

This approach is consistent with how the Electricity Authority's market design advisory group (MDAG) is approaching thinking about future constraints. MDAG predicts that New Zealand will become increasingly 'capacity constrained,' following a trend seen in overseas systems. As demand rises and various generation types (variable and constant) with varying ramp-up times come into play, ensuring effective operational coordination of these resources will become increasingly challenging.[57]

New generation after 2037 will be SCGT, wind, solar, and peaking gas (if permitted)

The new supply mix in New Zealand is most likely to consist of onshore wind, offshore wind, utility solar, minor additional geothermal and hydro and potentially new open-cycle gas-fired generation (for rapid response peaking). For simplicity, based on the cost projections, we modelled onshore wind, utility solar, SCGT, and gas peakers as technology options for new generation. Most of the parameters for each of these technologies (in particular, their fixed costs per kW of capacity and operating/fuel costs) are based on estimates in the Climate Change Commission's ENZ model. We used carbon prices from the CCC's Demonstration Path.

The 'availability factors' for technologies (which represent the probability that the technology will be available to generate at a given peak hour) are those used by Transpower in its Security of Supply Assessments. However, in the case of variable renewables (wind and solar), their availability factor is assumed to change with their usage: If wind and solar are used in a peaking function, their availability factor is the Transpower security of supply assessment value. In a baseload function, their availability factor is the (much higher) CCC value. This represents that when electricity demand is low relative to supply, the penalty for intermittency is lower because other generation options exist. We provide sensitivity analysis for using the different Transpower and CCC availability factors in Appendix C.

We also apply a penalty known as a 'peaking factor' to variable renewables as their share of generation increases. This accounts for the fact that wind and solar availability will increasingly drive electricity prices, as hydro levels do today. For instance, if wind penetration is high and winds are low across New Zealand, electricity prices will increase significantly, but wind generators will not be able to earn these revenues because the available wind will be insufficient. This reduces the economic attractiveness of new wind. Our peaking factor formula aligns with that used by the CCC. However, it's worth noting that it may underestimate the actual costs of wind dominance, as the CCC's model primarily emphasises meeting the total annual energy demand rather than the peak instantaneous demand in the North Island.

In each year, a two-stage process is used to determine the least-cost generation mix to meet the demand graph.

Firstly, wind and solar are built to their maximum economic level. We estimate how much new wind and solar can be built until the expected "spill"[58] erodes their economic advantage, in a

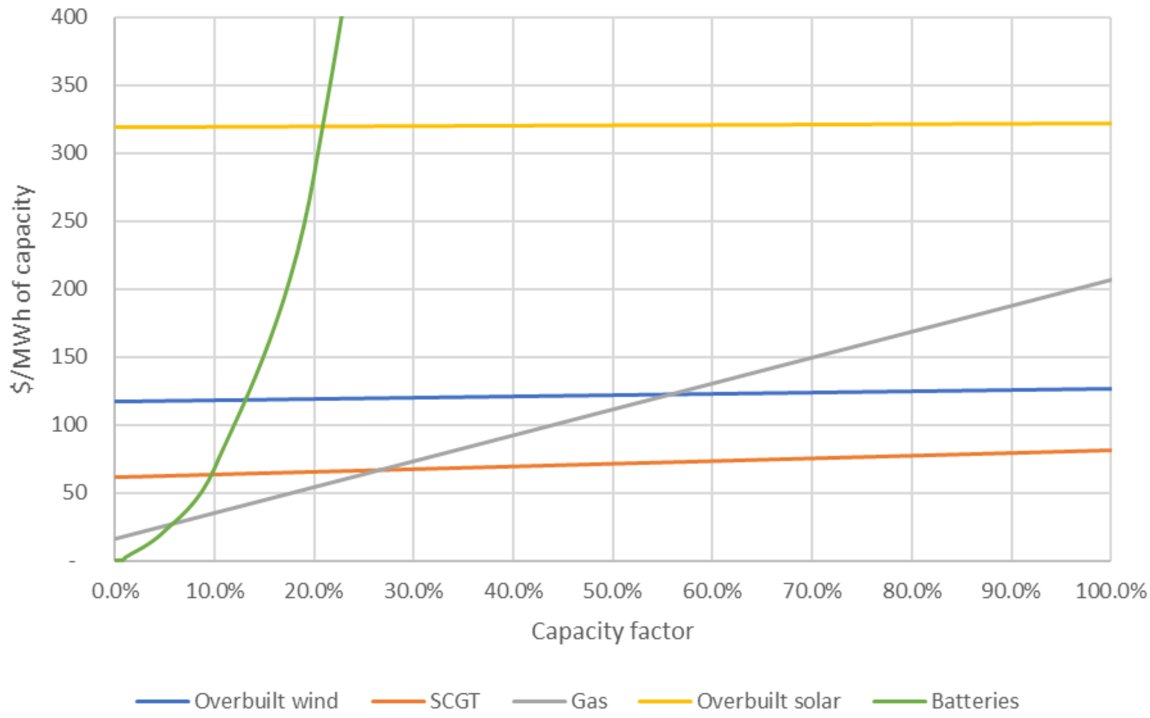
[57] Market Development Advisory Group. "Price Discovery in a Renewables-Based Electricity System: Options Paper." Electricity Authority, 2022. https://www.ea.govt.nz/documents/1006/MDAG_-_Price_discovery_in_a_renewables-based_electricity_system_-_options_paper.pdf.

[58] In the context of electricity generation and distribution, a "spill" typically refers to the excess electricity that cannot be used or stored efficiently and is therefore wasted.

per-MWh sense, over supercritical geothermal, which is the next cheapest source of energy in our model. Generators are assumed to build this amount, leaving the market with a 'residual load-duration curve' to satisfy firm capacity.

In order to meet this residual LDC, a screening curve (as depicted in Figure 3.4) is created to determine what the most affordable option is to meet the increase in demand. This approach accounts for the fact that some technologies (i.e., those with low fixed costs and high fuel costs, for example, gas peakers) are better suited for occasional operation, whereas those with high fixed costs and low fuel costs (for example, geothermal) are best suited for continual operation.

Figure 3.4: Screening curve for SCGT model base case in 2037



Source: Castalia generation model

For each category on the x-axis of the LDC, the cheapest technology option to supply that slice of increased electricity demand is selected from the screening curve. This process generates a least-cost stack of electricity generation options to meet the increase in demand, assuming no storage is available.

Storage in the modelled system assumed using the mid-point of CCC and market cost estimates

Energy storage provides a valuable alternative to peaking thermal generation or the need for substantial overbuilding of renewables. Hence, we incorporate battery energy storage into our modelling as an alternative means of addressing the rise in peak demand.

Our method is to compare the cost of providing each demand slice (for example, the increase in 99th percentile demand) with batteries to the annual cost of the least-cost generation option identified above. If batteries are cheaper, they are assumed to be used instead.

The annual cost of batteries is equal to the annual capital cost of the battery itself plus the cost of the energy to fill the battery. The latter is assumed to be the long-run marginal cost of wind at a 40 percent capacity factor. This assumes that there is not significant wind overbuild.

The price per MWh of batteries is based on the midpoint between the CCC's estimates and an estimate constructed by applying CCC's forecasts for battery price reductions to the much higher real-world prices paid by Meridian for their grid-scale battery at Ruakaka.

The capacity required for the battery is determined by analysing the 2021 energy load and determining how many hours of duration a battery would need to be available to meet the relevant percentile of demand in that year. This calculation embeds a requirement for a recharging period as long as the relevant discharging period to fully recharge the battery.

Other technologies may be available in time other than those explicitly modelled

Other technologies may be available in time. This includes offshore wind that could turn out to provide another more-firm renewable alternative to SCGT. Additionally, demand-side response could offer a more affordable alternative to batteries or gas peakers.

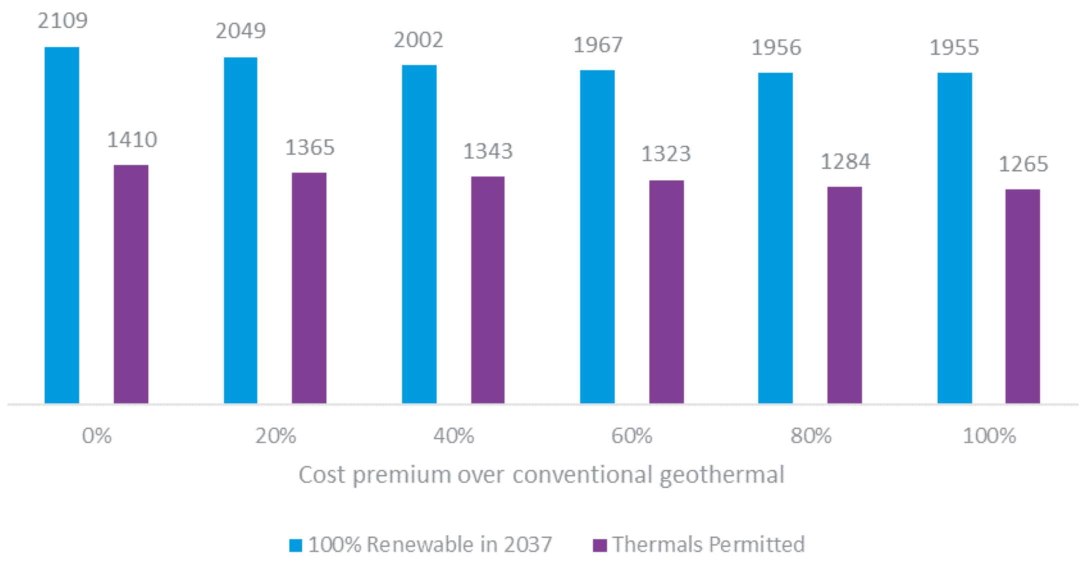
These emerging technologies were not explicitly included in our modelling. However, our model still offers valuable insights into the potential implications of these technological advancements through sensitivity tests, where we run the model with different parameter values. For instance, the impact of the availability of affordable offshore wind can be seen through the sensitivity of the model to the availability factor of wind. Similarly, a cheap demand-side response is effectively equivalent to very cheap batteries, a case which is examined in the sensitivity tests.

3.3 Demand remains robust under different SCGT sensitivities

The modelled demand for SCGT remains significant under different sensitivity tests. We carried out sensitivity analysis for several variables.

The estimates for how much SCGT could be built depend crucially on how much it costs. In our modelling, SCGT capital costs are expressed as a premium over the costs of conventional geothermal. As discussed in Section 1, SCGT is at the early stage of development and the costs are uncertain. As Figure 3.5 shows, if SCGT costs 20 percent more than a conventional geothermal and thermal generation is banned in 2037, it will make sense to build almost 2,050 MW of nameplate capacity between 2037 and 2050. If thermal generation is permitted, it would be economic to build 1,365 MW of SCGT capacity. Even if SCGT is twice as expensive as conventional geothermal, 1,265 MW will be economic to build even if thermal generation is permitted.

Figure 3.5: SCGT nameplate capacity at different price points



Source: Castalia generation model

We also completed sensitivity analysis for the following variables. The results are set out in more detail in Appendix C:

- Gas prices: We test scenarios where gas prices are significantly higher and lower than the CCC's forecasts for roughly flat gas prices. In a high gas price scenario, slightly more of the intermediate load task of gas is taken by SCGT.
- Availability assumptions for wind and solar generation: If the probability of wind and solar being available at peak (i.e., their peak availability factor) increases, they become a much more attractive option for satisfying peak and intermediate loads. This reduces the attractiveness of SCGT.
  - However, SCGT remains viable even if we use the CCC's overall capacity factors as peak availability factors at lower cost premiums.
  - Nonetheless, CCC's overall capacity factors are unrealistic proxies for peak availability factors because they:
    - Are higher than the current capacity factors achieved by wind and solar,
    - Are designed to determine the energy contribution, rather than firm capacity contribution, of the technologies, and
    - Do not account for the correlation between peak (winter) demand and low solar generation, in particular.
- Cost of battery electric storage: We tested three alternative paths for the price of battery electric storage, which primarily substitutes for gas peakers if thermal is permitted and for SCGT if thermal generation is banned. Under most scenarios, a significant amount of SCGT capacity would be built.

- Cost of carbon: We determined the impact on the generation mix of a $131/tonne cap on carbon prices. This cap represents the possibility of developing carbon capture, utilisation, and storage at that price point for natural gas plants.

4 SCGT could provide energy for other uses

SCGT could provide energy for other use cases. Conventional geothermal is already used in pulp and paper manufacturing and dairy processing. At present, industrial users use around 96 PJ of non-renewable, non-electricity energy per year. That is more energy than hydroelectricity generates in an average year. Most of this energy is devoted to the creation of heat for use in industrial processes.

SCGT might be able to be used directly as a heat source in such processes. There are, however, two key constraints on the use of SCGT for industrial heat purposes:

- SCGT heat is so far only likely to be available in the Taupo Volcanic Zone, meaning industrial users must be already located in the area or able to be affordably relocated
- Each SCGT well will likely produce exceptionally large amounts of energy: 120 MW_{th} of thermal energy is used as an indicative value. That's 3.8 PJ per well per year or 4 percent of total industrial demand. Therefore, only very large industrial users are likely to justify drilling operations unless the industrial use is co-located with electricity generation.

Two industries that may meet these prerequisites are milk processing and wood pellet manufacturing. There may be other "power-to-X" uses for SCGT, as described in section 1.2.3 above, that could emerge over time too.

4.1 Dairy processing is a potential use case for SCGT

Geothermal energy is already used in dairy processing at the Miraka dairy factory in Mokai. The heat is used to dry milk to produce milk powder and other products. Additional and abundant energy from SCGT could be used in low- or zero-emissions dairy processing. SCGT could provide heat for dairy processing in combination with an electricity generation plant. The seasonality of dairy production, with spring and summer peaks, complements the higher seasonal electricity demand in winter.

SCGT could have a total addressable market to supply 15 PJ of heat energy for dairy processing on the North Island

North Island dairy processing firms require just under 15 PJ of energy for heat. However, this heat demand is highly seasonal. A total of 26.7 PJ of fossil energy was used for dairy manufacturing heat in 2021.[59] Dairy production is expected to remain stable for some time as environmental compliance limits farm expansion and intensification. Given that only 55 percent of milk solids in the 2021/22 season were produced in the North Island, the total

[59] Energy End Use Database | EECA

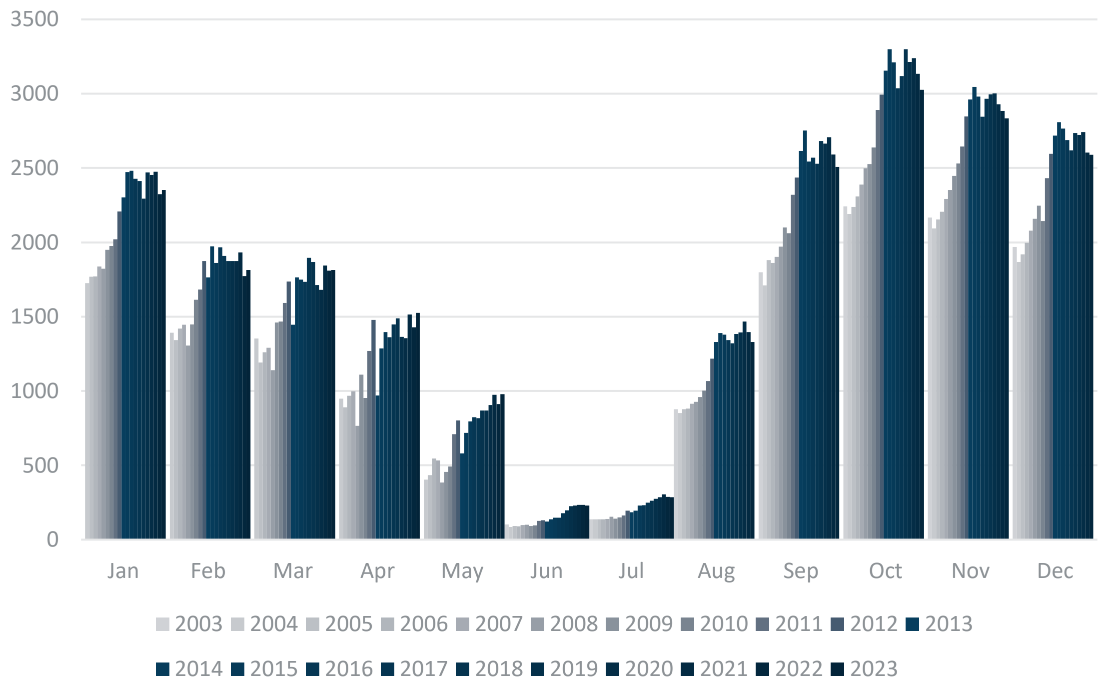
addressable market for SCGT is around 14.7 PJ per year. This is currently supplied by coal and natural gas boilers, plus the Miraka factory using geothermal heat. This demand is highly seasonal, with milk production being 14x in October compared to June, as illustrated in Table 2.1 and Figure 4.1.

Table 4.1: North Island milk production and energy demand in 2021

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Milksolids ('000 tons)	116	95	96	83	54	11	14	65	118	142	131	120
Thermal Energy (GWh)	453	369	375	323	213	44	57	255	461	554	511	466

Source: DCANZ, EECA

Figure 4.1: '000s of tonnes of milk collected for processing



Source: Dairy Companies Association of New Zealand

SCGT could provide energy for a mega-dairy factory and generate electricity during the dairy low season

A dairy factory using geothermal heat must be located close to the geothermal resources. Since geothermal energy is likely to be abundant and zero-emissions, it may be cost-effective to transport raw milk from farms to a mega-factory that uses geothermal energy. Electric boiler technology has low emissions but has efficiency losses, especially when reaching the temperatures required to dry milk powder. Since the SCGT energy could be available by 2037, existing dairy plants may reach end-of-life around that time. This opens up the possibility of constructing a new, larger facility in a central location within the Taupo Volcanic Zone to process North Island milk using renewable energy.

To estimate the maximum potential demand, we modelled a scenario where all North Island dairy production is concentrated in a single mega-factory in the Taupo Volcanic Zone. Assuming it ran 12 hours a day every day through October, it would generate a peak thermal energy demand of 1488 MW_{th}. This demand could be satisfied by around 15 supercritical wells.

SCGT powered dairy factory could be complemented by curtailable electricity generation facility

The 15 wells required to meet the maximum demand for dairy processing could supply heat for electricity generation outside of the peak dairy production period. A dairy/electricity cogeneration plan will match electricity price dynamics well.

- Seasonality: New Zealand electricity prices tend to be highest in winter because hydro dams have yet to be refilled from the winter snow (because it has not melted yet) and household heating demands are highest. This means the opportunity cost of providing dairy heat is highest when demand for it is lowest.
- Daily demand curve: Dairy factory demand can be shifted to the early morning to match when electricity prices are lowest. Unlike aluminium smelters (for instance), dairy factories do not need to be continuously on.
- Dry winters: When winters are dry, this means there is less water in the hydro dams and electricity prices are higher throughout the year. This is likely to be a more severe phenomenon as thermal generation is phased out of the generation mix. The Lake Onslow scheme is aimed at rectifying it. However, when winters are dry, this also tends to reduce milk production in farms across New Zealand, releasing SCGT power generation to supply the grid. This cannot necessarily be relied upon, but it is a useful added advantage.

High-level economic modelling suggests that in the 2021 calendar year, a paired SCGT curtailable generator and dairy processing plant could have earned approximately $660 million in revenue for energy produced. This is equivalent to earning electricity revenue of $169/MWh. By contrast, an SCGT plant on its own would have earned $682 million in electricity revenue.

This simulation was based on these assumptions:

- The dairy factory is either producing or not. If it is producing, it takes the full capacity of the SCGT plant.
- The dairy factory produces every day, even off-peak. It adjusts for lower seasonal quantities by producing for fewer hours.
- The dairy factory produces in the very early morning and, once it is on, continues operating until it meets its daily energy use requirement. It optimises its start time to produce during times of low electricity prices based on the average price per hour over the year.
- The presence of the SCGT power plant does not change the overall clearing price for electricity
- The SCGT power plant charges the dairy factory the same price per MWh of thermal energy as the 2021 natural gas price.

4.2 Wood pellet production using SCGT is possible

An alternative use for SCGT heat could be to dry wood pellets for use as a solid fuel. This fuel can act as a substitute for coal in, for example, coal boilers in dairy factories or coal power stations. A 2023 trial showed this is technically feasible with the three 250-MW Rankine units at the Huntly power station, using Canadian black biomass. The Fonterra Te Awamutu dairy factory converted its coal boiler to run on white pellets sourced from Nature's Flame (Taupo) from the 2020/21 dairy season. The Natures Flame facility uses geothermal heat to dry the pellet feedstock.

By economically producing wood pellets, it may be possible to retain the thermal generation capacity at the Huntly power station for use in dry winter years. This may be cheaper than building new generation or hydro storage, which would only be used in one of five winters.

In rough terms, it would take about 655,000 tonnes of white pellets to feed Huntly at an 80 percent capacity factor for three months. That would require 402 GWh of energy to dry, which is 3,353 well-hours of SCGT energy. If steam-exploded black pellets of the type used in the Huntly trial were used instead of white pellets, the required drying energy per unit of fuel would increase, but fuel demand would likely fall because such black pellets are slightly more energy-dense. The exact impact on overall energy use is unclear.[60]

5 Next steps

This report has demonstrated that SCGT could be an abundant, least-cost, zero-emissions and reliable source of energy for electricity generation and other industrial applications. The opportunity needs to be communicated to key Government stakeholders and potential commercial partners if the ambitious timeline of 2037 is to be met.

However, despite the potential benefits of SCGT, Government agencies have yet to include it in their analysis. For this reason, we recommend that GNS proactively initiate discussions with MBIE and CCC to explore how SCGT can contribute to addressing the energy trilemma. The objective of engaging with the Government is to highlight the potential advantages of SCGT and encourage investment to enhance its technology readiness and achieve regulatory alignment.

We estimate that SCGT could be commercially available by 2037 if regulatory consents are achieved swiftly. Therefore, we also recommend that GNS engage with the Ministry of Environment (MoE) to explore how SCGT (and conventional geothermal) could be added to the fast-track consenting process under the Resource Management Act that is already available to hydro, wind and solar.

In early November 2023, the Government is consulting on a series of energy sector policy initiatives. The table below provides an overview of the suggested engagement opportunities and proposed next steps.

[60] Newsroom, 1 March 2022, "Genesis imports US wood pellets to fuel Huntly renewable energy trial", available at: https://www.newsroom.co.nz/genesis-imports-us-wood-pellets-to-fuel-huntly-renewable-energy-trial

Table 5.1: Discussions with MBIE and CCC

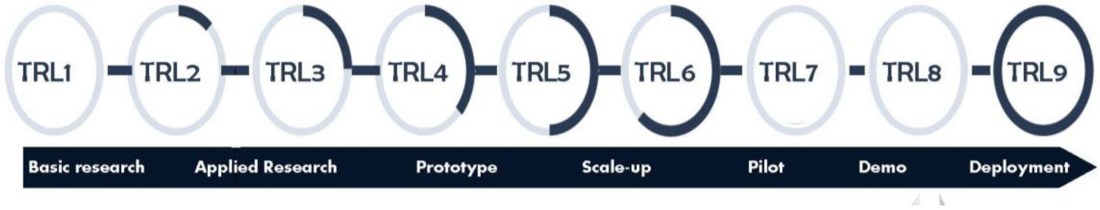
Government agency	Policy paper	Proposed next step:
MBIE	NZ Energy Strategy	GNS/Geothermal the Next Generation to submit on NZ Energy Strategy by 2 November 2023
	NZ Battery Project	GNS/Next Generation should engage with the NZ Battery Project team and highlight the role of SCGT MBIE has suggested already meeting to Castalia
	Gas Transition Plan	GNS/Next Generation should submit a short note on the Gas Transition Plan noting the potential for SCGT in industrial heat by 2 November 2023
	Measures for Transition to an Expanded and Highly Renewable Electricity System	GNS/Next Generation should submit a short note by 2 November 2023
CCC	Emissions budget 2026–2030	GNS/Next Generation should seek a meeting with electricity sector experts at CCC to highlight the potential role of SCGT
MoE	The Resource Management Act	GNS/Next Generation should seek a meeting with the MoE to consider adding SCGT to the fast-track consenting process

Source: https://www.mbie.govt.nz/have-your-say/consultation-on-advancing-new-zealands-energy-transition/
https://www.mbie.govt.nz/dmsdocument/27255-gas-transition-plan-issues-paper-pdf
https://www.mbie.govt.nz/dmsdocument/26909-measures-for-transition-to-an-expanded-and-highly-renewable-electricity-system-pdf

Appendix A: Technology Readiness

A nine-level technology readiness scale was adopted by the European Commission in 2014 (EC 2014). The scale is shown diagrammatically in Figure A.1.

Figure A.1: Diagrammatic Representation of the European Commission Technology Readiness scale



Source: EC 2014

Table A.1 describes the maturity levels of the technology readiness scale.

Table A.1: Maturity levels of the European Commission Technology Readiness scale

Maturity Level	Description
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in the lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in an operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in an operational environment (competitive manufacturing in the case of key enabling technologies or in space)

Source: EC 2014

Appendix B: Super-hot resource inventory

Figure B.1 shows the most recent estimates of New Zealand's super-hot resource inventory prepared by GNS' Chris Bromley (Bromley et al., 2023).

Figure B.1: Super-hot resource inventory in New Zealand

Table 2.2 : Inventory (excluding protected systems) of probable, 3.5-6 km deep, super-hot resources in New Zealand

No.	Location	Top Depth	Bottom D	Area	Volume	Top T	Bottom T	StoredHeat*	Capacity	Generation
TVZ		km (bsl)	km (bsl)	km^2	km^3	°C	°C	Exa-Joule	MWe	GWhr/yr
1	Kawerau	3.5	6	15	37.5	375	500	58	412	3428
2	S Tikitere	3.5	6		15.4	375	500	24	169	1408
3	Haroharo	3.5	6		64.3	375	500	99	706	5877
4	SW Reporoa	3.5	6		23.7	375	500	36	260	2166
5	W Ohaaki	3.5	6		13	375	500	20	143	1188
6	W Ngatamariki	3.5	6		13.6	375	500	21	149	1243
7	Rotokawa	3.5	6		41.1	375	500	63	451	3757
8	Mokai	3.5	6	5	12.5	375	500	19	137	1143
9	Wairakei	3.5	6	5	12.5	375	500	19	137	1143
10	Tauhara	3.5	6	15	37.5	375	500	58	412	3428
11	Tokaanu	3.5	6	10	25	375	500	38	275	2285
Northland										
12	Ngawha	3.5	6	10	25	375	500	38	275	2285
Vers.	CJB 14-7-23	TOTALS:			321			493	3527	29351

assumes rock: 1.3 specific heat capacity, 2700 density

assumes 2.5% heat recovery (4.6% of usable heat>200°C) over 35 yr life of consents for power plant

95% capacity factor, 30% turbine conversion efficiency

calculated values from deep Central TVZ geophysics data using leapfrog model of MT data, (<10 ohm-m)

calculated values from deep Okataina geophysics data using leapfrog model of MT data, (<15 ohm-m)

estimated values from geophysics, existing borehole data and modelling

excludes resources underlying protected geothermal systems (Rotorua, Waimangu, Waiotapu, Te Kopia, Tongariro)

default values

Source: GNS Science (authored by Chris Bromley), 16 July 2023. Author notes that the total generation potential estimate has a higher degree of confidence, but estimates for generation potential for individual locations may vary.

Appendix C: Sensitivity tests

C.1 Overall generation mix

These sensitivity tests show the megawatt nameplate capacity installed for each technology between 2037 and 2050 in the Castalia generation model in the identified scenario. For battery storage, the megawatt-hours of installed storage are reported instead. Other than the identified variable(s), all other parameters are held at their base case levels.

Table C.1: Sensitivity of generation mix to gas price assumptions

Gas price premium over CCC estimate	SCGT	Gas	Wind and solar	Battery storage
-40%	1365	256	838	897
0%	1349	271	838	897
100%	1413	178	838	1430

Source: Climate Change Commission, Castalia generation model

Table C.2: Sensitivity of generation mix to battery price assumptions

	SCGT	Gas	Wind and solar	Battery storage
Climate Change Commission	1365	46	838	4146
Midpoint	1365	256	838	897
Real world	1365	378	838	454

Source: Meridian, Climate Change Commission, Castalia generation model

Table C.3: Sensitivity of generation mix to carbon price/carbon storage

	SCGT	Gas	Wind and solar	Battery storage
No cap	1365	256	838	897
Capped at $131/tonne	1346	274	838	897

Source: Castalia NZ Gas Model, Castalia generation model

Table C.4: Sensitivity of generation mix to a ban on new gas while retaining existing gas

	SCGT	Gas	Wind and solar	Battery storage
No ban	1365	256	838	897
Ban	1499	0	838	2654

Source: Castalia NZ Gas Model, Castalia generation model

C.2 SCGT capacity

Table C.5: Availability factor scenarios

Scenario name	Wind peak availability	Solar peak availability
Transpower	25%	5%
Climate Change Commission	40%	25%
NWCL Stress Test	30%	5%

Source: Castalia generation model

Table C.6: Sensitivity of SCGT capacity to cost premiums and renewables policy

	100% Renewables in 2037	Thermals Permitted
0%	2109	1410
10%	2085	1386
20%	2049	1365
30%	2021	1358
40%	2002	1343
50%	1985	1339
60%	1967	1323
70%	1966	1313
80%	1956	1284
90%	1956	1284
100%	1955	1265

Source: Castalia generation model

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