Rejuvenizing Aged Conventional Geothermal Reservoirs with Supercritical Geothermal Energy

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ABSTRACT

New Zealand has set an ambitious target to achieve 100 percent renewable electricity generation by 2030 and net-zero emissions by 2050. In addition to hydro, solar and wind energy, geothermal is also expected to play a more important role in achieving these goals. But the problem we are facing is that the conventional geothermal energy potential for further development is limited and unlikely to meet the demand. Most of New Zealand's conventional high temperature geothermal fields have already been developed for electricity generation and the remaining are restricted for commercial development due to environmental concerns. Some of the developed geothermal fields have been expanding their generation capacity or have plans to do so already. While concerning the limited resource potentials and some of them are approaching the late stage of life spans, significantly largescale increase in power generation seems to be impossible with current development patterns.

A prospective solution to this problem is to develop deeper supercritical geothermal energy for electricity generation to make up the extra energy demand. Even though geothermal communities throughout the world have been trying to extract superhot fluids from the deeper heat source in the past two decades, and have indeed made some achievements, building a power plant making use of supercritical fluids still has a long way to go. The main obstacle, among lots of others, is the temperature and pressure being too high for the well-casing and wellhead equipment to cope with, resulting in well casing collapse and wellhead equipment failure. The author in this paper has proposed some innovative ideas to develop supercritical geothermal energy by using the existing conventional geothermal power generation facilities without directly coping with the super high temperature and pressure fluid. This new development strategy will greatly benefit the existing power plants by expanding their life spans and production capacities. The technical challenges we are facing in coping with supercritical geothermal fluids can also be by-passed, though not be solved at the early stage of supercritical development.

1. INTRODUCTION

As part of its commitment to fighting the global warming and climate change, New Zealand has set an ambitious target: achieving 100 percent renewable electricity generation by 2030 and net-zero carbon emissions by 2050 (Castalia 2023). While hydro-electricity generation is unlikely to expand beyond the current generation capacity. Greatly increasing renewable electricity generation will be extremely difficult to achieve through increased solar and wind energy production too. Additionally, solar and wind energy are weather dependent thus limiting our energy security and affordability. No doubt geothermal energy generation will play a more important role in achieving these ambitious goals.

In New Zealand, Some of the promising conventional high temperatures geothermal fields are restricted for commercial development due to environmental concerns or protecting the tourism industry. Most of the remaining onshore geothermal fields have been fully explored and developed for power generation and industrial use. Therefore the remaining conventional geothermal resources for further development are limited. Even though some expansion projects are under construction or in the planning, the increased generation capacity is far insufficient to meet the government targets for decarbonization.

To reach the above-mentioned targets, we must turn our attention to other alternative low carbon emissions energy sources and the best candidate is probably deeper supercritical geothermal energy. As proven in the Icelandic deep drilling projects, superhot or supercritical geothermal resources can be found near the young magmatic intrusions. These superhot fluids can provide far more abundant heat for power generation or industrial application.

While the experiences in the past few decades have proven that it is very difficult to develop a system to harness the superhot fluids, due to its ultrahigh temperature, pressure and different chemical properties. Well casing collapse and well equipment failure resulted in deep supercritical exploratory wells being abandoned.

A new idea has been brought forward in this paper: develop deeper supercritical or superhot geothermal resources to rejuvenate the aged geothermal fields to expand the life spans of the current plants and increase the generation capacities in the same fields.

The proposed ideas not only have economic and environmental benefits, but also promote the earlier utilization of supercritical geothermal energy.

2. CHALLENGES ENCOUNTERED IN ATTEMPTS FOR SUPERCRITICAL DEVELOPMENT

In the past few decades, some nations throughout the world have conducted a great deal of work in attempting to explore deeper superhot / supercritical energy. Below are some of the important examples:

2.1 IDDP-1 Iceland

IDDP-1 was drilled in 2009 in Krafla, Iceland. It was initially intended to drill 4500 m deep to reach critical conditions. While magma intrusion was unpredictably encountered at about 2104 m depth and the drilling operation had to be terminated and the well completed at about 2069 me. The well produced superheat steam with the recorded wellhead

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temperature of 450 °C, pressure of 138 bar, with an enthalpy of 3150 kJ/kg and estimated generation capacity of 35 MWe. After two years of flow testing, the well had to be quenched due to failure of the master valves. This caused collapse of the well casing and abandonment of the well (Fridlerfsson 2017). The equipment failure was caused by fluid corrosion and silica dust erosion and deposition (Galeczha 2025).

2.2 IDDP-2 Iceland

IDDP-2 was completed in 2016-2017 in Reykjanes, Iceland, by deepening an existing 2500 m deep production well to 4624 m. Supercritical conditions were measured at the bottom with temperature 535 °C and pressure 340 bar. The casing was unfortunately damaged at 2300 m depth during stimulation period by injecting cold water. The well eventually produces two phase fluid at temperatures of 167-220 °C, with the most contribution from 2300 m deep feed zone where the casing was damaged (Galeczha 2025).

2.3 Other nations

Supercritical conditions are not restricted to Iceland, but occur deep in any young volcanic-hosted geothermal systems. Supercritical conditions have been encountered during the drilling in the USA, Japan, Italy, Mexico, and Kenya (e.g., Reinsch et al., 2017).

In Japan, WD-1a was drilled in 1995 to the depth of 3729 m in Kakkonda, and encountered supercritical condition with estimated temperature exceeding 500 °C (NEDO website report 2025). The goal in Japan is to build five 100 MW-class power plants using supercritical geothermal resources during 2040-50. They have been developing innovative drilling technologies and multi-sensor and long-life optical fiber for downhole measurement at very high temperature.

Quaise Energy in US is pioneering a radical new drilling method using millimetre-wave electromagnetic high-powered microwaves to vaporize rock instead of grinding through it. In a recent full-scale demo near Houston, Texas, they drilled into granite using a 100-kilowatt gyrotron, with plans to scale up to a 1-megawatt system. This could unlock access to geothermal zones 2 to 12 miles deep, where temperatures exceed 400°C. Their goal is to refuel some fossil fuelled power plants with supercritical geothermal.

In New Zealand, a government funded program "Geothermal: The Next Generation" lead by GNS has made significant progress in the past five years. New seismic, magnetic, heat flow and gravity models were produced on the southern part of the central Taupō Volcanic Zone. A deep large area of partial melt was identified from seismic tomography. (Chambefort 2024).

Two exploratory wells have been proposed with depths of 2800 m and 4000-6000 m respectively. 400 – 600 °C supercritical conditions are anticipated. (Carey 2021).

3. AN INNOVATIVE IDEA TO DEVELOP SUPERCRITICAL GEOTHEMAL

Though the geothermal community across the globe have made considerable progress in tapping superhot / supercritical geothermal in the past few decades, but no pilot generation plant feeding with supercritical geothermal source has ever been built yet. Even the only well that produced super-heated steam in Iceland (IDDP-1) had to be shut down and abandoned after two years flow testing. As the international geothermal community has realized, supercritical / superhot geothermal resource contains order of magnitude of heat energy more than the subcritical resource, but numerous technical challenges should be addressed before the endless energy source can be harnessed by mankind.

The author here would like to propose a new strategy: directing the deeper superhot / supercritical fluid into the overlying subcritical reservoirs, instead of coping with the superhot fluid directly on the surface with wellhead equipment. The supercritical inflow in the conventional geothermal reservoirs will cool down and pass the heat energy to the subcritical fluid hence increase the enthalpy.

This development strategy is especially meaningful for those well-developed geothermal fields in their late life spans. Geothermal power plants are generally designed with a 35-year operational life spans. Though some early plants are still operating after 35 years, such as Wairakei Power Plant, some are inevitably experiencing reservoir cooling and pressure drop. As a result, some generation plants have to reduce their production capacities or install binary units to maintain the capacity.

If the deeper supercritical fluid is directed into the reservoirs above which are in the late lifespan, the latter can be rejuvenated with the superhot heat flow supply. While it may take thousands of years to renew a nearly depleted reservoir with natural heat flow.

4. PROPOSALS TO REJUVENATE AGED GEOTHERMAL FIELD WITH SUPERCRITICAL

The author has proposed a few strategies:

4.1 Single well scenario

- Drill a well to the conventional subcritical zones first, identify the feed zones and access the permeabilities and production / injection index of the well.
- Set production casings to the bottom of the well and cement it as normal.
- Continue drilling down to superhot / supercritical conditions. If sufficient permeability is encountered in the brittle / ductile transition zone, set production casing just above the B/D zone and set perforated liner in the permeable superhot / supercritical zone.
- Slowly and gradually warm up the well and clean the well by strictly controlled discharging. Test the well's properties and production potential with discharge and PTS logging.
- Place a packer at the bottom depth of casing shoe for a conventional production well.
- Perforate the production casing at the feed zones of the subcritical reservoirs.
- Clean and test the well by discharging and well logging as normal.
- Drill off the packer using the rig and set another packer just above the conventional reservoir.

- The pressure of the supercritical fluid is expected to be lithological which is much higher than the subcritical pressure. The supercritical fluid also has much lower density and viscosity, these physical properties also help flow from the B/D zone to the above subcritical zone. Refer to Figure 1.

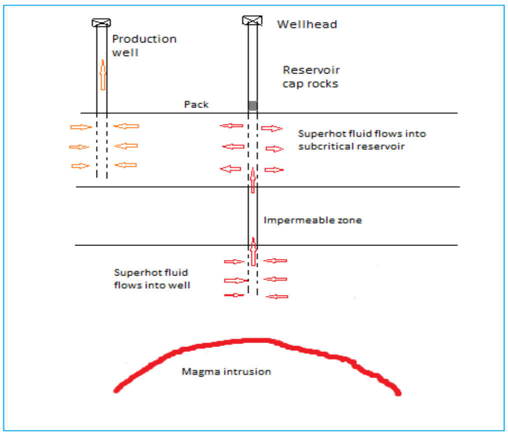

Figure 1: Simplified diagram showing single-well system.

Considerations of the well sitting:

- Close to the development center of the geothermal field, where the pressure drop is the largest.
- Near recharge flow path is also accepted, where the superhot inflow can heat up the cold recharge flow.

4.2 Multi-well scenario

One injection well and one supply well are combined for this scenario. When drilling into supercritical / superhot conditions and encounters poor permeability in the brittle-ductile zone, drill another well to the same depth. Apply hydro-fracturing or thermo-shocking techniques to create fractures between the two wells. Convert one of the wells into a supply well as described in scenario one. The injection well is to inject wastewater from the power plant into the supercritical zone. The injected water will pick up heat from the formations in the supercritical zone and enters the supply well and exits to the subcritical reservoir. Refer to Figure 2.

Considerations of the well sitting are similar to the scenario one. Furthermore, the distance between the two wells should be carefully calculated to make sure an adequate flow path for the injected water to heat up before reaching the supply well. But too large distance may cause insufficient fracturing.

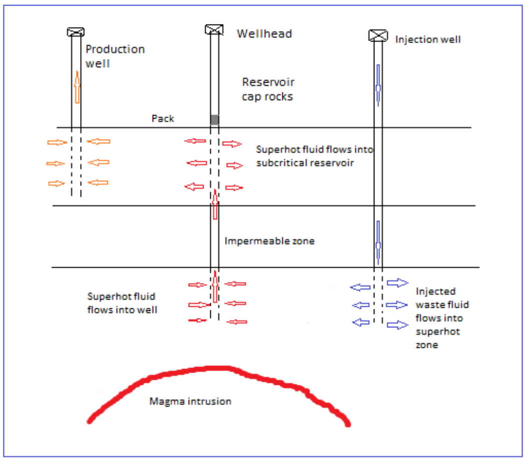

Figure 2: Simplified diagram showing multi-well system.

5. COMBINE SUPERCRITICAL TO CONVENTIONAL GEOTHERMAL IN UNDEVELOPED GEOTHERMAL FIELDS

When planning to develop a new geothermal field for the purpose of power generation or large-scale industrial use, both shallow conventional reservoir and the deep superhot resources should be considered as early as at the exploratory stage. If deep superhot conditions are detected or even anticipated, the upper overlying reservoir will still have commercial value even though the temperature is not high enough from a conventional point of view. In this situation, consider applying scenario two to combine supercritical and subcritical resources as a whole system for planning and development.

The other importance of this development strategy is that the previous evaluated as low commercial valued geothermal fields can become valuable if considering the deep resources. We have reasons to believe that in the future, review and reevaluate the historic data of the low valued geothermal resources may be necessary.

Numerical modelling should accordingly reflect the new development strategy, including the deep superhot flow into consideration.

6. BENEFITS AND CHALLENGES

6.1 Benefits

- Some aged geothermal power plants may greatly benefit from this kind of development strategy, from the economic point of view. These plants are reaching the end of their designed lifespan. Once the generation operation stopped, the facilities would be out of service and abandoned. The economic loss would be obviously huge. Prolonged lifespan would generate much more revenue for the shareholders.
- Compared with the normal development strategy of setting up a new plant using supercritical fluid directly, this strategy could greatly reduce the initial investment in equipment which requires better materials to cope with the ultra-high temperature and pressure.

- This new strategy would also have environmental benefits. Building new plants will have enormous adverse impacts on the environment resulting from roading, well paddling, pipelines and plants. The new method can greatly reduce the footprint too.
- The new strategy would greatly reduce the chance of dealing with the superhot fluids on the surface, hence developing new material and equipment that can withstand ultra-high temperature and pressure is not urgent for now.
- The timeline of harnessing supercritical geothermal for power generation could be brought forward due to reduced requirements for high grade materials and equipment.

5.2 Challenges

- Drilling into supercritical conditions will be difficult and risky based on the experience of IDDP. Unexpected encounters with magma would cause dill string stuck.
- Well casings may expose to superhigh temperatures in the supercritical zones. Special casing may be required at the bottom section of the well.
- Downhole measurement is impossible with the currently available logging tools and wireline. Better tools and equipment withstanding superhigh temperatures must be developed at a stage.
- Like encountered in conventional geothermal, scaling and corrosion may occur too. Anti-scaling and corrosion method for superhigh temperature should be developed.

7. CONCLUSION

The strategies proposed in this paper are the author's suggestions only. They have never been practically used in any applications yet. The author also understands that these suggestions are still immature or even absurd. It is only hoped that researchers and developers could find some helpful ideas in this paper.

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