Comparison of Icelandic Supercritical Well Forecasts with Subcritical Geothermal Production Well Outputs

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ABSTRACT

Possible energy production from supercritical geothermal reservoirs has been studied in Iceland for over twenty years with conceptual thinking and analysis performed as part of the Iceland Deep Drilling Project (IDDP). Icelandic works on well output simulations have been conducted seeking to estimate the possible production capacity of a supercritical well. The forecasting from this simulation work, together with NZ wellbore simulation undertaken by GNS Science, is compared to the output of subcritical geothermal production wells from six geothermal fields in the Taupo Volcanic Zone (TVZ).

The flow test measurements from the IDDP-1 well undertaken between 2010 and 2012 were analysed and the output from this superhot well has been summarised and compared to the production well dataset.

This comparative analysis is documented in this paper where thermal and exergetic power are computed and compared.

1. INTRODUCTION

The IDDP work has been focusing on drilling to encounter supercritical conditions, as discussed in studies by Fridleifsson et al. (2003) and Albertsson et al. (2003). These studies have contributed to the planning and conceptual understanding of the early IDDP work. Albertsson et al. (2003) presented supercritical modeling work and projected a substantial increase in production of 50 MWe compared to a 5 MWe typical subcritical Icelandic steam well.

The comparison presented in Albertsson et al. (2003) led to the introduction of the concept of a tenfold increase in electrical energy production from a supercritical well compared to a conventional Icelandic well. This potential increase has subsequently been reported in various publications, including Fridleifsson and Elders (2005), Fridleifsson et al. (2007), Dobson et al. (2017), and Fridleifsson and Elders (2017).

This paper includes summary analysis between the theoretically modeled production from supercritical wells and the production data from subcritical production wells in Taupo Volcanic Zone (TVZ) that is comprehensively reported in Rivera and Carey (2023).

The production data from recently drilled wells in six geothermal fields in TVZ (Mokai, Ngatamariki, Ohaaki, Rotokawa, Tauhara, and Wairakei) were assembled and plotted together with the forecasted output from the supercritical wells. Additionally, thermal and exergetic power calculations were performed for both the supercritical and subcritical production wells to compare the energy available at the wellhead independent of any power cycle.

2. ICELANDIC IDDP WELL SIMULATION

2.1 2003 Icelandic Modelling

The Icelandic modelling work was presented in Albertsson et al. (2003), which included a comparison between the production of a subcritical steam well and a forecasted supercritical well output. Both wells were simulated with a 9 5/8” diameter and produced at the same volumetric flowrate of 0.67 m^3/s at the feedzone.

The conventional steam well in the study was found to produce 10 kg/s of steam at 25 bar wellhead pressure, with an enthalpy of 2802 kJ/kg. On the other hand, the supercritical well drilled to 5000 m extracting fluid from a 550°C reservoir was forecasted to discharge 55 kg/s of fluid with an enthalpy of 3260 kJ/kg at an operating wellhead pressure of 195 bar. The net electrical power estimated for the Icelandic subcritical steam well was 4.98 MWe, while the IDDP simulated supercritical well was expected to generate 49.07 MWe.

The data from the subcritical steam well and the supercritical well output were used as data points in the comparative analysis presented in the GNS Science analysis.

2.2 IDDP-1 DISCHARGE TEST

Well IDDP-1 was completed in 2009 and was the first well drilled as part of the Iceland Deep Drilling Project, with the objective of exploring supercritical fluid conditions in the Krafla field at a depth of 4500 m. However, as the drilling encountered a layer of magma, at a shallower depth, it was stopped at 2096 m. High pressure and temperature conditions were still encountered but the supercritical fluid state has not been reached at this depth.

After over seven months of well heat up, the well underwent an intermittent discharge testing between March 2010 and July 2012 to characterise the flowing fluid. During the first few days, the fluid was wet but as the well heated the temperature increased and the fluid transitioned to superheated steam. The highest mass flow measured was approximately 50 kg/s, with an enthalpy approaching 3200 kJ/kg. During 2011, the discharge from the well was measured under various operating wellhead conditions, enabling the development of a bore output curve (Figure 1). The measured wellhead temperature and the calculated enthalpy are also plotted (Figure 2). The details of the discharge testing phases are presented in Table 1. Wellbore simulation output and calibration was done with this presented in Rivera and Carey (2023).

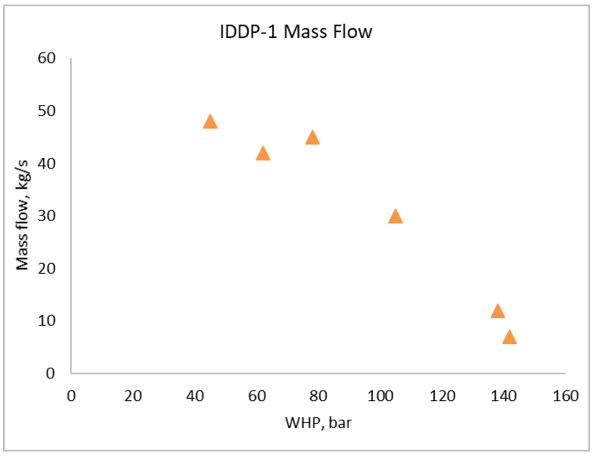

Figure 1: IDDP-1 measured mass flow rate during the 2010-2012 discharge testing.

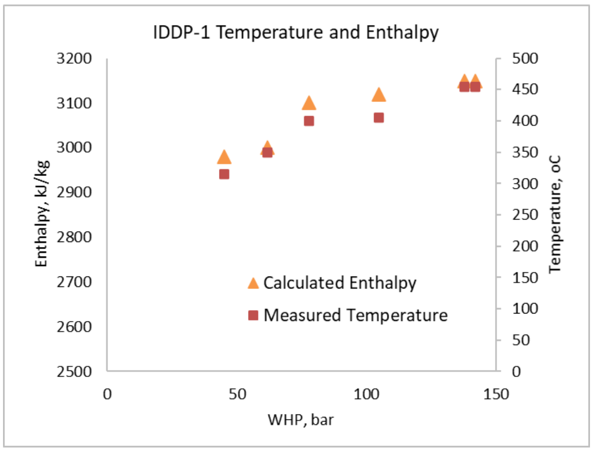

Figure 2: IDDP-1 measured temperature and calculated enthalpy during 2010-2012 discharge testing.

Table 1: IDDP-1 Discharge history as presented in Ingason et al., 2014.

Date	WHP (bar)	T (ºC)	Enthalpy (kJ/kg)	Flow kg/s
March 2010	70-120	285-325	2700(?)	30(?)
May-Aug 2010	20	210-380	2700-3200	30
May 2011	55-70	340-390	3030-3130	>50
Aug 2011	40-80	320-280	3000-3100	42-48
Sep 2011-Jul 2012	138-142	380-440	3000-3150	7-12

3. TVZ SUPERCRITICAL WELL SIMULATION

Wellbore modelling and simulation was undertaken to represent the production of a supercritical well in the Taupo Volcanic Zone (TVZ). In the simulation, formation properties for the TVZ region were considered together with projected reservoir pressure and temperature. Various well configurations with different wellbore sizes, feedzone depths, and reservoir feedzone parameters were considered and are discussed in detail in Rivera and Carey (2023).

In this paper, the results from the well model producing at 6000 m is described, with a well diameter of 9 5/8" / 7" with the transition in casing size occurring at 3500m. The feed base productivity index was set at $1x10^{-12}$ m^3 and is tested at an order of magnitude higher and lower. The productivity indices used are tabulated in Table 2. The temperature at the feed is assumed to be 500ºC and the pressure is computed to be hydrostatic from the wellhead down to the feedzone at 6000m using the overlying density of the fluid as a function of temperature.

Table 2: Feedzone productivity index data

Productivity Identifier (PI)	Productivity Index (m^3)
PI-1	$1.0x10^{-13}$
PI-2 (base)	$1.0x10^{-12}$
PI-3	$1.0x10^{-11}$

The simulation was undertaken using the GFlow wellbore simulator developed by GNS Science which is supercritical capable. The resulting mass flow rate and enthalpy at various wellhead pressures are plotted in Figures 3 and 4, respectively.

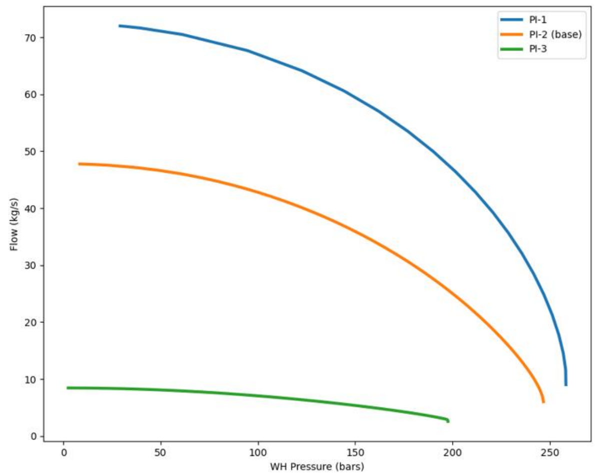

Figure 3: Simulated mass flow rate across a range of wellhead pressures for a 6000 m supercritical well producing from a feed temperature of 500ºC for different productivity indices.

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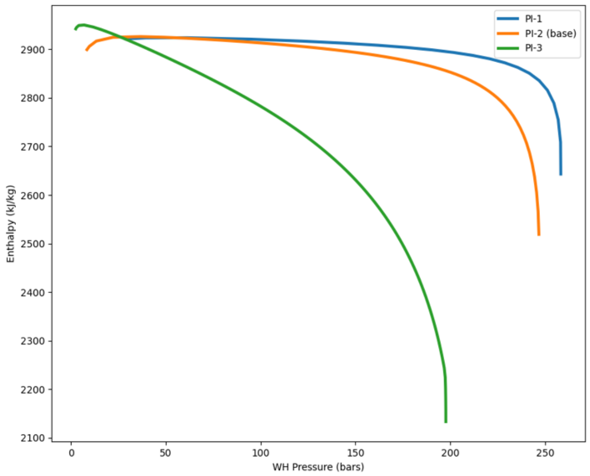

Figure 4: Simulated enthalpy across a range of wellhead pressures for a 6000 m supercritical well producing at temperature of 500°C for different productivity indices.

The range of fluid flow rates predicted is between 10 to 70 kg/s at an enthalpy of ~2900 kJ/kg. Lower wellhead enthalpy is expected from PI-3 due to the lower flow rate which results to greater thermal losses to the formation per unit of flow as the fluid traverses the wellbore. Generally, the fluid produced at the wellhead is expected to be superheated steam even though the conditions at the feedzone are supercritical. It is worth noting that the conditions for producing supercritical fluid at the wellhead occurs over only a small fraction of the overall operating conditions at very high wellhead pressures.

Exergetic power for the well outputs were computed with the results showing optimum exergetic power output at wellhead pressures between 50-120 bar (Rivera and Carey, 2023). Values from this wellhead pressure range were used to select the data points in the comparative graphical analysis presented in the next section.

4. WELL PRODUCTION COMPARATIVE ANALYSIS

Mass flow rate, enthalpy, and wellhead temperatures are plotted against well feed temperature (or maximum well temperature where the feed temperatures were not available) for the TVZ production wells and the supercritical simulations.

Thermal and exergetic power were also calculated and plotted.

Also plotted are the data from the 2003 Icelandic well model, and the IDDP-1 discharge test.

4.1 MASS FLOW RATE

Figure 5 identifies the production from the supercritical wells is approximately 30% of the mass produced by the largest TVZ production wells. The supercritical flow rates are comparable to the median of the mass flow rates of the TVZ wells.

We note that the mass flow rates of the supercritical wells could be higher than what are shown in the plot if the encountered pressures exceed the hydrostatic pressure assumed in the simulation (ie increasing up to lithostatic).

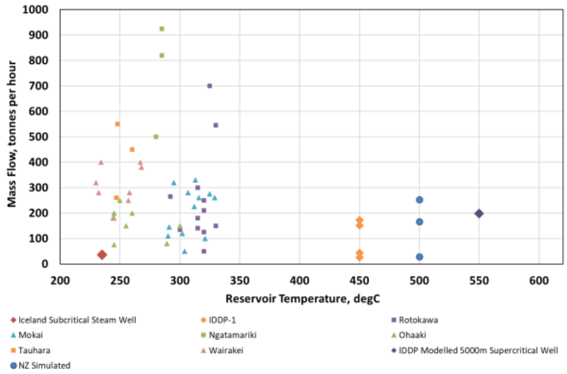

Figure 5: Mass flow rate vs well feed temperature

4.2 TEMPERATURE AND ENTHALPY

As shown in Figure 6, the supercritical wells all produce at an enthalpy of approximately 3000 kJ/kg, which is roughly 2.5 times higher than the enthalpy of the two-phase discharge from an average TVZ production well.

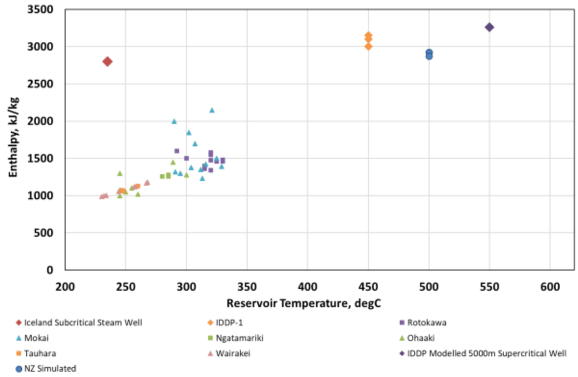

Figure 6: Wellhead enthalpy vs well feed temperature

The wellhead temperatures of the simulated NZ supercritical well fall within the range of 300 to 500°C, while the TVZ production wells operate at temperatures ranging from 150 to 260°C (Figure 7).

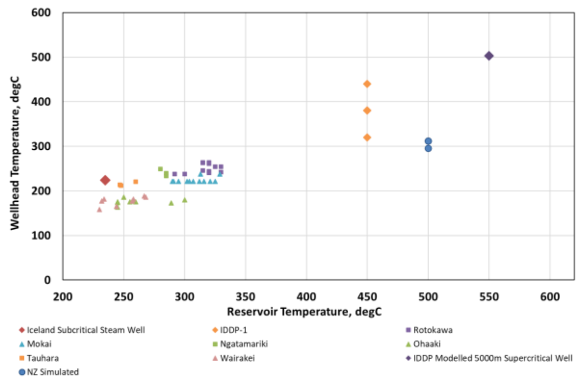

Figure 7: Wellhead temperature vs well feed temperature

4.3 THERMAL AND EXERGETIC POWER

Figure 8 and 9 plot the wellhead thermal and exergetic power for both the supercritical and subcritical geothermal wells. The exergy approach ensures the quality of thermodynamic fluid conditions are accounted for. Exergy is widely used in the public literature, including amongst others DiPippo (2016).

Exergy calculations have been made for the production well data and for the simulations using ambient dead state conditions at a temperature of 293.15 K (20°C) for the New Zealand situation and 285.15 K (12°C) for the Icelandic cases analysed.

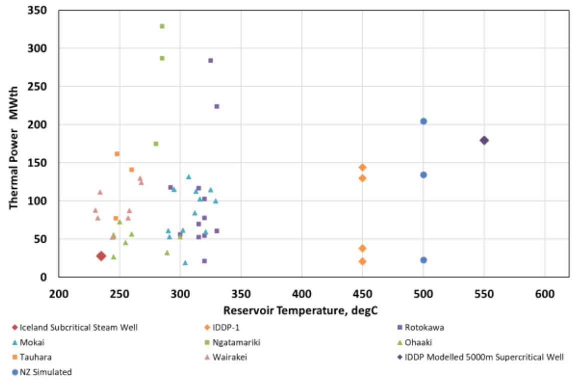

Figure 8: Thermal Power vs well feed temperature

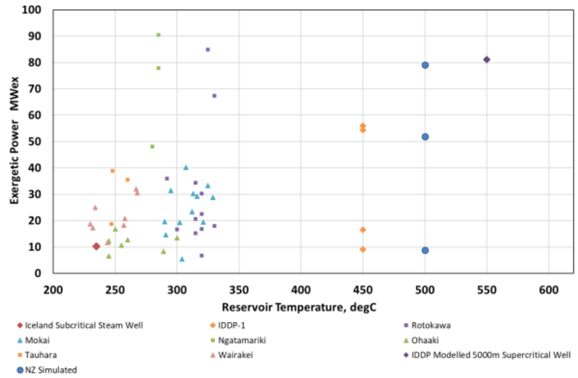

Figure 9: Exergetic power vs well feed temperature

The thermal power of both the NZ and the Icelandic supercritical wells is expected to be at around 200 MWth whereas large TVZ production wells have demonstrated capabilities of producing up to 350 MWth. The thermal power from the supercritical simulations is a little greater than the median values from the TVZ production wells and is comparable to the average thermal output.

For exergetic power, the simulated Icelandic supercritical well produces about 80 MWex which is comparable to the exergetic power of the largest producing wells in the TVZ (Figure 8).

The NZ supercritical well (PI-2 base model) is computed to produce about 50 MWex (Figure 8), which is 2.5 times the median of TVZ subcritical wells. The model with the high productivity index (PI-3, 1x10^{-11} m^3) produces an exergetic power output similar to the Icelandic supercritical well.

We note that the wellhead pressures selected from the TVZ supercritical well simulations are based on conditions that optimize exergetic power.

5. CONCLUSION

Several observations in conclusion:

- The operational production wells in the TVZ have a greater power output than a typical Icelandic subcritical steam well.
- Some of the operating production wells in the TVZ have exergetic power capacity similar to the simulated Icelandic and TVZ supercritical wells.
- From the comparative analysis, a TVZ supercritical geothermal well has the potential to produce work (exergetic power) equivalent to a larger subcritical geothermal production well and up to 2.5 times the exergetic power of the median TVZ production wells.

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