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STATE-OF-THE-ART IN POWER CYCLES FOR GEOHERMAL APPLICATIONS AND BOTTOMING CYCLES

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SUMMARY

The present study provides a thermal assessment of selected geothermal plants with the range of conditions expected to apply to South Australia. The thermal assessment was conducted in terms of thermal, exergetic efficiencies, and effectiveness of power cycles. To achieve the objectives of the study, a detailed comparison of the performance and operating conditions of selected geothermal power plants was compiled. The conventional cycles including binary, flash and Kalina cycles were compared with the supercritical cycle, developed at The University of Newcastle, under identical operational conditions. HYSYS modelling was also used to compare the power output of the Kalina cycle with that of the supercritical power cycle. The supercritical cycle overall performance was found to be significantly better than the conventional power cycles for geofluid temperatures ranging between 150°C-200°C.

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1. AIMS AND BACKGROUND

By and large the geothermal energy is an untapped energy resource despite its potential and clear environmental advantages (e.g. low CO₂ emissions) over other sources of energy, such as fossil fuels and nuclear energy. According to an estimate by the IEA (International Energy Agency), currently only 0.3% of the world's electricity is generated from geothermal sources [1]. However, geothermal power production is expected to steadily increase at a rate of 4.3% per year reaching a share of 0.6% of the global electricity production by the year 2030 [1-3]. Although the predicted growth in the geothermal power production sector should be considered as a positive sign of the worldwide move towards more renewable and environmentally friendly energy sources, the growth clearly falls short of expectations. The contribution of the geothermal energy to the world's electricity production by 2030 can be potentially one order of magnitude higher than the IEA's estimate, should the technical problems associated with the use of geothermal energy are resolved [2, 3].

Within this context, the study of geothermal power cycles is regarded as one of the key areas for major technological improvements since many of the problems associated with the geothermal power technology are underpinned by inefficient and often unsuitable power cycles for a given geothermal reservoir. Generally speaking, geothermal reservoirs can be characterised in terms of their source temperature and pressure, as well as, whether the source is dominated by water vapour (the so-called "*Dry-Steam*" reservoir) or liquid water (the so-called "*Hot-Water*" reservoir) or just high temperature fractured rocks (the so-called "*Hot-Dry-Rock*" reservoir). The production of power (i.e. electricity) from *Dry-Steam* and *Hot-Water* reservoirs involves the conversion of the thermal energy stored in the geothermal fluid into mechanical work and then electricity. For this purpose the geothermal fluid is brought to the surface using a dedicated well (Figure 1). The high temperature geothermal fluid is then run through a suitable power plant in which the stored heat of the fluid is partially converted to mechanical work, causing its temperature to drop. The cold geothermal fluid is then reinjected into the same reservoir through a separate well.

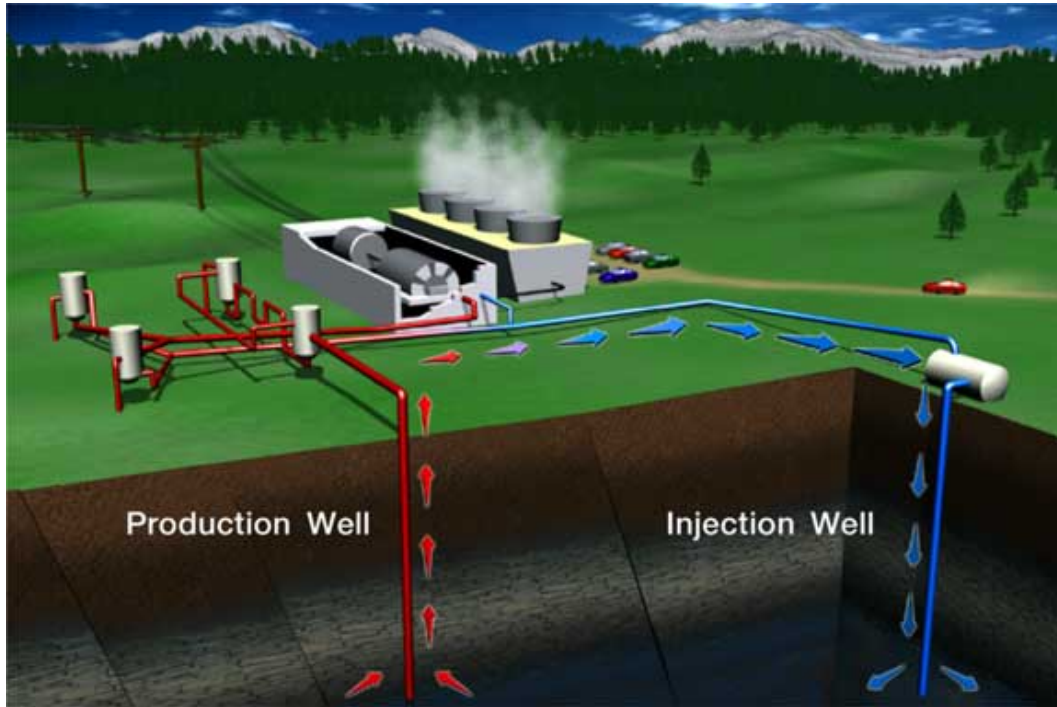


Figure 1: A typical geothermal power plant [4].

In the case of *Hot-Dry-Rock* reservoirs, high pressure fresh water is injected from the surface deep into the ground through the so-called recharge wells few kilometres upstream from the power plant. This causes the hot-dry bed which forms the geothermal resource to fracture, in turn, providing a very high contact surface area for heat exchange. As a result, the temperature of the fresh water flowing through the fractured bed increases to levels high enough for power generation. Similar to *Dry-Steam* and *Hot-Water* reservoir cases, the water (or steam) generated by forcing fresh water to flow through hot-dry rock is then brought to the surface to run a power plant and produce electricity.

1.1. Power Cycles Overview

Geothermal power cycles can be generally classified into following groups: (i) non-condensing direct steam cycles, (ii) condensing direct steam cycles, e.g. single flash and double flash, (iii) binary cycles, and (iv) combined cycles. The type of power cycle employed in a given geothermal application is dictated by the nature of the geothermal source. A brief description of various power cycles is presented below.

In non-condensing direct steam cycles (Figure 2), the high temperature steam ($T > 235^{\circ}\text{C}$) from the geothermal reservoir is used directly to run turbine/generator units in the power cycle.

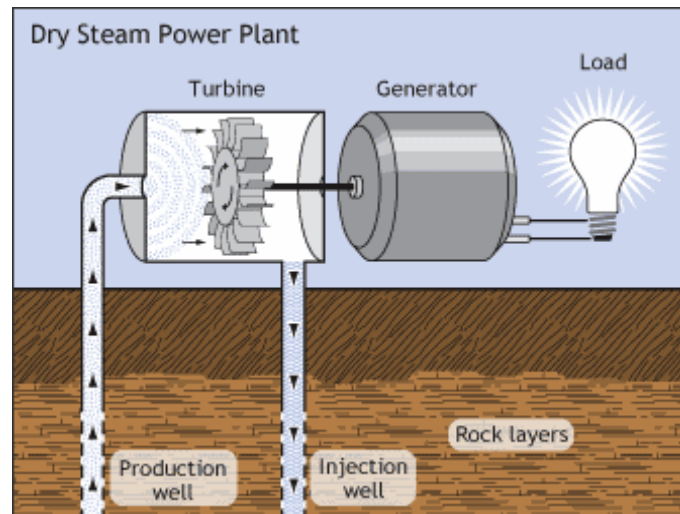


Figure 2: A schematic representation of a non-condensing power plant [6].

However, steam dominated reservoirs are unfortunately quite rare. The most common geothermal sources are of either water dominated or hot-dry rock nature. Depending on the temperature of the reservoir, various hydrothermal power cycles can be used to generate electricity. Condensing direct steam cycles are often preferable over the temperature range between 150°C and 200°C . In these cycles, some of the hot water from production well is flashed into steam in a separator (Figure 3). The steam is then used to power the turbine/generator units, generating electricity. Flashing of the geothermal fluid can be carried out in either single- or double-flash configurations.

For lower temperature reservoirs ($100\text{-}150^{\circ}\text{C}$), the preferred options are "Binary" power cycles where the geothermal fluid is passed through a heat exchanger to heat a secondary working fluid that runs the actual power cycle (Figure 4). The secondary working fluid is usually an organic fluid which vaporises at a lower temperature than water. One of the most well known and efficient binary power cycles purposely developed for geothermal applications is the Kalina cycle [7]. The Kalina cycle employs a multi-component zeotropic mixture of ammonia and water as its working fluid.

Although the cycle is based on an ideal Rankine vapour cycle, it has additional absorption and distillation equipment required to reconstitute the mixture at the low temperature end of the cycle.

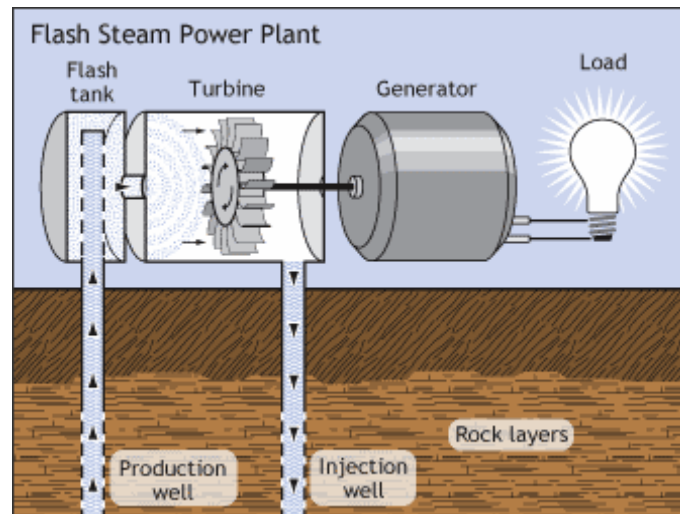


Figure 3: A schematic representation of a condensing direct steam power plant [6].

The conversion efficiency of geothermal plants can be improved using combined cycles where a hybrid of flash and binary cycles is employed. In such systems some of the geothermal fluid from the production well is first used in a flash cycle to run a primary turbine/generator unit. The condensate from the turbine outlet is then mixed with the remaining hot geothermal fluid and passed through a binary cycle where more electricity is generated.

The major limitation of conventional geothermal power cycles (e.g. flash, binary, and combined) is partly due to the fact that most power cycles currently employed in geothermal applications were originally designed for large-scale power production from fossil fuels where higher temperature sources are available for heat exchange. The majority of conventional geothermal power cycles employ either flash or organic Rankine cycles. These have been designed to operate under or near the saturation dome of the phase diagram of the working fluid. As a result, the evaporation and condensation of the working fluid both happen at constant temperatures. This, however, implies that there are great temperature mismatches between the working fluid and heat

source / sink during the heat addition or rejection processes. For a binary cycle, for example, the temperature difference between the working and geothermal fluids in the primary heat exchanger unit could be as high as 80-100°C. From a thermodynamics point of view, greater temperature differences in heat exchange units associated with a particular power cycle increase the generation of entropy and, thereby, reduce the exergetic efficiency of the heat exchange processes. This thermodynamic loss will adversely impact on the profitability of any system. The Kalina cycle avoids most of these exergetic losses, but incurs a significant penalty in mechanical complexity. As another alternative, the University of Newcastle is developing approaches to employ super-critical (SC) pressure cycles which also greatly reduce these exergetic losses, but with a much simpler system than required for a Kalina cycle [5].

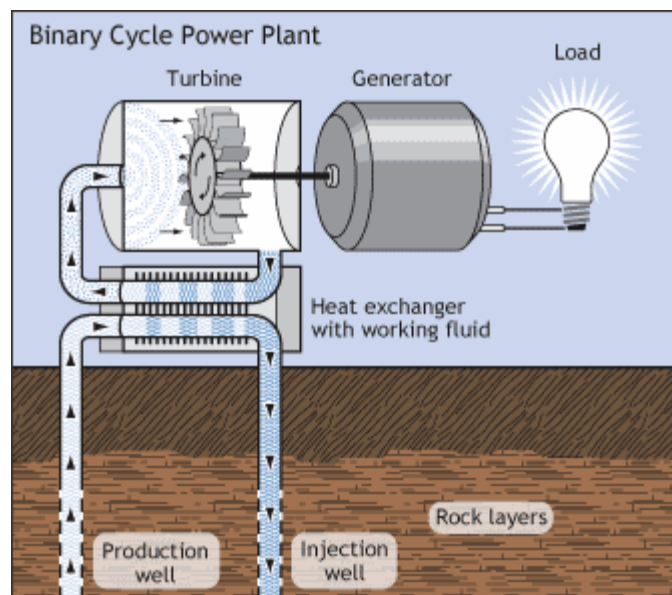


Figure 4: A schematic representation of a binary power plant [6].

While the number of geothermal plants installed around the world is increasing, these plants often operate under conditions significantly different from those in Australia. Typically they either avoid the need to re-inject the water underground (often into high pressure aquifers), operate with much shallower wells than proposed in Australia, or have a readily available low temperature sink for the condenser. This study provides an assessment of such systems under Australian local conditions.

Specifically, the study aims at:

- Compiling a detailed comparison of the performance and operating conditions of selected existing geothermal power plants (based on relevance and/or availability of data) with the range of conditions expected to apply in South Australia;
- Developing a detailed model of the Kalina cycle using HYSYS and compare with the Supercritical power cycle developed in Newcastle.

2. MODELLING

A theoretical study was conducted to compare the thermal performance of the conventional geothermal power cycles with the supercritical cycle developed at The University of Newcastle (SC-Newcastle). For this purpose, comprehensive literature search was carried out to identify cases with sufficient technical details for which comparisons between the conventional cycles and the SC-Newcastle can be made. Eleven cases (Table 1) were selected for further analysis / comparisons [8-9, 10]. An analytical model, developed in our earlier work, was employed to calculate the thermal conversion efficiency, $n(I)$, exergetic efficiency $n(II, EXE)$ and thermal effectiveness $n(II, Eff)$ of the power cycles. This model was developed based on the first and second laws of thermodynamics using similar approach to that of DiPippo [8]. A summary of the thermodynamic concepts is presented in the next section. The model was then used to calculate the thermal performance of the SC-Newcastle under the same conditions as the existing geothermal plants.

2.1 Thermodynamic Concepts

In this study the conversion efficiency was calculated using the first law of thermodynamics, while the exergetic efficiency and effectiveness were determined from the second law of thermodynamics.

The thermal conversion efficiency indicates how much of the energy delivered to the cycle from the geothermal source has been converted to useful work. The thermal efficiency, $n(I)$, is calculated using:

$$n(I) = \frac{W_{net}}{Q_{in}} = \frac{W_{exp} - W_{com} - W_{aux}}{\dot{m}_{geo}[h_{geo}(in) - h_{geo}(out)]} \quad (1)$$

where Q_{in} is the thermal energy delivered to the cycle, W_{net} the net power output, W_{exp} the power produced by expansion of the working fluid process through the turbine, W_{com} the power required for compressing the working fluid, W_{aux} the power consumed by auxiliary units attached to the cycle, \dot{m}_{geo} the mass flow rate of the geothermal fluid, $h_{geo}(in)$ the enthalpy of the hot geothermal fluid in the production well, and $h_{geo}(out)$ the enthalpy of the geothermal fluid in the rejection well.

The exergetic efficiency, $n(II, EXE)$, is a measure of the maximum useful work that can be extracted from a given geothermal source and, hence, indicates the maximum possible thermal conversion efficiency of a cycle for a given set of conditions. $n(II, EXE)$ is determined from:

$$n(II, EXE) = \frac{W_{net}}{EXE_{geo}(in)} \quad (2)$$

in which the exergy (i.e. availability) of the geothermal fluid in production well, $EXE_{geo}(in)$ is defined as:

$$EXE_{geo}(in) = \dot{m}_{geo} \times (h_{geo}(in) - h_0 - [T_0 \times s_{geo}(in)] - s_0). \quad (3)$$

The variables h_0 , T_0 and s_0 in equations 3 denote the enthalpy, temperature, and entropy of the surrounding (i.e. ambient conditions), respectively, while $s_{geo}(in)$ represents the entropy of the geothermal fluid in the production well.

Like exergetic efficiency the effectiveness, $n(II, Eff)$, is related to the availability (i.e. exergy) of the cycle and its surrounding. However, the effectiveness of a cycle shows of the total energy available in the geothermal source how much has been actually delivered to the cycle and then converted to work. The effectiveness is calculated from:

$$n(II, Eff) = \frac{W_{net}}{EXE_{geo}(in) - EXE_{geo}(out)} \quad (4)$$

where $EXE_{geo}(out)$ is the exergy of the geothermal fluid in the rejection well that can be worked out from:

$$EXE_{geo}(out) = \dot{m}_{geo} \times (h_{geo}(out) - h_0 - [T_0 \times s_{geo}(out)] - s_0). \quad (5)$$

The variable $s_{geo}(out)$ in equation (5) denotes the entropy of the rejection well geothermal fluid.

A HYSYS model was also developed to simulate the Kalina cycle. The results of the simulation and its comparison with the supercritical cycle are presented in the next section.

3. RESULTS AND DISCUSSION

The calculations were carried out for the SC-Newcastle under the same conditions as cases 1 to 11 listed in Table 1. The maximum pressure for the supercritical cycle was set at about 12 MPa with the geofluid temperature ranging between 125°C-230°C. The summary of the results are presented in Table 1. As can be seen, under identical set of conditions, the supercritical cycle developed at the University of Newcastle leads to higher efficiencies than those typically obtained from conventional geothermal cycles (i.e. binary, flash, Kalina). Figures 5 and 6 illustrate the plots of thermal and exergetic efficiencies as a function of the temperature difference between the geothermal fluid at the production and discharge wells, ΔT_{geo} , for various cycles. As shown in Figure 7, the Newcastle supercritical cycle consistently out performs the conventional cycles, in term of the thermal efficiency, over a broad range of conditions. The average thermal efficiency for the supercritical cycle is 1.5 times than the conventional cycles with a maximum of 18% for given conditions. Amongst the conventional cycles, the flash cycles were found to have the highest thermal efficiency reaching 16% at $\Delta T_{geo} = 78^\circ\text{C}$ and geofluid temperature of 229°C.

Similarly the exergetic efficiency of the supercritical cycle found to be far superior to that of conventional cycles for ΔT_{geo} lower than 120°C (Figure 6). The flash cycles despite their relatively good thermal efficiencies were found to suffer from exergetic losses and hence their effectiveness was relatively poor around 40% (Figure 7). The high exergetic efficiencies of the binary cycles obtained at ΔT_{geo} greater than 120°C was balanced out by their low thermal efficiencies resulting in an often lower effectiveness than the supercritical cycle. The Kalina and combined cycle cases were delivered much lower

efficiencies and effectiveness than the supercritical cycle. The high effectiveness obtained by the supercritical cycle is an indication that more of the available energy from the source can be harnessed and converted to work using this cycle.

Further, HYSYS models were developed to compare the performance of the Kalina cycle with the supercritical cycle. The models were used to determine the performance of the cycles in terms of their power output and thermal efficiency over a geothermal fluid temperature range of 150°C to 200°C. The calculations were performed for a geofluid flow rate of 200 kg/s while the working fluid flow rate was kept constant. The results of the HYSYS modelling are presented in Figures 8 and 9. As Figure 8 illustrates, a reduction in temperature reduces the thermal efficiencies of both cycles with the supercritical cycle having higher efficiencies than the Kalina cycle.

Also, the overall performance of the cycles was determined as a function of the geofluid temperature (Figure 9). For this purpose the net power output was calculated. As can be seen the cycle power output increases as the geofluid temperature rises. That is due to an increase in the heat content of the geofluid stream. The supercritical cycle power output however was significantly higher reaching twice as high as the Kalina cycle at 180°C.

Table 1: Thermodynamic assessment of geothermal power cycles.

Cycle	T(geo-in) [oC]	T(geo-out) [oC]	To (dead-state) [oC]	mdot (geo) [kg/s]	Qnet mdot*(hin-hout) [kW]	EXE(geo-in) [kW]	EXE(geo-out) [kW]	Wnet (kW)	n(I)	n(II,EXE)	n(II,Eff)
Husavik Kalina [8]	124.00	80.00	5.00	90.00	15957.00	7334.10	3240.00	1696.00	10.63%	23.12%	41.43%
Supercritical-Newcastle	124.00	80.00	5.00	90.00	15957.00	6562.80	3240.00	2067.02	12.95%	31.50%	62.21%
Otake Binary [8]	174.70	50.00	18.00	14.66	7777.81	1856.82	99.76	1000.00	12.86%	53.86%	56.91%
Supercritical-Newcastle	174.70	95.00	18.00	14.66	5012.84	1969.26	533.95	901.81	17.99%	45.79%	62.83%
Nigorikawa Binary [8]	140.00	92.00	13.00	49.97	10183.89	4635.82	1936.56	1000.00	9.82%	21.57%	37.05%
Supercritical-Newcastle	140.00	110.00	13.00	49.97	6386.56	4635.82	2829.51	1083.94	16.97%	23.40%	60.10%
Heber SIGC Multi-Unit Binary [8]	165.00	20.00	15.00	126.00	52003.97	15855.84	2295.72	6875.00	13.22%	43.36%	50.70%
Supercritical-Newcastle	165.00	95.00	15.00	126.00	52003.97	15855.84	4973.49	6961.26	18.45%	44.23%	64.67%
Brady Binary [9]	108.00	80.00	16.80	484.09	54421.40	24137.21	17427.24	4330.00	7.96%	17.94%	64.53%
Supercritical-Newcastle	108.00	85.00	16.80	484.09	46914.73	24137.21	14017.90	4808.76	10.25%	19.89%	47.36%
Single-Flash-1 [9]	229.40	151.00	20.00	230.20	80752.32	52512.83	22237.89	12830.00	15.89%	24.43%	42.38%
Supercritical-Newcastle	229.40	155.00	20.00	230.20	76780.55	52512.83	23490.05	13747.50	17.91%	26.18%	47.37%
Single-Flash-2 [9]	229.40	134.00	20.00	230.20	97584.08	52512.83	17249.42	13333.00	13.66%	25.39%	37.81%

Supercritical-Newcastle	229.40	134.00	20.00	230.20	97584.08	52512.83	17249.42	14346.98	14.70%	27.32%	40.69%
Double-Flash [9]	229.40	100.00	20.00	230.20	130818.06	52512.83	8957.21	16771.00	12.82%	31.94%	38.50%
Supercritical-Newcastle	229.40	120.00	20.00	230.20	111334.40	52512.83	13554.72	17802.37	15.99%	33.90%	45.70%
Binary Nevada [9]	229.40	55.00	20.00	230.20	174282.12	52512.83	1866.55	17314.00	9.93%	32.97%	34.19%
Supercritical-Newcastle	229.40	110.00	20.00	230.20	121116.83	52512.83	11154.34	17344.92	14.32%	33.03%	41.94%
Combined (Flash + Binary) [9]	229.40	69.00	20.00	230.20	160800.22	52512.83	3557.80	19749.00	12.28%	37.61%	40.34%
Supercritical-Newcastle	229.40	110.00	20.00	230.20	121116.83	52512.83	11154.34	20087.19	16.59%	38.25%	48.57%
Pseudo-Supercritical [10]	229.40	47.00	20.00	230.20	181977.70	52512.83	1132.53	19849.00	10.91%	37.80%	38.63%
Supercritical-Newcastle	229.40	108.00	20.00	230.20	123054.50	52512.83	10704.98	22580.50	18.35%	43.00%	54.01%

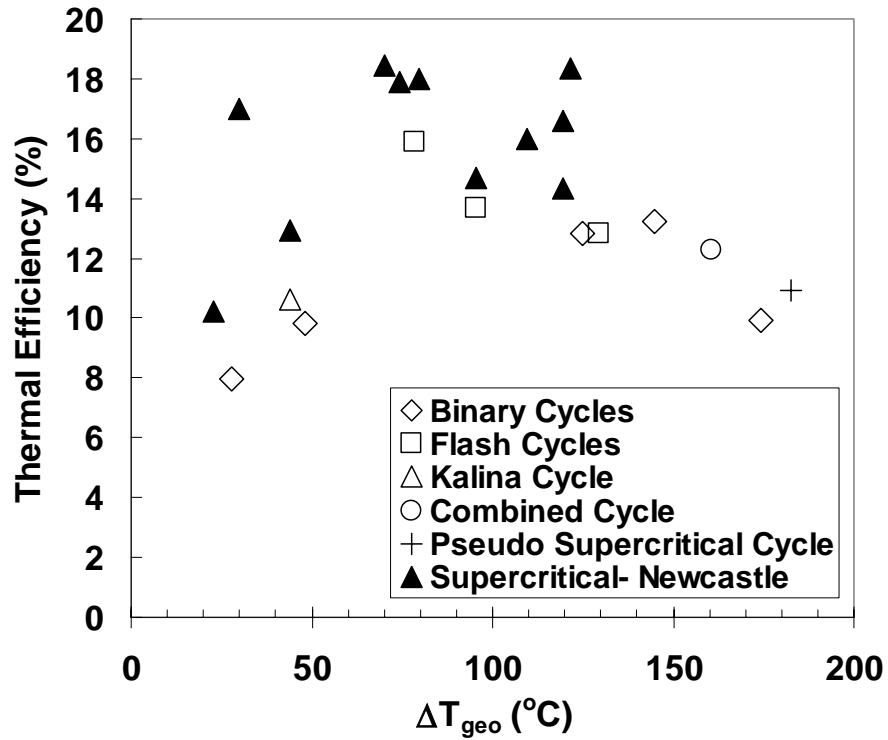


Figure 5: Comparison of the thermal efficiencies of various geothermal power cycles.

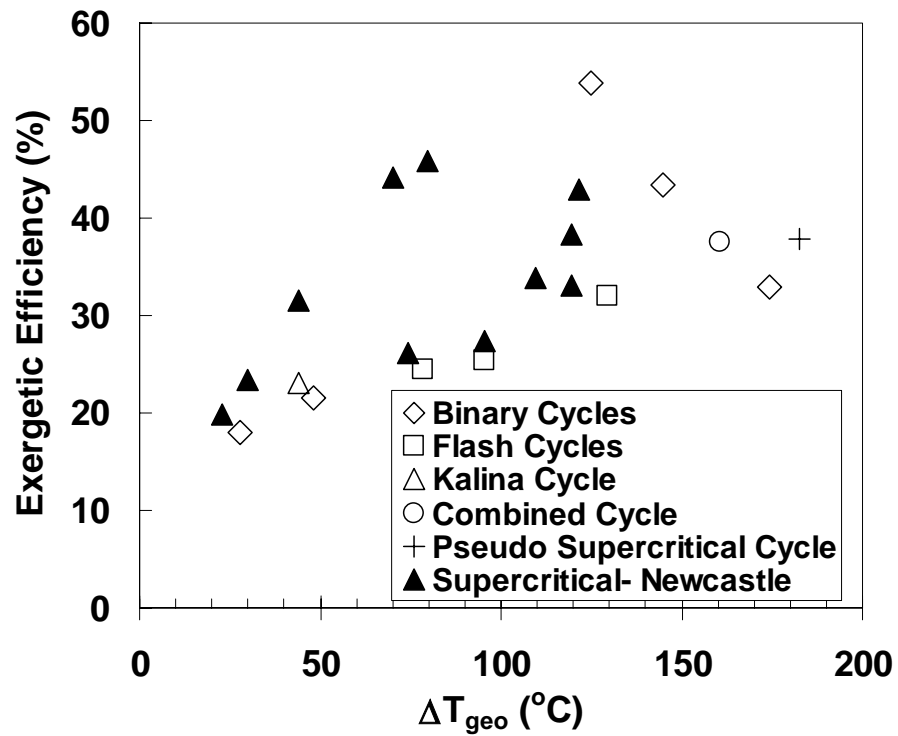


Figure 6: Comparison of the exergetic efficiencies of various geothermal power cycles.

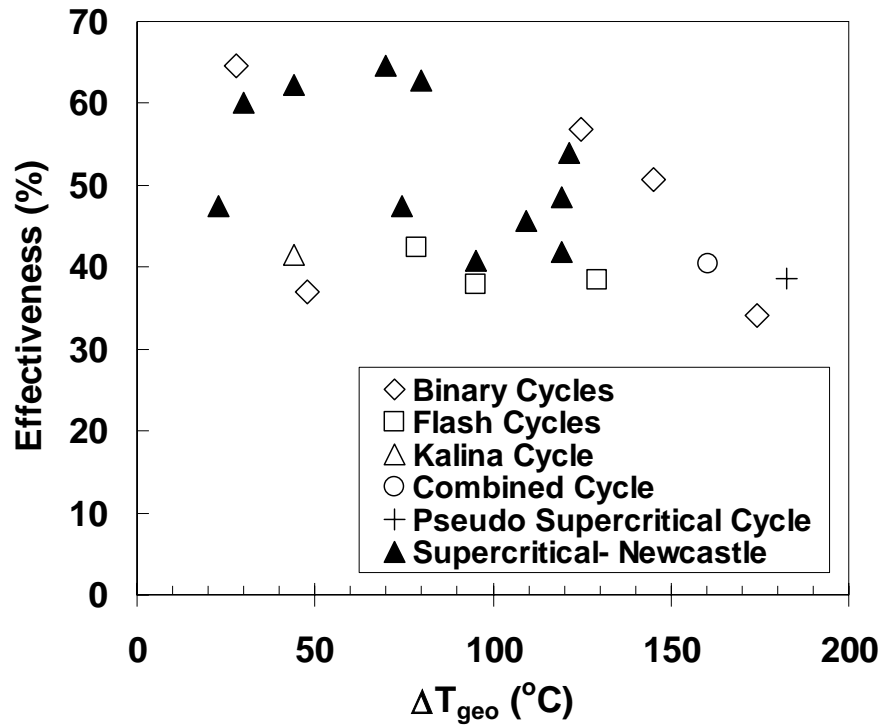


Figure 7: Comparison of effectiveness of various geothermal power cycles.

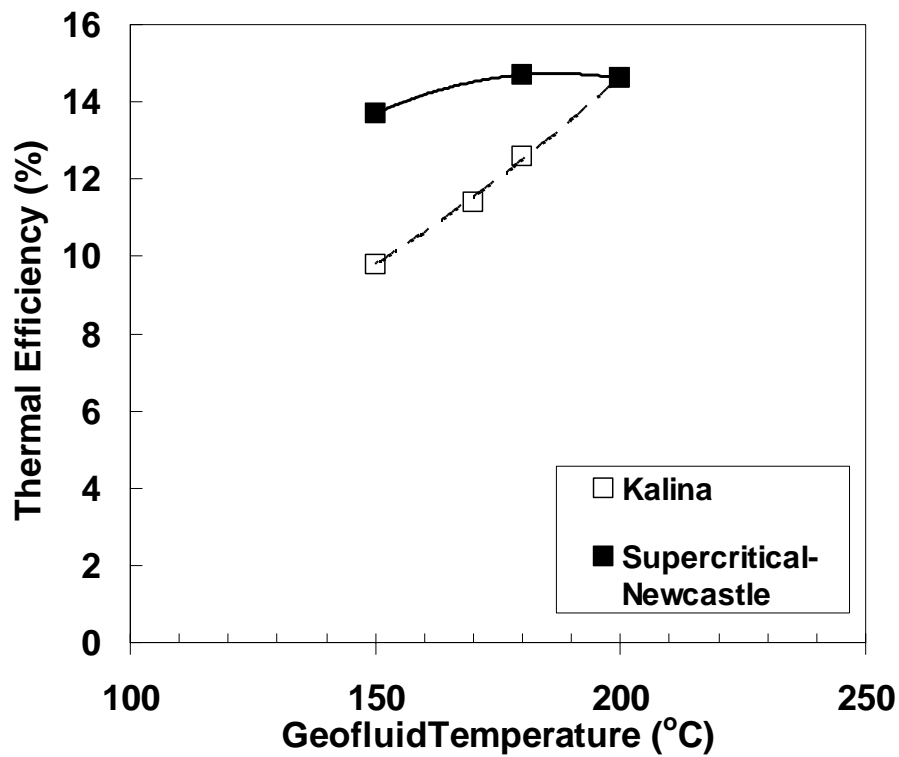


Figure 8: Comparison of Kalina and supercritical cycles in term of their thermal efficiencies.

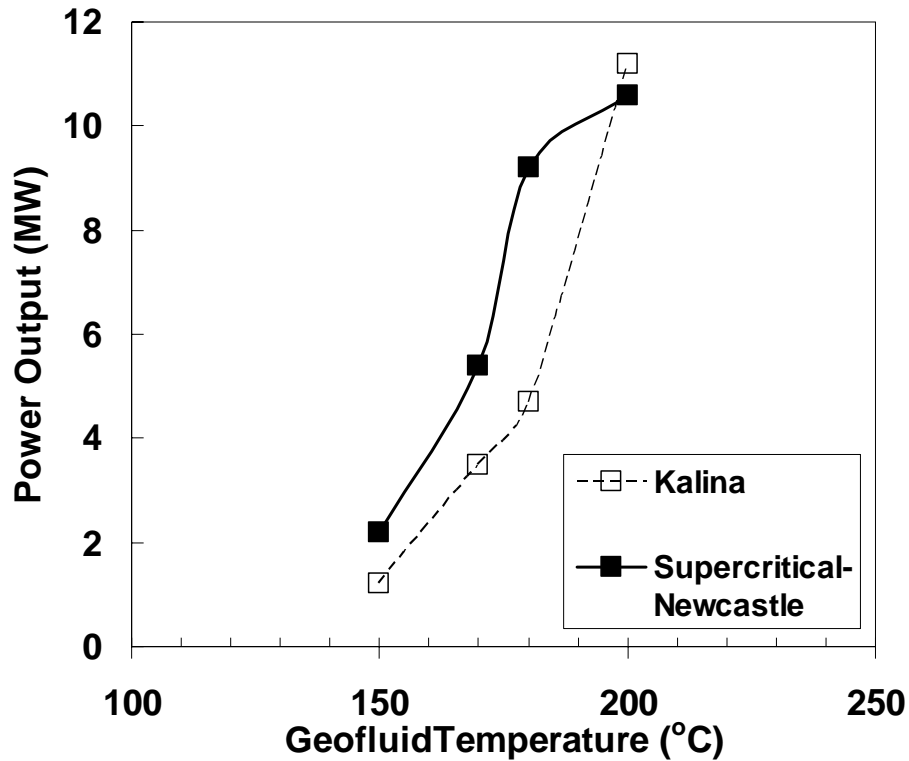


Figure 9: Comparison of Kalina and supercritical cycles in term of their power outputs.

4. CONCLUDING REMARKS

The analytical model developed at the University of Newcastle was employed to conduct a thermodynamic assessment of existing geothermal plants. The model was specifically used to determine the effectiveness, thermal and exergetic efficiencies of the geothermal power cycles evaluating their performance over a range of conditions applicable to Australia.

Also HYSYS simulation package was employed to determine the overall performance of Kalina cycle versus the supercritical cycle developed at the University of Newcastle. The comparison was made based on the net power output and thermal efficiency.

Overall, it was found that the supercritical cycle can perform significantly better than conventional power cycles namely, binary, flash, Kalina and combined cycles. For instance, the average thermal efficiency of the supercritical cycle was found to be at least 1.5 times higher than that of conventional cycles reaching thermal efficiencies as high as 18%. Also, the exergetic losses were found to be minimal under supercritical

conditions. That in turn resulted at higher net power outputs when the supercritical cycle was employed. This trend was observed for geofluid temperatures ranging between 150°C-200°C.

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