Economics of geothermal feedwater heating for steam Rankine cycles

David L. Battye*, Peter J. Ashman, Gus J. Nathan
Centre for Energy Technology
University of Adelaide, SA 5005.
* Corresponding author: david.battye@adelaide.edu.au

We have investigated the economics of geothermal feedwater heating (GFWH) in a steam Rankine cycle with base capacity of 583 MW (gross). The capital cost per kW geothermal power (before geofluid pumping) is compared with those of stand-alone geothermal plants of equal power. The economic benefits of GFWH over stand-alone plants for enhanced geothermal systems are, in order of importance:

- 67% less operating and maintenance cost
- 28% less capital cost
- 30-35% less geofluid pumping loads

The reduction in levelised geothermal energy cost is estimated to be 48%.

Keywords: geothermal power, cost, economics, hybrid.

Introduction

In steam Rankine cycles, boiler feedwater must be heated from a low temperature at the condenser outlet (typically ~40 °C) to temperatures of typically 250 °C before entering the boiler. In "regenerative" steam cycles, this is accomplished in a series of feedwater heaters, which use steam extracted from various stages in the turbine. One feedwater heater is a deaerator, in which extracted steam and feedwater are in direct contact, liberating oxygen and other gases in the feedwater for venting to atmosphere. The other feedwater heaters are shell-and-tube heat exchangers where feedwater flows in the tubes and steam condenses on the outside.

If feedwater heating can be accomplished using geothermal heat, the steam normally extracted for feedwater heating can instead generate power in the turbine. The extra power generated by geothermal feedwater heating (GFWH) offers the following potential benefits:

- Existing plants may be retrofitted to accommodate a proportion of geothermal power
- Geothermal power may be generated more cheaply than in a stand-alone plant
- Steam cycles may be adapted for GFWH with no novel technology required.

GFWH is suitable for coal, gas, solar-thermal and nuclear-fuelled boiler plants, but not combined-cycle gas turbine plants. The latter plants use hot exhaust gas for feedwater heating in the Rankine cycle section.

Interest in geothermal feedwater heating has existed since the 1970s, when it was investigated for application at sites in California and Utah (Parsons, 1978). It has been recently studied by Bruhn (2002), Buchta (2009) and Borsukiewicz-Gozdur (2010). All studies agree that geothermal power generation by GFWH is significantly more efficient thermodynamically than in conventional stand-alone plants. However, to the authors' knowledge, no previous comparison has been reported of the economic benefits of GFWH over stand alone geothermal power generation. We seek to provide such a comparison, specifically with respect to power generation from enhanced geothermal systems.

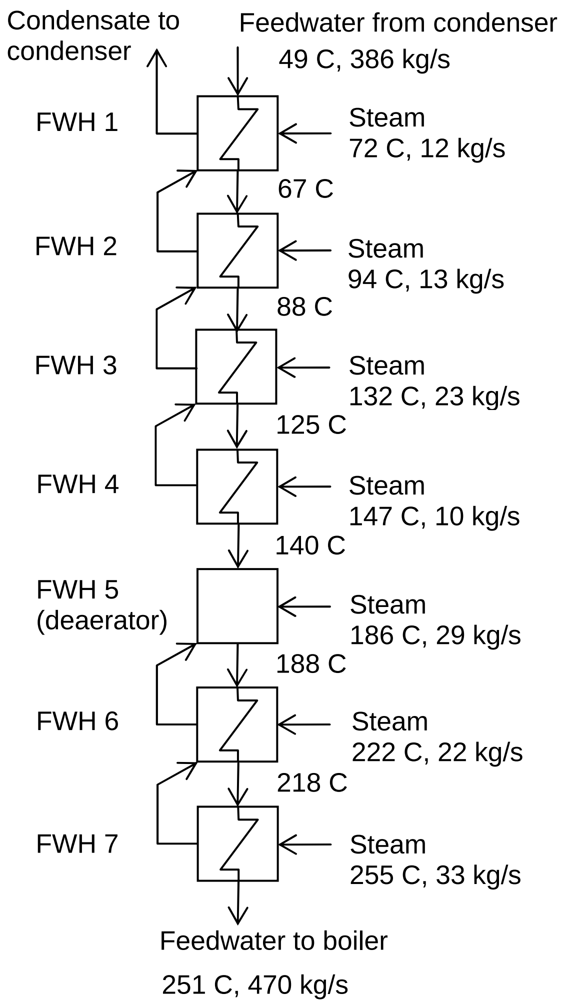

Figure 1: Feedwater heating section in a conventional 583 MW (gross) steam Rankine cycle. Steam flows extracted from turbine stages are shown at right. These steam flows may be replaced by a single flow of hot water from a geothermal reservoir.

Methodology

For our economic analysis we consider the case that GFWH is being used to provide extra capacity for a new Rankine steam cycle plant. This scenario is in contrast to the retrofit of an existing plant, where the capacity is typically fixed.

The basis for analysis is a 583 MW (gross) subcritical steam cycle with single reheat, for which design specifications and cost estimates have been reported (NETL, 2007). A process flow diagram of the feedwater heating section is shown in Figure 1. In the proposed GFWH scenario, feedwater is heated by geofluid instead of steam extracted from turbine stages. The otherwise extracted steam flows are then available for power generation in the turbine.

The temperature to which the feedwater is heated by the geofluid, T_{GFWH}, is a variable in the analysis. Above this temperature, we assume that feedwater heating is achieved by conventional heaters as per normal. However, the deaerator must be retained in the cycle, and may have to operate at higher temperatures than normal. We assume that the upper limit of GFWH input is one where feedwater is heated to 220 °C by geofluid, and a deaerator heats feedwater from 220 °C to 251 °C.

To estimate the increased costs of equipment in GFWH cases, the reported costs of components are increased in proportion to turbine exhaust steam flow (turbine, condenser, steam piping, and cooling system) or gross power (generator, accessory electrical plant, instrumentation and control).

The cost of feedwater heaters (apart from the deaerator) is proportional to the heat transfer surface area, which varies with the overall heat transfer coefficient, U, and mean temperature difference between geofluid and feedwater streams, MTD. We estimate that U is decreased by ~30% in GFWH, since the high film coefficients associated with condensing steam are absent. MTD is about 15 K on average in conventional feedwater heaters. In GFWH cases MTD is a variable. The resulting multiplier applied to the conventional feedwater heater train cost is:

$$f = 1 + \left(\frac{T_{GFWH} - 38}{213}\right)\left(\frac{21}{MTD} - 1\right)$$

Geofluid costs are estimated assuming:

- Flow of 80 kg/s per well drilled
- Drilling costs vary exponentially with depth according to:

  $C_{drill} = 0.5e^{0.0001491d}$ \$M, 2000 US

  (Entingh, 2006), where d is depth in feet.
- Other costs (stimulation, geofluid pumps and piping) are 20 % of drilling costs.

Geofluid costs (2009 US dollars) versus geofluid temperature are shown in Figure 2 for thermal gradients of 40 and 50 K/km.

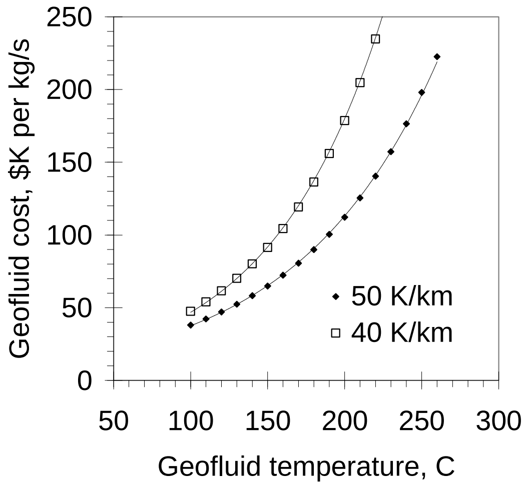

Figure 2: Geofluid cost versus geofluid temperature for thermal gradients of 40 and 50 K/km.

Estimates of the cost and performance of stand-alone geothermal power plants are based on data in the Next Generation Geothermal Power Plants report (Brugman et al., 1995 and CE Holt, 2006) and documentation for the Geothermal Electric Technologies Evaluation Model (GETEM) (Entingh, 2006).

All plants in the analysis are water-cooled and use a cooling tower.

The costs determined from the literature have been updated to 2009 US dollars using the Chemical Engineering Plant Cost Index.

Results and discussion

Figure 3 shows percentage extra gross power and exhaust steam flow versus T_{GFWH}. The effective geothermal power output (before geofluid pumping) ranges from 9.6 MW at 100 °C to 61 MW at 220 °C.

Figure 4 shows the consumption of geofluid per unit geothermal energy generated (net before geofluid pumping) versus geofluid temperature. The GFWH plants require significantly less geofluid than the stand-alone plants, typically 30-35% less above 200 °C. The explanation for this lies in the fact that the GFWH plants minimise thermodynamic inefficiency associated with heat transfer from the geofluid. The lower the MTD, the greater the thermodynamic benefit, but at the expense of higher heat exchanger costs.

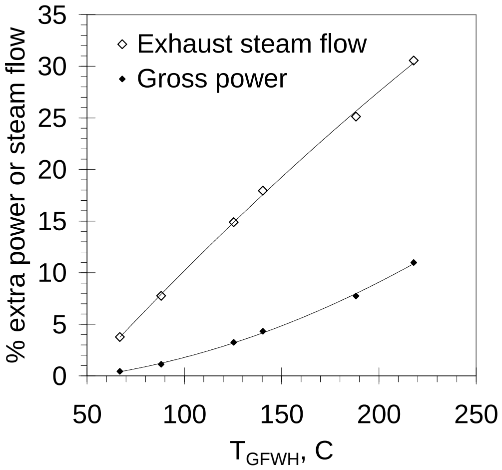

Figure 3: Percentage extra gross power and turbine exhaust steam flow versus geothermal feedwater heating temperature.

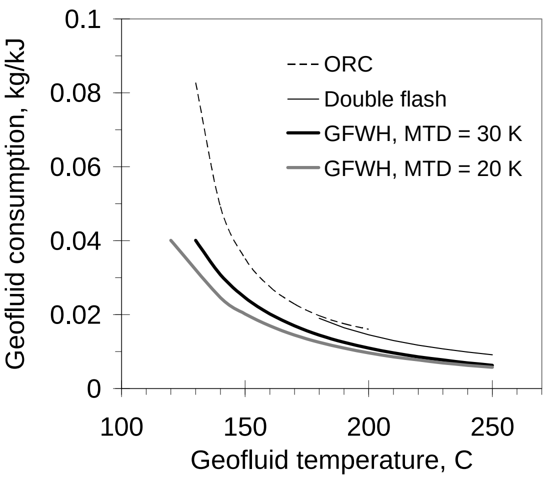

Figure 4: Geofluid consumption per unit geothermal energy generated (net before geofluid pumping) versus geofluid temperature.

Figure 5 compares plant costs for GFWH and stand-alone plants, ie. Organic Rankine Cycles (ORC) and double flash steam plants. Increasing geofluid temperature reduces the cost of all plants due to improving thermal efficiency. However, the stand-alone plant cost also decreases due to economies of scale. GFWH plant costs correspond to the increment on base plant cost. Since the base plant capacity is already many times greater than for the stand-alone plants, GFWH plant costs are much lower on average over the geofluid temperature range. At the upper geofluid temperatures in Figure 5, the GFWH plant costs are 15-25 % lower than for a double flash plant.

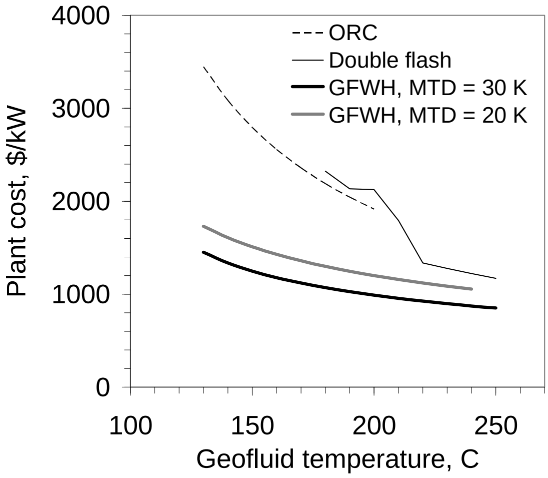

Figure 5: Plant cost versus geofluid temperature for equal power outputs. GFWH plant costs correspond to the increment on base plant cost.

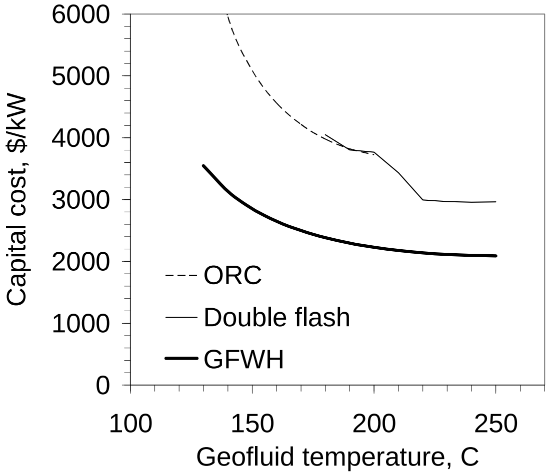

Figure 6: Capital cost versus geofluid temperature for thermal gradient of 50 K/km.

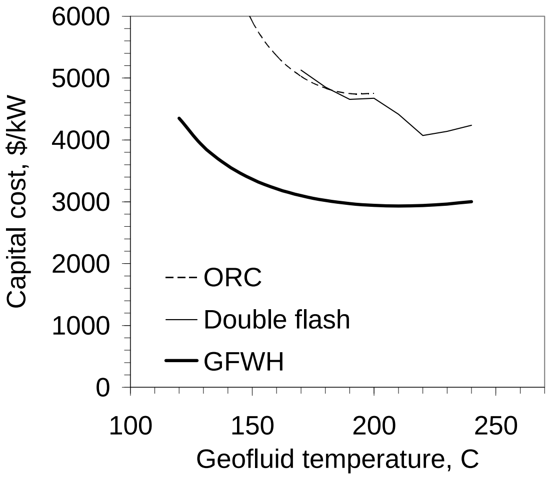

Figure 7: Capital cost versus geofluid temperature for thermal gradient of 40 K/km.

Total capital costs are shown in Figures 6 and 7 for thermal gradients of 50 K/m and 40 K/m respectively. Note that the $/kW value is for geothermal power before geofluid pumping. The value of MTD is optimised in each case: 30 K for 50 K/km and 20 K for 40 K/km. The following is observed:

- Optimal geofluid temperatures are 220 °C or greater.
- Optimal GFWH plants reduce total cost by 28% relative to optimal stand-alone plants in both cases.
- GFWH with a 40 K/km thermal gradient can generate power at the same cost as a stand-alone plant with a 50 K/km gradient.
- GFWH can generate power at the same cost as optimal stand-alone plants, but at geofluid temperatures of only 120-150 °C as opposed to 220 °C.

Relative to stand-alone plants, GFWH has the additional benefit of incurring less geofluid pumping power loads, which are not accounted for in the preceding analysis. Since GFWH consumes 30-35 % less geofluid above 200 °C, pumping loads are reduced by the same amount relative to stand-alone plants.

Another economic benefit is that geothermal operating and maintenance costs are drastically reduced by GFWH. For example, O&M costs in a 61 MW stand-alone geothermal plant are estimated at 7.3 $M/year (Sanyal, 2004) whereas 61 MW generated by GFWH only incurs 10 % of the annual O&M costs of the whole plant, ie. 2.4 $M/year (NETL, 2007), a saving of 67%.

A simple estimate of the reduction in the levelised cost of geothermal energy can be made using figures reported by Sanyal (2007) for EGS power. Table 1 illustrates how the estimate is made and suggests a reduction in total levelised cost approximating 48%.

Table 1: Estimate of reduction in levelised cost of geothermal energy by GFHW, based on estimates of Sanyal (2007) and preceding analysis.

	Levelised cost for stand-alone plant, ¢/kWh (US, 2007)	Reduction by GFWH	GFWH levelised cost, ¢/kWh (US, 2007)
O&M	2.75	1.84 (67%)	0.91
Capital and cost of money	2.68	0.75 (28%)	1.93
Total	**5.43**	**2.59 (48%)**	**2.84**

Concluding remarks

The economic analysis has shown geothermal feedwater heating in a purpose-built steam Rankine cycle to have economic merit. Given that good solar and EGS resources in Australia are generally co-located, solar-geothermal hybrids using GFWH are possible. Further work will investigate the economics of retrofitting existing steam Rankine cycle plants for GFWH.

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