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Assessment of geothermal assisted coal-fired power generation using an Australian case study

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ABSTRACT

A systematic techno-economic analysis of geothermal assisted power generation (GAPG) was performed for a 500 MW unit of a typical coal-fired power plant located at the upper Hunter region of New South Wales, Australia. Specifically, the GAPG viability and performance was examined by investigating the impacts of reservoir temperature, resource distance, hybridisation scheme, and economic conditions including carbon tax and Renewable Energy Certificates (REC). The process simulation package, Aspen HYSYS, was employed for all simulation purposes. Thermodynamically, GAPG system was found to increase the power output of the plant by up to 19% under the booster mode whilst in fuel saving mode the coal consumption reduced by up to 0.3 million tonne/year decreasing the Green House Gas (GHG) emission by up to 15% (0.6 million tonne/year). Economic analyses showed that for a typical HDR resource with a reservoir temperature about 150 °C located within a 5 km radius from the power plant, the GAPG system becomes economically competitive to the stand-alone fossil fuel based plant when minimum carbon tax and RECs rates of 40 $/tonne and 60 cents/kW h are introduced. The figure of merit analyses comparing GAPG system with both stand-alone fossil fuel and stand-alone geothermal plants showed that an economically feasible GAPG system requires the use of HDR resources located no further than 20 km from the plants. Reference maps were also developed to predict suitable conditions for which the hybrid plant outperforms the stand-alone plants.

1. Introduction

Fossil fuels have been widely used for power generation for decades due to their low cost and high-quality attributes. However, in the 21st century large-scale utilisation of fossil fuels for electricity generation raised public attentions on the potential problems caused by burning fossil fuels, for example energy security and global warming issues. For a healthier and more sustainable world economy, an energy mix of alternative energy sources along with the traditional energy resources should be considered as a potential solution [1].

Based on the above background, this study examined the feasibility and potential of the energy mix between geothermal and fossil fuels in Australia. Specifically, the study investigates the approach of hybridising Enhanced Geothermal Systems (EGS) (the preferred technology in Australia for harnessing the thermal energy stored in hot granite bodies or Hot Dry Rock, HDR, resources) with fossil fuel energy in an existing 500 MW unit conventional coal-fired power plant. The hybridising approach is implicated through the so-called geothermal assisted power generation (GAPG) concept. Essentially, this concept involves the use of low-grade geothermal energy instead of the turbine bled steam (i.e. the extracted steam) to preheat the feedwater in a conventional coal-fired power plant. The unused turbine bled steam is then returned to the turbine to generate extra electricity. Thermodynamically, the low-grade geothermal energy can be efficiently utilised in the highly efficient regenerative-steam-Rankine-cycle of the fossil fuel power plant replacing some of the high-grade fossil fuels for power generation, and subsequently increasing the thermal efficiency of the whole plant. Economically, co-locating a geothermal power plant with an existing/new fossil fuel power plant enables sharing of some costly items such as power generating facilities, land uses, and transmission lines.

Approaches enabling more efficient utilisation of low-medium-temperature geothermal resources have been extensively investi-

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gated [2–9]. Surprisingly, though, the GAPG concept as an effective solution to promote efficient geothermal utilisation was rarely examined in the recent years. Earlier studies conducted by Khalifa and co-workers [10] showed that thermodynamically GAPG concept can improve the utilisation efficiency of both geothermal and fossil fuel resources with 60% more work being potentially produced. Bruhn [11] examined the GAPG concept applied in two existing coal-fired power plants in Germany. His work [11] suggested that the GAPG system is not viable for low-temperature geothermal resources at 70 °C, but showed promising performances in exploiting medium-temperature geothermal resources around 120–150 °C. Bruhn [11] concluded that a geothermal-to-electricity cost of around 85 EUR/MW h is attainable using EGS concept in central Europe. More recently, Buchta and his co-workers [12,13] pointed out that GAPG system using low-temperature geothermal resources at around 130 °C was technically feasible particularly for those aged power plants with reduced boiler efficiency. Dipippo and his co-workers [14] demonstrated the thermodynamic advantages of the hybrid plant applying GAPG concept over the stand-alone plants using on-site hydrothermal resources with geofluid temperatures below 150 °C.

Anno et al. [15] economically compared the GAPG concept for power plants in the Western United State with that of a fossil fuel-only plant, confirming its economic viability for electricity generation in the Western United States assuming abundant coal and geothermal resources were available. However, their economic results obtained in the 1970s are considered out-of-date and limited to hydrothermal resources with reservoir temperatures of 55–85 °C. White and his co-workers [16] performed a technical and economic evaluation of the possible sites in Arizona, USA to build a totally new hybrid geothermal fossil-fuel power plant which applies GAPG concept using local hydrothermal resources. They estimated the electricity cost for the hybrid power plant could reach to 18.3 US$/MW h, even lower than the fossil fuel-only plant at 19.3 US$/MW h. The low cost of electricity using the hybrid plant is believed to be driven by the use of low-cost shallow hydrothermal resources.

The majority of the past studies clearly are site specific with case studies of GAPG concept being performed for locations at the United States [14,17,18], Germany [11,19], and Poland [12,13]. Also the focus was on using on-site hydrothermal resources whereby the distance between geothermal resource and power station was considered to be economically negligible, hence not including the cost of pipeline facilities between the two plants.

The applicability of the results in Australia where HDR resources are dominant is therefore questionable considering the following reasons. Firstly, from an economic viewpoint, the cost of exploring a HDR resource is much more expensive than the hydrothermal resources mainly due to drilling and fracturing steps. Secondly, most technical analyses were carried out assuming the hydrothermal geothermal resources to be located close to the coal-fired power plant. However, this assumption may not always apply especially when dealing with existing power plants.

Moreover, there is a lack of systematic study of GAPG concept which examines the effects of reservoir temperature, resource distance, and hybridisation scheme as well as various economic conditions on the performances of GAPG system. Thermodynamic analyses of GAPG system using the second-law of thermodynamics and economic studies of GAPG system using HDR resources are also absent. In addition, the figure of merit analysis to evaluate performances of GAPG system over those of the stand-alone fossil fuel and geothermal plants was limited to the use of on-site geothermal resources with a medium-to-high reservoir temperature between 150 °C and 250 °C and for a state-of-the-art steam power plant [10].

The work presented in this paper, therefore, filled the above identified knowledge gaps by undertaking a systematic techno-economic assessment of the hybrid geothermal–fossil fuel plant in an Australian context. The work is also part of a larger program of study at the University of Newcastle (Australia) on hybrid renewable energy systems [20–23]. To carry out the systematic study of GAPG system in Australia, we defined a series of hybridisation schemes covering steam replacing ratios between 0% and 100%, which indicates the fraction of turbine bled steam replaced by geothermal fluid. Reservoir characteristics required for those hybridisation schemes to work were evaluated, including reservoir temperature, resource distance, brine flow rate, and depth/number of well to be drilled. Using those characteristics and hybridisation schemes, both technical and economic feasibility and performances of GAPG system were investigated. Technical analyses examine the impacts of various reservoir temperatures, resource distances, and hybridisation schemes on net power output and thermal efficiency, whilst economic analyses examine the impacts of different economic conditions including carbon tax and RECs on electricity cost and NPV. The minimum required carbon tax and RECs for GAPG system to become superior to the fossil fuel-only plant were also discussed. Moreover, both exergy and figure of merit analyses of GAPG system were carried out. Figure of merit analysis was extended to low-to-high-temperature geothermal resources with reservoir temperatures at 90–260 °C and for GAPG system using both on-site and off-site geothermal resources.

Through modelling and simulations, this paper, therefore, aims at providing technical and economic recommendations for the industry/government regarding the design, operating, and economic conditions of a successful GAPG system.

2. Methodology

Technical analyses of GAPG system were performed using process simulation package Aspen HYSYS, whereas economic analyses were carried out using cost of electricity approach, net present value, and sensitivity analysis.

2.1. GAPG system simulation

GAPG system was established by hybridising HDR resources in a conventional 500 MW unit coal-fired power plant at the upper Hunter region of New South Wales, Australia. This location was selected as there are considerable medium-to-high grade geothermal resources in 50-km radius of the coal-fired power plants. The distribution of geothermal resources in the upper Hunter region of NSW, Australia is shown in Fig. 1.

The 500 MW unit coal-fired power plant was established according to the original heat and mass balance design of the power cycle [24]. General information of the fossil fuel-only plant can be seen in Table 1, whilst thermodynamic properties of the main streams in the power cycle, including vapour fraction, temperature, pressure, mass flow rate, calculated enthalpy and entropy values, are given in Table 2. The 500 MW unit coal-fired power plant which uses steam Rankine cycle as the base power cycle consisted of (i) a series of high, intermediate, and, low pressure turbines to convert thermal energy into electricity, (ii) a condenser to condense the turbine exhaust, (iii) a pump to circulate the condensate, (iv) a series of high, intermediate, and low pressure feedwater heaters to preheat the condensate, and (v) a boiler to generate steam by burning coal. The flow diagram of the coal-fired power plant is shown in Fig. 2.

Fig. 2 also becomes the power cycle configuration of GAPG system after hybridising geothermal fluid via points A, B, C, and D, which corresponds to four different hybrid configurations. For each