Energy Conversion and Management 74 (2013) 88–101

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

An in-depth assessment of hybrid solar–geothermal power generation

Cheng Zhou [a], Elham Doroodchi [b], Behdad Moghtaderi [a,*]

[a] Priority Research Centre for Energy, Discipline of Chemical Engineering, School of Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia
[b] Priority Research Centre for Advanced Particle Processing and Transport, Discipline of Chemical Engineering, School of Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia

ARTICLE INFO

Article history:
Received 15 January 2013
Accepted 12 May 2013

Keywords:
Hybrid renewable energy system
Solar
Geothermal
Cost of electricity

ABSTRACT

A major problem faced by many standalone geothermal power plants, particularly in hot and arid climates such as Australia, is the adverse effects of diurnal temperature change on the operation of air-cooled condensers which typically leads to fluctuation in the power output and degradation of thermal efficiency. This study is concerned with the assessment of hybrid solar–geothermal power plants as a means of boosting the power output and where possible moderating the impact of diurnal temperature change. The ultimate goal is to explore the potential benefits from the synergies between the solar and geothermal energy sources. For this purpose the performances of the hybrid systems in terms of power output and the cost of electricity were compared with that of stand-alone solar and geothermal plants. Moreover, the influence of various controlling parameters including the ambient temperature, solar irradiance, geographical location, resource quality, and the operating mode of the power cycle on the performance of the hybrid system were investigated under steady-state conditions. Unsteady-state case studies were also performed to examine the dynamic behaviour of hybrid systems. These case studies were carried out for three different Australian geographic locations using raw hourly meteorological data of a typical year. The process simulation package Aspen-HYSYS was used to simulate plant configurations of interest. Thermodynamic analyses carried out for a reservoir temperature of 120 °C and a fixed brine flow rate of 50 kg/s revealed that under Australian climatic conditions (with a typical ambient temperature of 31 °C in summer) a hybrid plant would outperform stand-alone geothermal and solar power plants if at least 68% of its energy input is met by solar energy (i.e. a solar energy fraction of ≈68%). This figure drops to about 19% for reservoir temperatures greater than 170 °C. Case studies also showed that, for a mid-range reservoir temperature of 150 °C, the cost of electricity production can be reduced by 20% when a hybrid plant is used instead of the stand-alone Enhanced Geothermal System (EGS).

1. Introduction

1.1. Background

The rising energy demand, the limited supply of fossil fuels and their detrimental environmental impacts (e.g. global warming) have intensified the worldwide search for cleaner sources of energy [1]. Among renewable energy sources, geothermal energy has a special place largely because of its vast worldwide resources and its capacity to provide base-load electricity due to non-intermittent nature of geothermal energy. One of the key technology options to harness geothermal energy is Enhanced Geothermal Systems (EGS) which are particularly suited to hot granite formations (Hot Dry Rock or HDR) often found in countries like Australia where geothermal resources are predominately non-hydrothermal (due to lack of water) and/or inaccessible due to lack of permeability. The EGS technology is based on extracting the heat from hot granite formations (as high as 250 °C) at depths of 3–5 km underground. In this cyclic approach high pressure water (i.e. "geofluid") is first pumped down a borehole (known as injection well) into a bed of hot fractured rock and forced to travel through the bed capturing the heat content of the rocks. The hot water is then extracted from a second borehole (known as production well) and fed into a binary power plant (typically an organic Rankine-cycle, ORC) where its thermal energy is converted to electricity. The cooled water exiting the power plant is then injected back into the reservoir (i.e. granite formation) to resume the cycle [2].

A major impediment in the development/deployment of EGS in hot and arid climates such as Australia is the cooling issue. Most geothermal resources in Australia are located in the centre of the continent (e.g. Great Artesian Basin) which is an arid region with limited supply of water. As a result, air-cooling is the most viable option for satisfying the cooling demands of geothermal power

* Corresponding author. Tel.: +61 2 4985 4411; fax: +61 2 4921 6893.
E-mail address: Behdad.Moghtaderi@newcastle.edu.au (B. Moghtaderi).

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.05.014

plants in this region. However, the diurnal temperature change (i.e. variation of ambient temperature between day and night) in such climatic regions is usually quite drastic, particularly in summer, and as such air-cooling becomes ineffective during some parts of the day when the air-cooled condenser cannot reject the excess heat of the power plant due to high ambient air temperatures. This, in turn, leads to a considerable reduction in thermal efficiency and fluctuations in the power output [3].

Another inherent problem in implementation of EGS is the low overall efficiency of the power plant due to the low enthalpy of typical geothermal resources. A higher energy utilisation rate is possible if higher grade forms of energy (e.g. solar energy) are incorporated into the system, thereby, uplifting the thermal efficiency.

The issues of air-cooling and low enthalpy resource associated with the application of EGS in hot and arid regions can be alleviated if geothermal and solar energies are effectively hybridised through a combined and integrated technology platform. It is well known that the variation in solar irradiance in a typical day follows a similar trend to that of the ambient air temperature. Therefore, in theory the uplift in thermal efficiency of a hybrid geothermal–solar plant due to the introduction of solar energy should balance the negative impact of the air-cooling on the thermal efficiency when the ambient air reaches its highest daily value. Interestingly, many existing and potentially suitable geothermal sites for EGS applications in Australia are endowed with high quality solar irradiation. Hence, by hybridising solar energy into an otherwise geothermal plant, the average temperature of the working fluid and, thereby, the thermal efficiency and electrical output of the plant can be significantly increased according to the Carnot principle. Current investigations of renewable energy systems have highlighted the high cost of generating electricity using stand-alone renewable power plants [2,4–7] and indeed suggested that one of the most effective approaches to reduce the cost of electricity generation and improve plant efficiency is the hybridisation of different renewable technology platforms [8–11]. In the case of geothermal energy, such hybridisation can also decelerate the depletion of heat content of the geothermal reservoir overtime and hence extend its lifespan.

Given the above background, this study is concerned with an in-depth assessment of hybrid solar–geothermal power generation under conditions pertinent to the Australian climatic conditions. The results and conclusions, however, can be extended to other parts of the world such as Western United State, Mexico and Turkey where high-quality solar and geothermal resources co-exist.

It should be highlighted that the primary focus of the assessment provided in this paper is the technical aspects of the hybrid solar–geothermal concept although a limited series of economic analyses has been included to evaluate and compare the cost of electricity production for various stand-alone and hybrid systems. The capital cost comparison or other types of economic analysis for these systems are beyond the scope of the present paper and are not covered here.

1.2. Past studies on hybrid solar–geothermal power generation concept

Hybrid solar–geothermal power generation has been the focus of many studies over the past few decades, with a range of different hybrid configurations being investigated including:

- *Solar superheating configuration* – where solar energy is mainly used to superheat the working fluid of the geothermal power cycle [7,10–17].
- *Solar preheating configuration* – where solar energy is used to preheat the brine either by increasing the brine temperature or its dryness fraction (i.e. the steam quality) [9,10,14,15,18–22].
- *Geothermal preheating configuration* – where geothermal energy is used to preheat the feedwater in a steam Rankine cycle type solar thermal power plant [8].

A summary of the major studies conducted to date on the hybrid solar–geothermal power generation concept is presented in Table 1. It is reminded that rather than providing an exhaustive list of hybrid solar–geothermal related literature, we discuss those references here that describe key technological breakthroughs in the field of hybrid solar–geothermal power generation. The findings of past studies show that (see Table 1) thermodynamically the thermal efficiency of a hybrid solar–geothermal plant, defined as the power output divided by total heat input, is always higher than a stand-alone geothermal plant and less than a stand-alone solar thermal plant [8,13]. That is mainly due to the greater exergy contents of solar resources compared with geothermal resources. Moreover, the cost of electricity generated from a hybrid solar–geothermal plant is typically higher than the conventional geothermal power plants (i.e. hydrothermal plants) but less than a stand-alone solar thermal plant. That is largely due to the greater capital costs associated with the solar collectors [8,11]. Also past studies show that the application of the solar superheating configuration for some power generation platforms is restricted by the limitations in the design temperature [14].

Unfortunately past studies on hybrid solar–geothermal power generation have largely focused on hydrothermal type geothermal reservoirs under mild to cold climatic conditions in the northern hemisphere. The relevance of the findings of these studies in Australia where as noted earlier geothermal resources are predominately hot dry granite formations (i.e. also known as HDR) and ambient temperatures are generally high is limited. Moreover, as Table 1 shows, most of the geothermal power plants examined in the past studies were fitted with water cooled condensers whereas due to scarcity of water resources in Australia the air-cooled Organic Rankine Cycle (ORC) type binary units are the preferred platforms in this country [2,23,24]. In such power cycles, as discussed before, the heat sink (i.e. air) is largely subjected to the diurnal swings in the ambient temperature. Studies of air-cooled hybrid solar–geothermal plants in hot climatic conditions are generally scarce. Narrowing this knowledge gap is the motivation behind the present study.

1.3. Aims and objectives of the present study

The work presented in this paper is part of a larger program of study underway at the University of Newcastle (Australia) on hybrid renewable energy systems. The primary goal of this work was to undertake a systematic techno-economic assessment of the hybrid solar–geothermal plants in an Australian context where air-cooled binary ORC geothermal plants are employed as part of an EGS scheme. To achieve the broad objectives of the project, the effect of controlling parameters such as the ambient temperature, solar irradiance, resource quality and power cycle configuration on the performance of the hybrid plant were systematically examined under steady-state conditions in terms of both the power output and the cost of electricity production. The results were then compared with the performance of the corresponding stand-alone geothermal and solar thermal plants assuming the same energy resources and energy intensity. Also three hypothetical case studies were performed for three different Australian geographical and climatic zones to evaluate the performance