Applied Energy 131 (2014) 158–170

Contents lists available at ScienceDirect

Applied Energy

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

Hybrid solar–geothermal power generation: Optimal retrofitting

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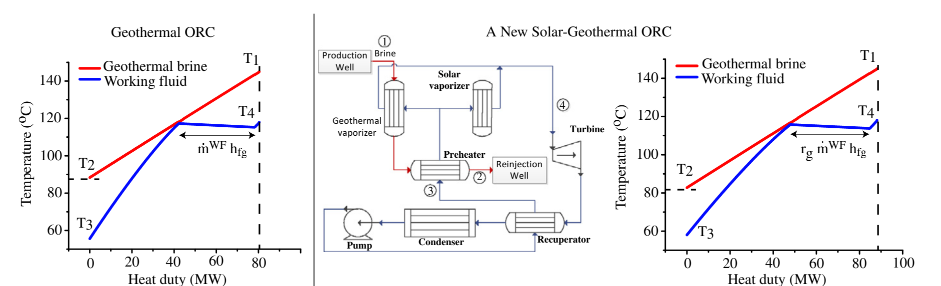
HIGHLIGHTS

- Developed a coupled model for a hybrid geothermal–solar system.
- New hybrid geothermal–solar gives higher efficiency than combined systems.
- Optimized the operation of the hybrid geothermal–solar system.
- Identified synergy between two renewable energy sources.

GRAPHICAL ABSTRACT



Pinch diagram of geothermal preheater+vaporizer showing 80.5 MW utilization of geothermal energy

Pinch diagram of geothermal preheater+vaporizer showing 88 MW utilization of geothermal energy

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 9 May 2014
Accepted 9 June 2014

Keywords:
Organic Rankine cycle
Geothermal energy
Solar energy
Parabolic trough
Retrofit

ABSTRACT

A model is developed for an existing organic Rankine cycle (ORC) utilizing a low-temperature geothermal brine including the performance characteristics of the components. The model is validated with a set of 7200 operation data collected in one-year. The operation of the ORC is optimized allowing for variable number of working turbines. The developed model is retrofitted with a low-temperature solar trough system. A new hybridization strategy is developed that achieves a significant boost in the net output power of the system compared to the geothermal ORC. This hybridization approach enables better extraction of geothermal energy. The hybrid system shows higher second-law efficiency (up to 3.4% difference) compared to combined individual geothermal and solar systems. With this hybridization approach, the hybrid system is a better option than individual geothermal and solar system at all ambient temperatures.

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1. Introduction

Access to clean, affordable and reliable energy has been a cornerstone of the world's increasing prosperity and economic growth since the beginning of the industrial revolution. Our use of energy in the twenty-first century must also be sustainable [1]. The renewable energy resources have received enormous interest in the last decade due to their potential of sustainability. Of particular interest are the medium and low temperature resources due to their ubiquitous availability. The organic Rankine cycle (ORC) is one of the promising cycles used to obtain electricity from various thermal energy resources such as solar, biomass and geothermal [2–14]. Among these energy resources, geothermal energy is an important component for transition to renewable energy sources. This source of energy is cheap, sustainable, and dispatchable. Furthermore, it has the same potential as the global energy need [15–21]. Each energy resource has its own strengths and weaknesses. Hybridization of renewable energy resources is an approach to compensate

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http://dx.doi.org/10.1016/j.apenergy.2014.06.010
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Nomenclature

Latin

$\dot{m}$	mass flow rate (kg/s)
$\dot{q}_{sol}$	thermal energy input by the solar trough to ORC
$\dot{V}$	volumetric flow rate (m^3/s)
$\dot{W}$	power (kW)
e_1	shadowing parameter
e_2	tracking error
e_3	geometry error
e_4	dirt on mirror
e_5	dirt on receiver
e_6	random error
f_f	drive frequency of fan (rpm)
f_p	drive frequency of pump (rpm)
h_{fg}	specific enthalpy of vaporization (J/kg)
r_g	ratio of mass flow rate in the geothermal vaporizer
w	specific work (J/kg)
x	specific exergy (J/kg)
ACC	air-cooled condenser
DNI	direct normal insolation
GB	geothermal brine
ORC	organic Rankine cycle
P	pressure (kPa)
s	specific entropy (J/(kg K))
T	temperature (°C)
WF	working fluid

Greek

α	absorptance of pipe
$\Delta\dot{Q}^{GB}$	additional energy extracted from the geothermal source
$\Delta\eta_{II}$	the incremental second-law efficiency
ΔP_{pump}	pressure rise by the pump (kPa)
ΔT_p	pinch at the vaporizer (°C)
ΔT_{tu}	superheat at inlet of turbine (°C)
η_s	isentropic efficiency of turbine
$\eta_{II,g}$	geothermal efficiency (modified second law efficiency of cycle)
$\eta_{II\text{-}H}$	second-law efficiency of the hybrid system
η_I	thermal efficiency (first law efficiency of cycle)
ρ_m	clean mirror reflectance
τ	transmittance of glass

Superscript

GB	geothermal brine
L	liquid
sat	saturation
V	vapor
WF	working fluid
air	air

Subscripts

max	maximum
min	minimum
amb	ambient
pa	parasitic
tu	turbine

the drawbacks of an individual system with the other one. The optimal hybridization strategy depends on the type of the energy resources combined [22]. The critical question in any hybridization approach is: Does hybrid system perform better than the linear combination of the involved individual systems?

Here, we focus on an existing ORC power plant utilizing a low-temperature geothermal brine and we hybridize this ORC with a low-temperature solar trough system. The solar system can be incorporated into the system into two ways: (1) heating configuration to provide more thermal energy in heating section of working fluid of ORC and/or (2) cooling configuration to be incorporated in an absorption chiller system to boost the condensation capacity of the ORC [23–25]. Here, we incorporated the solar trough system in the heating configuration.

Hybridization of solar thermal and geothermal energy has been considered in the literature [5,26,27]. Astolfi et al. [26] have studied a hybrid binary geothermal–solar system utilizing an intermediate enthalpy geothermal source. The ORC in [26] is of supercritical type and has Isobutane as its working fluid (WF) with geothermal brine at 150 °C. The considered system employs an air-cooled condensation system (ACC). The solar source is employed in series with the geothermal brine to increase the mass flow rate and/or maximum temperature of the WF. The authors have analyzed the performance of the system at ambient temperature of 15 °C. To obtain the output power as a function of ambient temperature for fixed direct normal irradiation (DNI), the authors have offered a correction function that correlates the output power linearly to the ambient temperature. They suggested that the slope of the function depends on the maximum temperature of the cycle. The authors have determined the first law-efficiency of the hybrid geothermal–solar system. With thermal energy input by the solar source from 0% to 80% of that of geothermal source, the first law-efficiency increases almost linearly from 13.5% to 17.2%. Lentz and Almanza [28] have studied three configurations for hybridization of a flash geothermal power plant with a solar trough system. The hybridization is aimed to boost the mass flow rate of the WF. They have suggested that incorporation of solar system to reheat the condensed fluid after the condenser is the winner option. The heated fluid is combined with the brine coming out of the well. This hybridization approach leads to less salinity of mixture of vapor and the brine and reduces the scaling problem which results into longer lifetime of the system. Mir et al. [29] have investigated the hybridization of a flash geothermal system with a solar system. Two scenarios were considered: (1) utilization of solar system to boost the electricity of the hybrid system and (2) utilization of solar system to reduce the flow rate of the geothermal brine by keeping a constant electricity generation.

Greenhut [27] has studied various configurations for hybridization of a solar trough system with a binary geothermal power plant. The geothermal system utilizes a geothermal source with the temperature of T^{GB} = 132.2 °C and $\dot{m}^{GB}$ = 47.31 kg/s and has Isopentane as its WF. In the first configuration, the author employed the thermal energy by the solar system to increase the superheat of the vapor after the vaporizer (superheat concept). In the second configuration, he used the trough system to preheat the brine before entering to the ORC (brine preheat concept). In the third configuration, he utilized thermal energy by the solar system to reheat the outgoing brine and reinject it to the system (brine recirculation concept). In the fourth configuration, he combined the second and third configurations and formed a brine preheat-recirculation configuration. A portion of solar energy is used for preheating and the other portion is used in the recirculation heating. In the fifth configuration, he introduced brine cascade reheat concept in which a portion of outlet brine from a unit of the power

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