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Thermo-economic analysis of a hybrid solar-binary geothermal power plant

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ABSTRACT

An integrated model is developed for a hybrid solar-binary geothermal system. The system consists of an existing ORC (organic Rankine cycle) utilizing a low-temperature geothermal brine and a solar trough system. The hybrid system is based on the new parallel configuration developed by Ghasemi et al. (2014) which performs better than combined individual systems. The operation of the hybrid system is optimized maximizing the net power output and evaluated for representative days of year 2013. The design of the solar trough system is based on the objective of maximizing net power of the hybrid system at nominal conditions. This design results in a 7% solar share of net power output. The optimized constant-flow and variable-flow solar configurations lead to 5.5% and 6.3% boost in the net power output compared to the optimized geothermal ORC, respectively. The LEC (levelized electricity cost) is used as an economic performance metric to analyze the hybrid system. The analysis shows that LEC can be decreased by 2% for the hybrid compared to a stand-alone geothermal system. An optimization of the stand-alone geothermal ORC results in 8% reduction in LCE suggesting as a better option compared to the hybridization of the geothermal system at this time.

1. Introduction

The rising trend in global energy demand and environmental problems stimulates a move toward renewable energy resources [1,2]. The medium- and low-temperature resources are among the most appealing options due to their ubiquitous availability [3–10]. All renewable energy resource and corresponding energy conversion technology feature advantages and limitations. Hybridization of various resources is an approach to cover the limitations of a resource with the other one [11–16]. The hybridization approach depends on the type of the resource and the economical benefits of the hybridization approach [17–19]. Among the renewable energy resources, solar energy is the most abundant resource and can in principle cover a multiple of the global energy needs [20]. There are mainly two approaches to harvest this resource of energy, solar-photovoltaic and solar-thermal. In general, the first approach is mostly used at low optical concentrations and the second approach is at high optical concentrations. Here, we focus on the second approach, concentrated solar-thermal harvesting. In spite of the abundance of solar energy, its transient nature makes it non-dispatchable unless utilized along with a storage system [21,22]. To overcome this drawback of the solar harvesting, one can hybridize this resource with a dispatchable non-renewable [17], or renewable energy resource [21,22]. Geothermal energy [23] is a good candidate for this purpose due to large potential and geographical coincidence of geothermal resources with high solar irradiation areas. For example, available geothermal resources are located at the boundaries of Pacific Ocean (namely West United States, Central America, West of South America, and East Asia), South Europe and Africa. Thus, this synergy promises an approach for dispatchable utilization of solar energy. Moreover, as shown for instance in Ref. [21,22], the use of solar energy can increase the, relatively low, conversion efficiency of geothermal energy. In addition to large-scale solar systems, small-scale solar driven ORC (organic Rankine cycles) have received interest for cost-effective decentralized energy supply especially in remote regions [24–27].

We focus on hybridization of a binary geothermal system and a solar trough system. In binary geothermal systems, ORC is an efficient method of energy harvesting. Different aspects of this method

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Nomenclature

Latin

$\dot{m}^{air}$	mass flow rate of air in ACC (kg s^{-1})
$\dot{m}^{b}$	mass flow rate of brine (kg s^{-1})
$\dot{m}^{HTF}$	mass flow rate of heat transfer fluid
$\dot{m}^{WF}$	mass flow rate of working fluid (kg s^{-1})
A	area of collector aperture (m^2)
AF	annuity factor
a	year
ACC	air-cooled condenser
Cap	capital cost (USD kW^{-1})
d	order of day in a year
DNI	direct normal irradiance (Wm^{-2})
E_{gen}^{ann}	annual electricity output (MWh)
EES	Engineering Equation Solver
EIA	Energy Information Administration
e_1	shadowing loss parameter
e_2	tracking error parameter
e_3	geometry error parameter
e_4	dirt on mirror parameter
e_5	dirt on receiver parameter
e_6	random error parameter
F^{ann}	annualized present value of fixed cost (USD)
f	solar share based on thermal energy output
GB	geothermal brine
h	specific enthalpy (kJ kg^{-1})
h_v	convection heat transfer coefficient of air in partial vacuum (W m^{-2} K^{-1})
HTF	heat transfer fluid
HX	heat exchanger
I	total investment cost (USD)
I^{ann}	annualized present value of total investment cost (USD year^{-1})
K	incidence angle modifier
LEC	levelized electricity cost (USD MWh^{-1})
LT	local time
n	lifetime of the plant (year)
OM^{ann}	annualized present value of operation and maintenance cost (USD year^{-1})
OM	operation and maintenance
ORC	organic Rankine cycle
P	pressure (kPa)
r	interest rate value (%)
R_f	reflectivity of clean mirror
SQP	sequential quadratic programming
T	temperature (°C)
TO	thermal oil
u^{wind}	wind speed (m s^{-1})
USD	US dollar
υ^{HTF}	velocity of heat transfer fluid (m s^{-1})
$\dot{W}$	output work (kW)
WF	working fluid
X	specific exergy (kJ kg^{-1})

Greek

ΔT	superheat at inlet of turbine (°C)
η_I	thermal efficiency (First law efficiency of cycle)
$\eta_{II,g}$	geothermal efficiency (Modified second law efficiency of cycle)
η_{opt}	optical efficiency of absorber
α	absorptance of absorber
θ	incidence angle (°)
κ	thermal conductivity (W m^{-1} K^{-1})
ρ_m	clean mirror reflectance
τ	transmittance of the glass envelope
ϕ	latitude of solar trough system (°)

Superscript

i	inner
o	outer
ann	annualized

Subscript

max	maximum
min	minimum
amb	ambient
glas	glass envelop of solar trough system
HTF	heat transfer fluid
pipe	absorber pipe of solar trough system
pump	pump of geothermal system

such as design, optimum working fluid and optimum operation conditions are widely investigated [28–35]. The literature provides a backbone for rational design and operation of geothermal ORCs. Moreover the hybridization of this dispatchable resource with other renewable resources such as biomass and solar has been investigated and several strategies for efficient performance proposed. However, all of these approaches are in the context of utilizing the additional thermal energy in series for the vaporization process while geothermal brine is used to preheat the WF (working fluid) [14,17,19,36–39]. Ghasemi et al. [21,22] developed a new approach for hybridization of a binary geothermal and solar trough system that performs better than the combined individual systems. In this approach, the thermal energy from the solar trough system is utilized in parallel with the geothermal brine in the vaporization process. The introduction of solar system in this configuration has three main advantages over the geothermal ORC: 1) boosts the available thermal energy and consequently increased net output power; 2) provides higher utilization of geothermal energy compared to sole geothermal ORC to further increase the net power output 3) Keep the system dispatchable.

In addition to technical merit of hybrid solar-geothermal systems, several studies assessed the economic performance of hybrid geothermal-solar system. Zhou [15] investigated the technical and economic performance of a hybrid geothermal-solar system in supercritical and subcritical ORCs. They suggested that hybridization of a geothermal plant using a supercritical ORC with solar energy boosts the annual electricity production by 19%. Zhou et al. [16] assessed the cost of electricity from hybrid solar-geothermal system and compared it with stand-alone solar and geothermal systems. They concluded that the LEC (levelized electricity cost) can be reduced by 20% when a hybrid plant is used instead of the stand-alone enhanced geothermal system (i.e. geothermal systems which extract heat from hot granite formations by injecting water into the ground). Astolfi et al. [14] analyzed a combined concentrating solar power system and a geothermal binary plant based on a supercritical ORC. In their economic analysis only the incremental net