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Technoeconomic and exergy analysis of a solar geothermal hybrid electric power plant using a novel combined cycle

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ABSTRACT

A novel Solar Geothermal Hybrid Electric Power Plant (SGHEPP) based on the hybridization of an existing binary Geothermal Electric Power Plant by adding a solar-powered steam-Rankine topping cycle is proposed. The proposed SGHEPP has several benefits. First, the hybridization scheme does not require the binary bottoming cycle to be physically modified or operated outside its design conditions. Second, the proposed SGHEPP has a higher turbine inlet temperature, which results in higher solar-to-electricity conversion efficiencies. Third, the daily energy production for the SGHEPP peaks on sunny summer days when electricity prices are generally highest. And fourth, the design reduces the consumption of geothermal resources, which can extend the useful life of declining and marginal geothermal fields. Annual simulations are run for a representative plant in southwestern Turkey and used to assess the plant's energetic, exergetic, and economic performance. The performance of four designs are compared that differ with respect to how the geothermal resources are managed and the size of the solar field. A representative design has an incremental solar efficiency of 12.2% and consumes up to 17% less brine than a similar stand-alone geothermal plant. The calculated solar based LCOE for each design is in the range of 163–172 USD MWh^{-1}.

1. Introduction

Solar and geothermal energy are both considered sustainable, environmentally friendly, and carbon free energy resources. Solar Thermal Electricity (STE) power plants and Geothermal Electric Power Plants (GEPP) are now each commercialized technologies, and they are being adopted in specific places in the world where energy resources and economic factors are favorable. Globally, many areas have large solar and geothermal resources, and in these regions the two resources can be utilized in a single Solar Geothermal Hybrid Electric Power Plant (SGHEPP) that can potentially create significant economic value through several synergies [1]. From a thermal perspective, most GEPPs in arid climates use dry cooling towers, resulting in a significant drop in efficiency and power output as the air temperatures rise during the summer months, which is often when electricity prices are highest [2]. Arid climates typically also have large solar resources that peak on sunny summer days, and in contrast to a GEPP the power output from a SGHEPP typically peaks on sunny summer days. STE power plants without storage have variable and intermittent output, and while adding thermal energy storage can reduce variability and intermittency, practically this variability and intermittency can never be eliminated. In contrast a SGHEPP without storage can generate electricity continuously or operate as a dispatchable power plant the entire year. From a cost perspective, capital costs savings are found by sharing equipment between the solar and geothermal portions such as the power block of the hybrid power plant. Additionally, operations and maintenance costs can be reduced compared to separate STE and GEPPs [1]. From a geothermal resource perspective, the usable lifetime of a GEPP is based on the life of the geothermal resource, which can decline over time as the resource is exploited. Decreasing the rate at which the geothermal brine is extracted by replacing some of the geothermal energy with solar thermal energy can help to lengthen the working lifetime of the geothermal field, leading not simply to a longer lifetime, but also to more actual gallons of brine being extracted during its lifetime [3].

Based on the characteristics of a geothermal resource, one of three types of power blocks is generally used in GEPPs: (1) dry steam; (2) flash (both single and double); and (3) binary cycles [4]. Dry steam and flash GEPPs utilize an open cycle where the geothermal brine passes directly through the turbine, while the binary cycle GEPPs utilize a closed cycle with an organic working fluid and are sometimes referred to as Organic Rankine Cycles (ORCs). Generally, in comparison to dry

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Nomenclature

Abbreviations

BC	bottoming cycle
CSP	concentrating solar power
DNI	Direct Normal Irradiance
GEPP	geothermal electric power plant
HTF	heat transfer fluid
IAM	Incidence Angle Modifier
LCOE	Levelized Cost of Electricity
ORC	Organic Rankine cycle
PT	Parabolic Trough
SGHEPP	solar geothermal hybrid electric power plant
STE	solar thermal electric
TC	topping cycle
TMY3	Typical Meteorological Year 3

Variables

$A_{coll,o}$	nominal collector area, m^2
AF	annuity factor, %
a_0, a_1, a_2	constants for IAM, units vary and are as shown in Table 1
c_1, c_2, c_3, c_4	constants for thermal losses, units vary and are as shown in Table 1
f_{shad}	shading factor
$G_{b,n}$	direct normal irradiance, W m^{-2}
i	interest rate, %
IC	investment cost, USD
L	loss, units vary
M_s	Solar Multiple, –
OM	annual operation and maintenance cost, USD yr^{-1}
$\dot{Q}$	heat transfer, W
T	temperature, °C
t	time, hour
$\dot{W}$	work, W
y	lifetime

Greek letters

η	efficiency, fraction or %
θ	angle of incidence, °

Subscripts

abs	absorber
amb	ambient
b	beam
BC	bottoming cycle
byn	binary
coll	collector
cond	condenser
cpl	coupling
D	destruction
db	dry bulb
dct	dry cooling tower
e	exit
ew	east-west tracking surface
f	focus
gen	generator
geo	geothermal
HX	Heat Exchanger
i	inlet
inc	incremental
inj	injection
L	loss
LA	loss per area
n	normal
o	nominal/dead state
opt	optical
orc	organic Rankine cycle
p	pump
s	solar
SF	solar field
shad	shading
TC	topping cycle
th	thermal
tur	turbine
u	useful

steam and flash geothermal cycles, binary GEPPs are the most cost effective system for geothermal resources with a wellhead temperature of less than 180 °C, which are the most abundant resources found worldwide [5,6]. In 2014, the most widely used type of GEPP in terms of units was the binary cycle, with 203 units in operation globally, generating 1245 MW_e of power [4]. However, in terms of installed generating capacity, binary GEPPs account for only 10.4% of the global total. According to annual reports, binary cycle technologies are still under development and their installations are growing more rapidly than the other types of GEPPs [4].

Several researchers have proposed combining solar thermal and geothermal technologies into a SGHEPP to take advantage of the economic and thermal benefits of a hybrid system. To date, the SGHEPPs proposed use a solar field to increase the enthalpy of the geothermal brine in an open single- or double-flash Rankine cycle [3,7–9] or of the working fluid in a binary cycle [1,2,10–16]. The operational modes studied can typically be classified into one of two categories based on the performance objective. The first operational mode is termed *Constant Geothermal Mode* herein where the geothermal brine mass flow rate is maintained constant, and the addition of solar thermal energy maximizes the power output from the SGHEPP. The second is termed *Conserve Geothermal Mode* herein where geothermal resources are conserved, and a constant thermal input to the power block is maintained by using solar thermal energy to replace some of the geothermal energy by allowing the geothermal brine flow rate to vary.

SGHEPP using open flash Rankine cycles were initially studied by Lentz and Almanza [7,8] who proposed a model for adding a Direct Steam Generation solar field to the Cerro Prieto geothermal flash plant in Mexico. The objective is to obtain a 10% increase in steam flow by adding parabolic trough (PT) collectors at different points in the geothermal cycle. In the proposed system the geothermal brine is run directly through the PT collectors, which they noted may cause scaling problems in practice. Mir et al. [9] modeled adding solar heat to a single-flash GEPP in Northern Chile by integrating PT collectors, and both Constant Geothermal and Conserve Geothermal Modes were studied. The Constant Geothermal Mode yielded an 11.36% increase in annual power production, while the Geothermal Conservation Mode yielded a 10.36% reduction in geothermal resource use. In another recent study, Cardemil et al. [3] analyzed the impact of hybridizing a single-flash and a double-flash GEPP with a solar concentrating collector field in northern Chile. Energy and exergy analyses of the designed cycles were performed for four different geothermal reservoir characteristics for both Constant Geothermal and Conserve Geothermal Modes. Results show that integrating solar thermal collectors into