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Performance assessment of an integrated solar combined cycle in the southern of Algeria

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HIGHLIGHTS

- It is to assess the performance on an ISCC.
- A simple model to estimate the DNI is suggested.
- A thermodynamic model is then highlighted.
- Solar to electricity efficiency has been discussed.

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ABSTRACT

Among all the hybrid solar thermal technologies available up to now, the Integrated Solar Combined Cycle (ISCC) is nowadays the most efficient system for converting solar energy into electricity. This power plant is a combination of a parabolic trough solar field with a conventional combined cycle. In the present article, the performance of an ISCC plant under southern Algerian climate has been investigated. To do so, a thermodynamic model has been developed to evaluate solar radiation intensity as well as the overall performance of the hybrid solar power plant.

The analysis has shown that solar to electricity efficiency could reach up to 14.4% during sunny periods. Furthermore, an overall thermal efficiency of about 60% is feasible. It has also been found that the amount of electricity produced increases with several operation parameters such as the time of the day, the mass flow rate of the heat transfer fluid and the angle of incidence on the collector surface.

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1. Introduction

The use of parabolic trough technology for power generation and mechanical drive applications is dated as far back as 1913. At this year, the first solar power plant has been built in Al Maadi, Egypt for pumping water irrigation (Duffie and Beckman, 1991; Raafat, 1994). More than one century later (during the 1980s), nine Solar Electric Generating Systems (SEGSs) have been installed in California desert. Then years after, the integration of parabolic trough technology into the fossil fuel combined cycle has been introduced to improve solar energy conversion. The combination of solar field with a combined cycle results in the so called Integrated Solar Combined Cycle (ISCC). This concept has attracted much more interest during the last decade. Typical ISCC is illustrated in Fig. 1. It mainly consists of two gas turbines, an oversized steam turbine and a large parabolic trough solar field.

The first analysis of the ISCC in Tunisia has been carried out by Allani et al. (1997). The authors have obtained that the ISCC is more profitable than SEGS. Dersch et al. (2004) have used GateCycle and IPSEpro in order to compare the performance of the ISCC to SEGS and Combined Cycle (CC) power plants. They have concluded that the ISCC is the most efficient. Kane and Favrat (1999) have focused on the heat exchangers of the ISCC. They have proved that the ISCC with double pressure-reheat and smaller solar field provides better performance.

Bakos and Parsa (2013) have used TRNSYS-STEC software for the economic assessment of the ISCC in Southern Greece. It has been found that the ISCCS more cost-effective. Cau et al. (2012) have also used the GateCycle to analysis the performance of the proposed innovative concept of the ISCC with CO2 as a HTF. The results have shown that the solar energy conversion efficiency is around 25%. Li and Yang (2014) have compared an (ISCC) of two-stage solar input with one-stage. Where the proposed configuration of (ISCC) with two-stage solar input improves the solar-to-electricity efficiency by 1.2%. And later, Li and Yang (2015)

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Nomenclature

A	Area, (m^2)
N_c	Number of collectors
H_h	Monthly mean daily global solar irradiation on a horizontal surface (kWh/m^2·day)
$H_{d,h}$	Monthly mean daily diffuse solar irradiation on a horizontal surface (kWh/m^2·day)
H_i	Monthly average daily direct irradiation on a horizontal surface (kWh/ m^2·day)
I_h	Monthly mean hourly global solar irradiation on a horizontal surface (kWh/m^2)
$I_{b,h}$	Monthly mean hourly direct solar irradiation on a horizontal surface (kWh/m^2)
$I_{d,h}$	Monthly mean hourly diffuse solar irradiation on a horizontal surface (kWh/m^2)
I_i	Direct solar irradiation on a tilted surface (W/m^2)
r_t	Daily ratio for global radiation
r_d	Daily ratio for diffuse radiation
LHV	Lower Heating Value, (J/kg)
nj	Number of day of year
n_o	Real day of the year
$\dot{Q}$	Useful energy, (MWth)
W_C W_G and W_{ST}	Compressor, gas and steam turbine works (J/kg)
h_1 h_2 h_3 and h_4	Enthalpy of the steam at the turbine inlet and outlet, enthalpy at the condenser and the pump exit (kJ/kg)
C_{pg}	Specific heat of flue gas (kJ/kg·K)
C_{pa}	Specific heat of air (kJ/kg·K)
$T_{2'}$, $T_{3'}$	Temperature entering and leaving of chamber combustion (K)
$\dot{Q}_{HL,rec}$	Heat loss from the receiver in the solar field (W/m^2)
$\dot{Q}_{HL,pip}$	Heat loss from the pipes in the solar field (W/m^2)
$\dot{Q}_{sol,field}$	Thermal power from the solar field, (MWth)
Q_{fuel}	Fuel energy input (MWth)
Q_{add}	Heat supplied in the combustion (MWth)
Q_{ex}	Heat of exhaust gases in HRSG (MWth)
Q_{SG}	Heat of steam generation (MWth)
N	Power production (MWe)
N_{AUX}	Auxiliary power consumption (MWe)
T	Temperature, (K)
U_0, U_1	Constant determined from empirical test, (W/m^2 °C)
U_L	Heat transfer loss coefficient, (W/m^2·K)
E_{Loss}	Performance factor that accounts for losses from ends of heat collector element
R_{shad}	Performance factor that accounts for mutual shading of parallel collector rows during early morning and late evening
f_{clean}	Cleanliness factor

Greek symbols

$K(i)$	Angle of incidence modifier (°)
i	Angle of incidence (°)
φ	Latitude (°)
δ_s	Declination solar (°)
ω_s	Sunrise hour angle (°)
i_z	Solar zenith angle (°)
$\dot{m}_a$	Air mass flow rate, (kg/s)
$\dot{m}_f$	Fuel mass flow rate, (kg/s)
$\dot{m}_s$	Steam flow rate at the operational condition, (kg/s)
$\dot{m}_g$	Mass flow rate of the exhaust gases, (kg/s)
η_m	Isentropic efficiency of the steam turbine (%)
η_p	Isentropic efficiency of the pump (%)
η_o	Optical efficiency

Subscripts

a	air
amb	ambient
abs	absorber
ap	aperture
c	collector
o	optical
sol	solar
h	hour
min	minute
s	second
f	fluid
in	inlet
out	outlet

Abbreviations

ISCC	Integrated Solar Combined Cycle
IGCC	Integrated Gasification Combined Cycle
CSP	Concentrated Solar Power
CC	Combined Cycle
DNI	Direct Normal Irradiation
GSR	Global Solar Radiation on a horizontal surface data
DSR	Diffuse Solar Radiation on a horizontal surface data
HRSG	Heat Recovery Steam Generator
HSSG	Heat Solar Steam Generator
GT	Gas Turbine
ST	Steam Turbine
FP	Feed water Pump
PTC	Parabolic Trough Collector
HTF	Heat Transfer Fluid
SEGS	Solar electric generating system

proposed a two novel (ISCC), where studied the impacts of solar multiples on system performance with two pressure level DSG solar fields (ISCC-2DSG), with and without of thermal storage. Popov (2014) has been used Thermoflex together with SAM for comparing the two proposed concepts for the ISCC. Where the first one, photovoltaic panels is used to power the inlet cooling system of the gas turbine and is the second one, the inlet cooling system is accomplished with an absorption chiller supplied with DSG Linear Fresnel field. The results showed that the novel configurations provide better thermal efficiency than traditional concept. Baghernejad and Yaghoubi (2011) have suggested a model in MATLAB for the energy and exergy analysis of the ISCC of Yazd, Iran. The simulations have shown that the exergy efficiency of the ISCC can reach 46.8%, while the exergy destruction cost reduced by 14.82%. Khaldi (2012) has proposed a program in Cycle-Tempo for the energy and exergy analysis of the ISCC that have been built in Algeria. The author has found that the energy and the exergy efficiencies of the power plant can achieve 56% and 53% respectively. Derbal-Mokrane et al. (2012) and Behar et al. (2011) have interested on the performance analysis of the ISCC of Hassi R'mel, Algeria. The first authors have used TRNSYS for the simulation, while the second authors have developed a mathematical program using visual FORTRAN. Zhu et al. (2015) developed a model of a three pressure level NGCC with solar integration using the software IPSEpro. They calculated solar thermal-to-electrical efficiencies in

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