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Optimization, selection and feasibility study of solar parabolic trough power plants for Algerian conditions

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ABSTRACT

In the present study, optimization of two parabolic trough solar thermal power plants integrated with thermal energy storage (TES), and fuel backup system (FBS) has been performed. The first plant uses Therminol VP-1 as heat transfer fluid in the solar field and the second plant uses molten salt. The optimization is carried out with solar multiple (SM) and full load hours of TES as the parameters, with an objective of minimizing the levelized cost of electricity (LCOE) and maximizing the annual energy yield. A 4E (energy–exergy–environment–economic) comparison of the optimized plants alongside the Andasol 1 as reference plant is studied. The molten salt plant resulting as the best technology, from the optimization and 4E comparative study has been chosen for the viability analysis of ten locations in Algeria with semi-arid and arid climatic conditions. The results indicate that Andasol 1 reference plant has the highest mean annual energy efficiency (17.25%) and exergy efficiency (23.30%). Whereas, the highest capacity factor (54.60%) and power generation (236.90 GW h) are exhibited by the molten salt plant. The molten salt plant has least annual water usage of about 800,482 m^3, but demands more land for the operation. Nevertheless the oil plant emits the lowest amount of CO_2 gas (less than 40.3 kilo tonnes). From the economic viewpoint, molten salt seems to be the best technology compared to other plants due to its lowest investment cost (less than 360 million dollars) and lower levelized cost of electricity (LCOE) (8.48 ¢/kW h). The viability study proposes Tamanrasset, as the best location for erection of a parabolic trough solar thermal power plant with a low LCOE of 7.55 ¢/kW h, and a high annual power generation (more than 266 GW h). According to the feasibility analysis, the semi-arid and arid Algerian sites are suitable for realization of PTSTPP with integrated TES and FBS; especially the southern locations (19°N–32°N, 8°W–12°E).

1. Introduction

Algeria is located in north-west Africa, between 19° and 38° north latitudes and 8° west and 12° east longitudes, with a total area of 2,381,741 km^2. The country is by far the largest African country and has significant variations in its climatic, topographic and socio-economic characteristics [1]. Algeria, with a total population of 37.9 million inhabitants (till January 2013), from more than 8.68 million in 1948, has experienced a growth of over 250% in population during the last 50 years [2].

Algeria is one of the most important players in African and world energy markets, both as a significant hydrocarbon producer and as an exporter. According to the International Energy Agency (IEA) statistics for 2011, Algeria has produced a total amount of energy of 145,846 kTOE (1,696,188 GW h). The main sources of this energy production are from crude oil (52.10%), followed by gas (44.80%). The energy needs have increased due to population growth and economic development over the last decades. The energy consumption of Algeria was 41,852 kTOE (486,739 GW h) in 2011 with CO_2 emissions more than 123,475 kilo tonnes [3].

Algeria is experiencing a continual increase in population, energy consumption, gases emissions, and major changes in economic trends in the last decades. In view of these factors and abiding the Kyoto Protocol, the Algerian government has launched the renewable energy and energy efficiency program. This program was launched in 2011, with a total cost of 120 billion USD [4]. The program leans on a strategy focused on developing and expanding the use of inexhaustible energy resources, such as solar

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Nomenclature

A	collector's aperture area (m^2)
C_{env}	environmental cost according to CO_2 rejected (US$)
CF	capacity factor
C_{inv}	total investment cost (US$)
$C_{O\&M}$	annual operating and maintenance costs (US$)
crf	capital recovery factor
d_r	relative earth–sun distance
$\dot{Ex}_i$	exergy received by the SF (kW h)
$\dot{Ex}_{in}$	total exergy received by the PB (kW h)
$\dot{Ex}_u$	useful exergy delivered by the receiver (kW h)
f	dilution factor ($1.3 * 10^{-5}$) [30]
f_{backup}	fossil fill fraction ($0 < f_{backup} < 1$)
h_{SFo}	enthalpy at the outlet solar field (kJ/kg)
h_{SFi}	enthalpy at the inlet of the SF (kJ/kg)
H_0	monthly mean daily extraterrestrial solar irradiance on a horizontal surface (kW/m^2)
H_{BN}	monthly mean daily direct normal irradiance ($kW\,h/m^2$)
$\overline{H}_{BN}$	monthly direct normal irradiance (kW/m^2)
$\overline{\overline{H}}_{BN}$	annual direct normal irradiance (kW/m^2)
H_D	monthly mean daily diffuse solar irradiance on a horizontal surface (kW/m^2)
H_G	monthly mean daily global solar irradiance on a horizontal surface ($kW\,h/m^2$)
I_{BH}	monthly mean hourly direct solar irradiance on a horizontal surface (kW/m^2)
I_{BN}	monthly mean hourly direct normal irradiance (kW/m^2)
I_{sc}	solar constant (kW/m^2)
I_D	monthly mean hourly diffuse solar irradiance on a horizontal surface (kW/m^2)
I_G	monthly mean hourly global solar irradiance on a horizontal surface (kW/m^2)
k_d	annual discount rate
$\dot{m}_{PB}$	mass flow rate of the HTF in the PB (kg/s)
$\dot{m}_{SF}$	mass flow rate of the HTF in the SF (kg/s)
N	depreciation operation time of the system (years)
ND	number of the days in a year
PG_{net}	net power generation (kW h)
$\dot{Q}_{backup}$	thermal energy must be supplied in the FBS (kW h)
$\dot{Q}_i$	total incident solar energy received by collector's aperture area (kW h)
$\dot{Q}_{in}$	total thermal energy received by the PB (kW h)
$\dot{Q}_u$	total useful energy delivered by the SF (kW h)
$\dot{Q}_{total}$	the total energy needed to reach the thermodynamic state (kW h)
S	sunshine duration (hr).
S_0	maximum possible sunshine duration (day length) (hr).
s_{SFi}	entropy at the inlet of the SF (kJ/kg °C)
s_{SF0}	entropy at the outlet of the SF (kJ/kg °C)
T_{amb}	ambient temperature (K)
T_{sun}	temperature of the sun (K)
w_{des}	design cycle thermal requirement (kW)
δ	declination angle (°)
ω_s	sunrise hour angle (°)
φ	latitude (°)
$\eta_{cyclesdes}$	design point cycle efficiency
$\eta_{I,O}$	overall energy efficiency of the plant
$\eta_{I,PB}$	energy efficiency of the PB
$\eta_{I,SF}$	energy efficiency of the SF
$\eta_{II,O}$	overall exergy efficiency of the plant
$\eta_{II,PB}$	exergy efficiency of the PB
$\eta_{II,SF}$	exergy efficiency of the SF
θ	angle of incidence (degree)
Δ_{tes}	total number of desired storage hours (h)

Abbreviation

4E	energy–exergy–environmental–economic
FBS	fuel back-up system
CSP	concentrating solar power
DNI	direct normal irradiance
DSG	direct steam generation
HPT	high pressure turbine
HTF	heat transfer fluid
IEA	international energy agency
kTOE	kilotonne of oil equivalent
LCOE	levelized cost of electricity
LPT	low pressure turbine
NREL	National Renewable Energy Laboratory
PB	power block
PTC	parabolic trough collector
PTSTPP	parabolic trough solar thermal power plant
SAM	Solar Advisor Model
SF	solar field
SM	solar multiple
STEC	solar thermal electric components
TES	thermal energy storage
TMY	typical meteorological year

energy in order to diversify energy sources and prepare Algeria for tomorrow. The strategic choice is motivated by the enormous potential of solar energy, in which it is one of the most important sources in the world.

The geographic location in the Sunbelt region, climatic conditions such as low precipitation, plenty of unused flat land in proximity to transmission grids, road networks, and the abundant sunshine in Algeria are conducive for the production of electricity from concentrating solar thermal power [5]. The concentrating solar power (CSP) technology incorporates four different alternatives: parabolic trough power plants, linear Fresnel power plants, solar power towers and dish-Stirling systems. The parabolic trough power plant is considered as one of the most proven, mature and commercial concentrating solar power for implementation in arid and semi-arid regions [6]. It focuses sunlight onto a solar receiver by using mirrors, which is finally converted to heat or electricity. This technology ranges from remote power systems of few kilowatts to grid-connected power plants of hundreds of megawatts [5]. In general parabolic trough solar thermal power plant (PTSTPP) consists of a solar field, power block, and thermal energy storage (TES). In addition to these systems, a fuel back-up system can be used for enhancing the plant's potential [7]. The levelized cost of electricity (LCOE) is a decisive parameter for feasibility analysis of solar thermal power plants [8]. The LCOE depends on plant configuration, working fluid, performance of the plant, and capital, operation and maintenance costs of the plant. Large number of researchers and academicians across the globe are working in this direction. Most of these studies and projects are based on oil or water-steam as heat transfer fluids in the solar field. Reddy and Kumar [6] analyzed a design for a solar parabolic trough field for power generation using oil and water as working fluids, and studied the feasibility of this technology under Indian climatic conditions. A comparative study in terms of design, yield and investment analyses between plants using oil and water as heat transfer fluid (HTF) with integrated solar thermal storage has been conducted by Feldhoff et al. [9]. According to them, the main