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Methodology of determining the optimum performances of future concentrating solar thermal power plants in Algeria

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A B S T R A C T

The newly adopted version of the National Renewable Energy Program of Algeria offers the country the possibility to integrate 27% of renewable energy in the national energy mix. Preservation of fossil resources, diversification of electricity production and contribution to sustainable development are among challenges that face the country nowadays. The objective of this paper is to propose a methodology and outline a procedure to determine the best configuration and the optimum design of future solar thermal power plants with minimum levelized cost of electricity (LCOE) and maximum annual power generation as objectives. Our study is based on a Concentrating Solar Power (CSP) plant of capacity of 50 MW to be erected in Hassi R'mel City, in the south of Algeria. In this methodology, the size of the solar field, the fossil fill fraction of backup system and full load hours of storage are optimized for the minimum LCOE using the concept of solar multiple. Moreover, different models, technologies and scenarios for parabolic trough and central tower receiver power plant are presented. LCOE presents a basis of comparison for weighted average costs of different power generation technologies. It is clearly shown that the solar power plant based on central receiver tower technology with 48% of backup system and 8 h of storage is the most attractive and optimum plant. It was also found from financial analysis that the LCOE can decreases by 13% with less interest rate and tax deductions.

1. Introduction

It is obvious that energy is the major concern of the 21st century. In order to meet the world energy demand and reduces the effects of fossil fuels, renewable energies are becoming more and more interesting. Indeed, electricity generation from solar energy is currently one of the main research areas in the field of renewable energy. In a country such as Algeria, where this source of energy is abundant, it is possible that fossil fuels that generate electricity can be replaced by solar energy. From all solar technologies available for power generation up to now, Concentrating Solar Power (CSP) technologies are now the most competitive commercial solar options for large scale power plants as well as for smaller electricity and heat generating systems. CSP plant has an inherent capacity to store heat energy for short periods of time for later conversion to electricity. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sundown. CSP plants must also be equipped with backup systems based on combustible fuels [1,2]. With these factors, CSP is set to take its place as an important part of the world's energy mix.

The preferred choice for current CSP plants is based on large scale power generation units (often in the range of 20–50 MW) mainly due to their higher conversion efficiency and lower specific capital costs. However, the construction of large-size CSP units requires the availability of large areas and noteworthy capital investments (a typical 50 MWe CSP plant requires a total capital investment of about 250–300 M€ and the availability of about 150–250 ha of land) [3].

Among the CSP technologies, plants based on parabolic trough collector (PTC), using synthetic or organic oil as heat transfer fluid (HTF), are found to be more attractive commercially [4,5]. In such plants, the maximum temperature can be reached to 400 °C and it can be raised up to 540 °C by using molten salt as a HTF, which allowing steam turbines to operate at much greater efficiency [6–9]. The direct steam generation (DSG) in plants with PTC field is

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Nomenclature

I_0	Investment expenditures
A_t	Annual total costs in year t
$M_{t,el}$	Produced quantity of electricity in the respective year in kWh
i	Real interest rate in %
n	Economic operational lifetime in years
t	Year of lifetime (1, 2, … n)
$C_{After\ Tax}$	After tax cash flow in Year n
N	Analysis period in years
$d_{nominal}$	Nominal discount rates

Abbreviations

LCOE	Levelized Cost Of Energy
CSP	Concentrating Solar Power
SAM	System Advisor Model
DSG	Direct Steam Generation
NREL	National Renewable Energy Laboratory
CTRSTPP	Central Tower Receiver Solar Thermal Power Plant
SPT	Solar Power Tower
PTCSTPP	Parabolic Trough Concentrating Solar Thermal Power Plant
DLR	German Aerospace Centre
DNI	Direct Normal Irradiation
TMY	Typical Meteorological Year
HTF	Heat Transfer Fluid
TES	Thermal Energy Storage
NPV	Net Present Value
IR	Inflation Rate
TIC	Total Installed Cost
IRR	Internal Rate of Return
RES	Renewable Energies
FNERC	National Fund of Renewable Energy and Cogeneration
SM	Solar Multiple
FFF	Fossil Fill Fraction
CF	Capacity Factor
FLH	Full Load Hours
PTC	Parabolic Trough Collector
SCA	Solar Collector Assembly
HCE	Heat Collector Element
SONELGAZ	Company of Electricity and gas (Algeria)
BS	Backup System
HSS	Hitec Solar Salt

also an economically viable option [10–16]. Several studies have been carried out to evaluate the performance of PTC technology for power generation [12,17–21].

Solar power tower (SPT) is the second most installed CSP plant technology after PTC, and gradually gaining acceptance [22,23]. Now, some commercial SPT plants are in operation using DSG option [24], and other plants use molten salts as HTF as well as storage medium [25,26]. Behar et al. [27] as well as Ho et Iverson [28], respectively, have presented a review on design of central receiver and SPT system.

Detailed studies on economic aspects of CSP plants have been reported by Feldhoff JF et al. [12], Krishnamurthy et al. [29], and Kost et al. [30]. Feldhoff JF et al. [12], carried out a comparison in terms of techno-economic potential of two references PTC plants (the first one with DSG mode and the other with synthetic oil) of capacity 100 MWe with integrated thermal storage. The study tells that the LCOE of DSG mode is much higher compared to that of synthetic oil based plant integrated with storage system. Furthermore, it was found that there are a few comparative studies between PTC and SPT. Franchini et al. [31], have presented the comparative analysis between two CSP plants, using PTC and SPT technologies.

Currently, for the case of Algeria, just five studies have been carried out to evaluate the performances of CSP plants, three of them for PTC plants and two others for SPT plants. Boukelia et al., have presented two studies; the first one based on the optimization of two parabolic trough solar thermal power plants integrated with thermal energy storage (TES), and fuel backup system (FBS). The first plant is using Therminol VP-1 as HTF in the solar field while the second plant based on molten salt [32]. Then, the second study is performed a thermodynamic, economic and environmental analyses of concentrating solar power plants which assist in identifying the most effective and viable configuration. The results of this study show that Tamanrasset is 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) [33]. Finally, the last study for PTC has been published by Ameur et al., with the scope of determining an optimum design for a projected parabolic trough solar power plant (PTSPP) under Algerian climate through different funding scenarios [34].

For SPT technology, Boudaoud et al., have presented a techno-economic analysis for the implementation of a probable molten salt cavity receiver thermal power plant in Algeria. The System Advisor Model (SAM) has been used to perform the technical performance and the economic assessment for different locations in Algeria. The analysis has shown that hybrid central receiver systems are really attractive solutions for rapid deployment of CSP technology in Algeria [35]. Benammar et al., have developed a mathematical model based on energy analysis for modeling and simulation of SPT plants performances without energy storage. The analysis of the results shows the existence of an optimal receiver efficiency value for each steam mass flow, receiver surface temperature and receiver surface area [36].

Now, there is no comparative study between different CSP technologies, destined for Algerian climate. For this reason and for limited studies represented previously, our study involves estimation of annual electricity output, levelized cost of electricity and capacity factor for different likely combinations of the values of solar multiple, full load hours and fossil fill fraction for plant models. Different scenarios have been simulated using SAM software [37], in order to determine the best configuration and optimum design of a PTC and SPT solar thermal power plant in Algeria with minimum cost of electricity and maximum annual energy to the end user for 50 MW of installed capacity. Finally, a financial analysis has been presented with new scenario concerning loan and taxes.

1.1. New RE program 2015

For the case of Algeria, it has been announced in the renewable energy and energy efficiency program a new motivated CSP projects. In this ambitious program, CSP plants represent about 70% of the total power projects to be installed [38,39]. Moreover CSP can be a competitive source of bulk power in peak and inter mediate loads in the sunniest regions by 2020, and of base load power by 2025–2030 [40].