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Solar thermal power plants – A review of configurations and performance comparison

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ABSTRACT

A detailed review and thermal performance comparison of fifteen power generation technologies including fossil, solar and hybrid options has been presented. The modeling of each part of the power plants has been carried out. For the solar field, a detailed modeling that comprises the heat transfer in the receiver tube, optics of the collector and the heat losses from the piping, has been carried out . In order to develop mathematical models for the fifteen power plants, the gas turbine and the steam turbine have been modeled and results were successively validated. Various integration of solar parabolic trough technology into the three reference Power Conversion Cycles (PCSs) including Brayton cycle, Rankine cycle and combined cycle have been considered. Six performance indicators have been used to rank the configurations. Some of these configurations are originally proposed in the present study and important findings are highlighted.

1. Introduction

Solar thermal power plants are not an innovation of the last few years. Records of their use date as far back as 1878 when a small solar power plant made up of a parabolic dish concentrator connected to an engine was exhibited at the World's Fair in Paris [1,2]. In 1913, the first parabolic trough solar thermal power plant has been implemented in Egypt. After the energy crisis of 1970s, nine parabolic trough power plants were installed during 1984–1991.

Over the last twenty years, R&D efforts on solar thermal power plants have been growing sharply particularly in the US, Spain, Germany, China, South Africa and Australia. As a result significant solar power plants have been installed. These plants are mostly based on the parabolic trough technology as it is the most mature compared with central receiver and linear Fresnel. Indeed, the solar heat from the parabolic trough solar field could be integrated into three power conversion cycles, i.e., Rankine cycle, Brayton cycle or combined cycle.

The integration of parabolic trough technology into the Rankine cycle has been the first applied technique. In the 1980s, a total of nine Solar Electric Generating Systems (SEGSs) have been built in the southern California desert. Since that, many studies have been focused on the solar parabolic trough Rankine-based plants. Poullikkas [3] has studied the economic feasibility of SEGS in the Mediterranean region. The sensitivity analysis has revealed that the implantation of Solar Parabolic Trough – Rankine Cycle, known as SEGS, is strongly related to the size of the plant, the degree of storage and the investment cost. Al-Soud and Hrayshat [4] have focused on the annual performance and economic assessment of a 50 MW SEGS under Jordanian climate. The authors highlight that SEGS might provide better solution for power generation in Jordon and even for MENA countries. Montes et al. [5] have optimized the solar multiple for a SEGS. It has been shown that the optimum solar multiple depends mainly on the solar field size, the design point conditions and the power plant configuration. Deng and Boehm [6] have simulated the performance of a SEGS with three different three cooling systems, i.e., the conventional dry cooling, the conventional wet cooling, and the flattened-tube surface. The authors have indicated that the dry cooling could be an excellent solution for implanting solar power plants in dry climate regions, if some improvements are made such as the use of advanced heat exchange surface. Blanco-Marigorta et al. [7] have interested in the effect of cooling technology on the performance of a SEGS. The authors have found that the lower the operation pressure condenser the attractive the wet cooling; however, the higher the pressure the more attractive is the dry cooling technology. Jones et al. [8] have used TRNSYS software to

Abbreviations: BC, Brayton cycle; CC, combined cycle; CSP, concentrating solar power; DLR, German Aerospace Center; DNI, direct normal irradiation; DSG, direct steam generation; GT, gas turbine unit; HCE, heat collection element; HRSG, heat recovery steam generator; HSSG, heat solar steam generator; HTF, heat transfer fluid; ISCCS, integrated solar combined cycle system; NREL, National Renewable Energy Laboratory; MBD, mean bias difference; PTC, parabolic trough collector; SEGS, solar electricity generating system; ST, steam turbine unit; SR, solar reheat; SS, solar salt; SP, solar preheating; RRC, regenerative Rankine cycle

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Nomenclature

A	area [m^2]
C_f	friction coefficient [-]
D	diameter [m]
f_D	friction coefficient [-]
L	length [m]
k	thermal conductivity [W/m K]
m	mass flow [m^3/s]
Nu_D	Nusselt number based on the diameter D [-]
p	actual pressure [mbar]
p_0	standard pressure [mbar]
T	temperature [°C, K]
V	flow velocity [m/s]
m_R	cooling air mass flow rate [kg/s]
m_k	compressor air mass flow rate [kg/s]
M_f	gas turbine fuel consumption [kg/s]
m_f	fuel mass flow rate [kg/s]

Greek symbols

δ	thickness [m]
ε_{pipe}	pipe roughness [m]
θ	angle of incidence [°]

predict the SEGS VI plant performance on short time scales for sunny and cloudy days. The transient effects such as start-up, shutdown, and cloud have been considered. The authors have found good agreement between model predictions and plant measurements, with errors less than 10%. Larraín et al. [9] have developed a thermodynamic model for predicting the backup fraction required for a SEGS. The model is able to estimate the hourly direct normal irradiance for an artificial month from the monthly means of global horizontal irradiance, and predicts the yearly backup requirement for 24 h operation of the plant. Zarza et al. [10] have built and tested the first commercial SEGS with DSG technology (INDITEP project). The design of the solar field is based on the experience acquired during the DISS project. Manzolini et al. [11] have proposed a SEGS with hybrid solar field that combines the indirect (HTF) and direct (DSG) technology. The proposed design allows improving the overall solar to electric efficiency and it potentially reduces the solar field costs which are a significant part of the total investment costs. Cabello et al. [12] have optimized a SEGS using genetic algorithms. Suresh et al. [13] have used Cycle-Tempo program to analysis the solar thermal aided coal-fired subcritical and supercritical SEGS's. Gupta and Kaushik [14] have investigated the effect of bleed pressure, mass fractions of bleed steam, and the number of feed water heater on the efficiency of 5 MW SEGS. The energy analysis has been indicated maximum energy losses at the condenser followed by solar collector field while the exergy analysis revealed that the solar field is the main source of exergy destruction. Zhai et al. [15] have carried out energy, exergy and cost analysis of SEGS with tri-generation technology based on helical screw expander and silica gel–water adsorption chiller for cooling, heating and power generation. Lentz and Almanza [16] have introduced a new configuration of SEGS that use solar energy to enhance the performance of 100 WM geothermal plant located in Cerro Prieto, Mexico.

Compared with Rankine-based cycles, the idea of integrating solar energy into the Brayton cycle (gas turbine) is very recent. Livshits and Kribus [17] have proposed the use of solar heat collected by a parabolic trough field to improve the performance of steam-injection SHGT. An overall conversion efficiency of 40–55% could be obtained with a solar fraction of up to 50%.

Bianchini et al. [18] has proposed the integration of 26.4 MWe steam injection gas turbine with a steam reforming natural gas reactor that is powered by 3.3 MWth parabolic trough solar field. Selwynraj et al. [19] have carried out an annual exergetic analysis of the steam-injection SHGT over a wide range of operating parameters including compressor pressure ratio, turbine inlet temperature and steam to air fraction. In other work, Selwynraj et al. [20] carried out an economic assessment of the steam-injection SHGT under Indian climate taking into account different operation strategies. Another study of Selwynraj et al. [21] have focused on the annual performance of the steam injection SHGT. Sánchez-Orgaz et al. [22] have evaluated the effect of recuperator effectiveness on the performance of multi-stage SHGT. Turchi et al. [23] have introduced a novel configuration of the solar parabolic trough CC-GT. In other work, Turchi et al. [24] have proposed a configuration of the solar parabolic trough CC-GT, in which the GT exhaust gases are used to supplement the thermal energy storage. Khaldi [25] has suggested the use of air bottoming cycle instead of steam bottoming cycle in the solar parabolic trough CC-GT.

The integration of parabolic trough technology into the combined cycle has also attracting a lot of interests to improve the solar-to-electric efficiency. Allani et al. [26] have studied the technical and economic feasibility of implanting ISCCS in Tunisia. Results have shown that maximum power strategy offers higher potential for CO_2 mitigation. Montes et al. [27] have investigated different solar hybridization sizes of 220 MW ISCCS for the Canary Islands, Spain. El-Sayed [28] has proposed the implementation of ISCCS at Kuraymat, Egypt. Kelly et al. [29] have used GateCycle software to determine the optimal ISCCS with three pressure levels. F. Khaldi [30] has used the Cycle-Tempo program to assess the energy and exergy analysis of the first ISCCS in Algeria. Derbal-Mokranea et al. [31] have used the TRNSYS – STEC software to simulate the annual performance the ISCCS in Algeria. Elhaj et al. [32] have investigated the impact of the SF, the gas turbine and the steam turbine on the performance of ISCCS. Baghernejad and Yaghoubi [33] have focused on the energy and exergy analysis of Yazd ISCCS. On other work, Baghernejad and Yaghoubi [34] have performed the energy and exergy analysis on the ISCCS located in Yazd, Iran. The analysis has revealed that the major energy losses take place at the condenser of the steam cycle. Elhaj et al. [35] have considered the exergy analysis of ISCCS. The authors found that the combustor and solar field are the main sources of exergy losses. Brakmann et al. [36] have highlighted the technical data of Beni Mathar ISCCS, Morocco. In other technical report, Brakmann et al. [37] have reported the design data and the construction progress of Kuraymat ISCCS, Eygpt. Behar et al. [38] have developed a mathematical program to investigate the performance of Hassi R'Mel ISCCS. A fossil-based efficiency of about 67% has been obtained during summer days. Elhaj et al. [39] have developed a mathematical model, to predict the benefits of modifying an existed gas turbine, located in Misurata city (Libya), into an ISCCS. Gamal Elsaket [40] have developed a mathematical code for predicting the performance of ISCCS under Lybian climatic conditions. The author suggests modification of existed gas turbine into ISCCS. the Cau et al. [41] have introduced an advanced ISCCS concept that employs CO2 as a heat transfer fluid. Baghernejad and Yaghoubi [42] have applied multi-objective evolutionary algorithms to determine the optimum solutions that simultaneously satisfy exergetic and economic objectives of 400 MW ISCCS in Yazd, Iran.

Besides the above reviewed articles that have been focused on the performance analysis and feasibilty studies of integrating solar energy collected by a parabolic trough technology into the state-of-the-art power conversion cycles (gas turbine, steam turbine and combined cycle), some authors have carried out a comparative studies between various concepts to select the most efficient for a given objective. Hosseinia et al. [43] have technically and economically compared six thermal power plants including fossil and solar plants. Nezammahalleh et al. [44] have compared the performance of ISCCS to those of SEGS.