Renewable and Sustainable Energy Reviews 81 (2018) 1087–1095

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Technical feasibility of a sustainable Concentrated Solar Power in Morocco through an energy analysis

T. Bouhal[a,b,*], Y. Agrouaz[a,b], T. Kousksou[a], A. Allouhi[b], T. El Rhafiki[c], A. Jamil[b], M. Bakkas[c]

[a] Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME), Université de Pau et des Pays de l'Adour – IFR – A. Jules Ferry, 64000 Pau, France

[b] Ecole Supérieure de Technologie de Fès, Université de Sidi Mohamed Ben Abdellah (USM.B.A), Route d'Imouzzer, BP 242, Fez Morocco

[c] Ecole Nationale Supérieure d'Arts et Métiers ENSAM, Université Moulay Ismail (U.M.I), Marjane II, BP-4024 Meknès Ismailia, Morocco

ARTICLE INFO

Keywords:
Concentrated solar power
Parabolic trough solar collectors
Physical modelling
Heat transfer
Site selection
Morocco

ABSTRACT

Morocco imports about 96% of its required energy needs. Solar energy, as one of the most abundant and valuable renewable energy alternatives in the country, offers interesting opportunities for Morocco. In order to minimize its strong foreign energy dependence, Morocco hosts actually the largest Concentrated Solar Power (CSP) using parabolic trough collectors (PTC) as a technology for converting solar irradiation into thermal energy for electricity generation. The purpose of this paper is to assess the thermal performance of this technology and the potential projects concerned by Moroccan Solar Plan. A physical model is developed to determine flow parameters and heat transfer applied to PTC technology. Annual simulations in six climatic regions in Morocco were carried out. Several suggestions were drawn with regards to the design and parametric studies effectuated under Ouarzazate CSP project. It is found that the location and the climate are determinant parameters on the global performance of the parabolic trough solar collectors.

1. Introduction

The rising economic competitiveness of Concentrated Solar Power (CSP) with fossil fuels will perform a determinant role in the future [1,2]. At present times, the most advanced technology for solar thermal power production is represented by CSP. One principal focus of interest, and a big contributor to the actual popularity of CSP, concerns the desert regions of North Africa [3,4]. The export of electricity to Europe from the desert locations of the Middle East and North Africa (MENA), which receive some of the highest solar irradiation in the world, is considered as the most encouraging near-term prospect for CSP expansion [5,6]. There have been various models and new methods published to optimize the Parabolic Trough Collectors (PTC) and solar air heaters to have better performance applying the method of Least Squares Support Vector Machine [7,8].

Many researchers all through the globe, have been interested by the technical feasibility of CSP plants in different countries. In Tunisia, a work based on the possibility to interconnect concentrating solar power technology with Europe was carried out by Balghouthi et al. [9]. Based on the results of this study, it was found that Tunisia is in an ideal location for the transfer of electricity produced by CSP plants in North Africa to Europe. This study also proposed the CSP Project to be economically competitive provided that the majority of the plant equipments be manufactured locally in Tunisia. In the desert areas of the Middle East and North Africa (MENA), an optimization of dry-cooled parabolic trough (CSP) plants was conducted by Qoaider et al. [10]. Their simulation results show that plants with large thermal energy storage systems and oversized solar field have a better performance, as well as produce power at lower costs in comparison to smaller plants. A conclusion was made, that at a plant site with pre-eminent solar conditions available, the CSP dry-cooled power plants provide an alternative for green power production. The future economics of concentrating solar power (CSP) for electricity production in Egypt were investigated by Shouman et al. [11]. More specifically, a road map strategy for the launch of CSP in the Egyptian markets was presented by them, removing the main barriers for financing and starting market introduction in the peak and medium load segments of the power supply. The conclusion made was that Egypt is the suitable location for CSP projects worldwide.

A feasibility investigation of a CSP power plant in Chile under a Power Purchase Agreements (PPA) model was conducted by Serverta et al. [12]. The roles of upfront and soft financing grants to narrow the gap for the first CSP projects in Northern Chile were highlighted. It was found that CSP technology associated with thermal energy storage suits

* Corresponding author at: Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME), Université de Pau et des Pays de l'Adour – IFR – A. Jules Ferry, 64000 Pau, France.

E-mail address: bouhal.tarik@univ-pau.fr (T. Bouhal).

http://dx.doi.org/10.1016/j.rser.2017.08.056
Received 21 June 2016; Received in revised form 12 June 2017; Accepted 12 August 2017

Fig. 1. Concentrated solar power using a parabolic trough collector: 160 MW power plant, Noor I in Ouarzazate solar complex, Morocco.

better to the demand profile of energy needs.

Morocco has emerged as among the first in establishing regulatory frameworks and policies for promoting renewable energy sources and energy efficiency, especially in the solar and the wind energy sectors in the Mediterranean area [13,14]. Morocco has initiated the most ambitious strategy with the Moroccan Solar Plan (MSP) playing a fundamental role in the MENA region, demanding that 52% of the installed capacity for electricity production is from renewable energies (RCREEE, 2010 [15]). Hence, by 2020, the plan for the installation of 2 GW solar power production capacity using Concentrated Solar Power (CSP) has been adopted. The 160 MW CSP power station Noor I which is a large-gangway parabolic trough CSP plant was officially commissioned in the province of Ouarzazate in Morocco (see Fig. 1). The first phase encloses the construction of 300 MW plant, the second phase involves the construction of 200 MW and 150 MW plants for Noor II and Noor III respectively, and the third phase involves the construction of the Noor IV CSP plant with a capacity of 70 MW [16].

In accordance with the International Renewable Energy Agency (IRENA), the strategic geographical position offers Morocco to become a regional hub with network interconnections. A series of actions have been taken to follow this program, including legislations, the establishment of renewable energy and energy efficiency agencies and the engagement of different domestic and international stakeholders [13–15].

Recently, the Moroccan Agency for Energy Efficiency (AMEE) in collaboration with the National Center of Meteorology has developed a new climatic zoning map for Morocco [17,18]. These new zones divide the climate of Morocco into six parts with the same solar irradiation, altitude and other significant indicators. Each zone is marked by a reference city (Fig. 2). Table 1 regroups the different cities of each climatic zone.

The originality of the present work is to use the proposed zoning to predict the thermal behavior of the potential CSP projects based on PTC technology concerned by Moroccan Solar Plan. In this way, the current study proposes a detailed thermal analysis of PTC technology for concentrated solar power (CSP) under Moroccan conditions. A physical model is presented to analyze the flow parameters and heat transfer applied to parabolic trough solar collectors. A set of simulations in six chosen areas in Morocco was carried out.

2. Physical model

2.1. Parabolic Trough Collector (PTC)

The Parabolic Trough Collector (PTC) which is a sub-technology of the Concentrated Solar Power systems, is the lowest cost large-scale and most proven solar power alternative available today and is also one of the main renewable energy options for electricity production. The power plants based on PTC usually use a Heat Transfer Fluid (HTF) to collect heat energy which makes it possible to integrate this heat in a Rankine water/steam power cycle to generate electricity [19–21]. The PTCs are composed of parabolic trough-shaped mirrors, which reflect the incident radiation from the sun on the solar receiver tube. As illustrated in Fig. 3, the HTF flows across the receiver tube of PTC and is heated up under the effect of incident radiation. Then, the HTF is collected to be sent to the power block, where it passes through a set of heat exchangers and produces superheated steam at high temperatures. The superheated steam drives a steam turbine where rotational mechanical energy is then converted into electricity [22,7,23]. A thermal oil is commonly used as a working fluid that circulate through the absorber tube and transform the solar irradiation into thermal energy and carries heat to heat exchangers or analogous for driving a Rankine steam turbine.

The Parabolic Trough Receiver (receiver tube) (see Fig. 4) comprises of a tube of stainless steel accompanied by a selective metal-ceramic coating enclosed by an evacuated anti-reflective glass tube. The vacuum envelope mainly enables to notably preserve the surface of the absorber from oxidation and to decrease thermal losses at increased operating temperatures.

The vacuum in the receiver tube should be below the conduction band Knudsen gas to decrease convective losses in the annular space, which is naturally preserved near to 0.0001 mmHg. The metal-ceramic multilayer hedge is positioned over the steel tube to afford low thermal emissivity and optimum optical properties with significant absorptivity of direct solar radiation at the temperature of operation to minimize heat radiation. The glass envelope has an outer to minimize both anti-reflective coating and Fresnel reflective losses from the glass surface [7,24,25].

2.2. Mathematical formulation

In the following section, the mathematical model of the receiver tube is presented. This model was performed by dividing the receiver into "n" control volumes (CVs), with temperature continuity at the boundary surfaces (Fig. 5). A characteristic of the CV is shown graphically in Fig. 5, where 'i' and 'i+1' represent the inlet and the outlet sections, respectively. Taking into consideration the characteristic geometry of the receiver, the governing equations have been considered assuming the following assumptions:

- The radial heat fluxes are assumed uniform and normal to the surfaces for each CV and are evaluated at the average temperature between the outlet and the inlet sections $\frac{(T_i + T_{i+1})}{2}$.
- Axial heat conduction inside the HTF is neglected.