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Assessment of a solar parabolic trough power plant for electricity generation under Mediterranean and arid climate conditions in Algeria

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Abstract

In Algeria, the climate is transitional between maritime in the north and semi-arid to arid in the middle and the south. The Sahara which represents more than 80% of the total area of Algeria is characterized by the high level of solar energy potential. In the other hand, concentrating solar thermal technologies represent 70 % of the total power to be installed in the framework of the national plan of renewable energy and energy efficiency which consists of installing up 22000 MW of power generating capacity from renewable sources between 2011 and 2030 to achieve. The most important part of this plan is dedicated to the parabolic trough technology. In this purpose, this article presents an assessment of a plant of 100 MW for electricity generation based on parabolic trough technology. This plant will be located in four typical sites of Algerian climate conditions (Tamanrasset, Bechar, Ghardia and Alger). The NREL's SAM software (system Advisor Model) is used to evaluate the plant's energetic and economic performances such as monthly energy production, annual energy output and Levelized cost of energy (LCOE).

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Keywords: Solar energy, parabolic trough, techno-economic, SAM, Algeria.

1. Introduction

The Algerian energy sector has historically been at the centre of the country's development notably in the recent years where the electricity demand reached more than 10%. Many indicators make Algeria an ideal country for the implementation of the Concentrating Solar Thermal plants (CSTP), such as its geographic situation in the solar belt region with an ideal Direct Normal Irradiation level. In this way, Algeria envisages the substitution of the fossil energies by the renewable energy, especially solar energy.

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The government of Algeria has committed itself to develop solar energy as its largest renewable energy source; to cover 20% of the national electricity needs by 2030 with renewable energy and 35% in 2040[1]. The long term goal is to be met primarily from the concentrated solar thermal power plant which would make it among the world's most ambitious CSTP programs [2].

In July 2011, Algeria inaugurated its first Concentrating Solar Power plant. It is a hybrid 150 MW integrated solar combined cycle system (ISCCS) with 30 MW of solar output. Many other ambitious projects are in different stages of consideration, as seen in Table 1.

In this purpose, this article presents a preliminary attempt towards the conditions and parameters making the solar parabolic trough power plant as a technical feasible and economic viable technology for electricity production under various Algerian climate conditions. An output of 100 MW has been taken as reference case in order to value whether the implementation of this technology is economically feasible.

Table 1, New CSTT proposed projects in the Algerian investment plan

Data	Proposed projects name			Total
	SPPII	SPPIII	Hassi R'Mel II	
Location	Naama	Meghair	Hassi R'Mel	
Projected operation date	2013	2014	2012	
Overall output capacity (MWe)	400	400	400	1200
Net Solar output capacity (MWe)	70	80	70	220
Estimated cost x10^6 US$	285	322	285	892

2. Solar parabolic trough technology : A brief description

Solar parabolic trough plant, shown in figure 1, uses parabolic trough shaped mirror reflectors to focus the sun's direct beam radiation on a linear receiver located at the focus of the parabola, as shown in Figure 1. A heat transfer fluid (HTF) circulates through the receiver and returns to a series of heat exchangers in the power block where the fluid is used to generate high pressure superheated steam. The super-heated steam is then fed to a conventional reheat steam turbine/generator to produce electricity. With the sunlight concentrated by about 70-100 times, the operating temperature achieved are in the range of 350-550°C [3]. Another existing and interesting option is called Integrated Solar Combined Cycle (ISCC), in which two different thermodynamic cycles, a steam-turbine Rankine cycle and gas-turbine Brayton cycle, are combined in a single system through a Heat Recovery Steam Generator (HRSG) [4]. The ISCC systems allow the achievement of a significant improvement in the conversion efficiency of solar energy, reduce the importance of energy storage system [5] and reduce the solar energy production costs [6].

An alternative for the integration of a parabolic trough solar field in a steam turbine power plant is generating steam in the solar field called the direct steam generation technology (DSG). In this technology, the water is used and converted directly to steam within the heat collection pipes of the collector field and then used immediately to drive the plant's steam turbine without the need for heat exchangers [7]. Parabolic solar troughs are usually aligned with their long axes from north to south and they are mounted on supports that allow them to track the sun from east to west across the sky. These supports may be made of Steel or Aluminium [8].

The solar parabolic trough technology is the most developed, and it has been commercialized in various solar power plants over the world [9]. From the available CSP technologies, parabolic trough system is the most widespread today, with around 29 plants in operation and around 1220 MWe of installed power in the world, corresponding to 96.3% of the total operational CSP as of the beginning of 2011. The first parabolic trough systems were installed in 1912 in Egypt for powering an irrigation system. The capacity of this facility was 500 kW[10]. Most of the plants in operation are located in Spain with 1000 MW already connected as of October 2011[11], thanks to the eleven active parabolic trough power plants: solova of 150 MW, Andasol of 100MW, Ibersol Ciudad Real of 50 MW, Alvarado I of 50 Mw, La Florida of 50 MW, Majadas de Tiétar of 50 MW, La Dehesa of 50 MW, Palma del Rio 1 of 50 MW, Palma del Rio 2 of 50 MW and Manchasol 1 of 50 MW. USA is the second world's country with higher parabolic trough plants installed with the nine solar power plants of SEGS in California (354 MW) which developed by Luz international limited between 1984 and 1990 [12,13]. About the ISCC technology, there are many plants in operation in particular in North Africa and Middle East countries and in Italy (Sicily) with the Archimede plant of 750 MW in which 5 MW is coming from solar energy. This plant was inaugurated in July 2010.

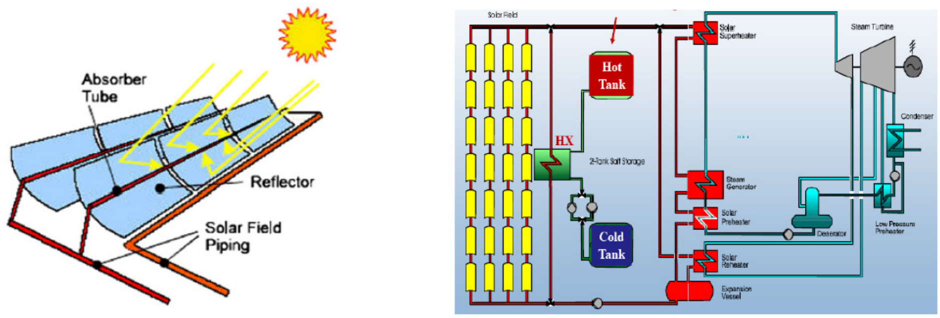

Fig.1, Parabolic trough: functional principle (left) and operational scheme of the Andasol power plant (right)

3. Algeria topography and its solar potential

Algeria is situated in the centre of North Africa between the 38–35° of latitude north and 8–128° longitude east, it has an area of 2, 381,741 km^2. The Sahara represents 86% of the area of the country. The climate is transitional between maritime (north) and semi-arid to arid (middle and south). According to a study of the German Aerospace Agency (DLR), Algeria has with 1.787.000 km² the largest long term land potential for the CSTP. Solar radiation fall between 5.6 kWh/m2 and 7.2 kWh/m^2, this corresponds to 1700 kWh/m²/yr in the north and 2650 kWh/m²/yr in the south, it is considered as being one of the best insolated areas in the world. The average solar duration over the quasi-totality of the national territory exceeds 2000 hours annually and may reach 3900 hours in the Sahara. The technical and economical potential for electricity generation by CSTP in Algeria is about 170000 TWh [14].

4. Simulation Study

The climatic conditions are a decisive parameter to determine the suitability of such site for the implementation of CSP technologies that does not appear to be economical on sites with DNI below 1800 kWh/m^2/year [15]. In this study, three representative sites covering all the southern region of Algeria have been chosen to simulate the proposed solar tower power plant as following:

- **Tamanrasset** (Arid region): located in the south extreme of Algeria (latitude 22°.47' N, longitude 5°.31' E, altitude 1377 and sum of direct normal irradiation is 2691 kWh/m2/year). The overall mean temperature is about 21.7 °C. The overall mean value of wind speed is about 3.2 m/s.
- **Bechar** (semi-arid region): located in the south western region of Algeria (latitude 31°.37' N, longitude 2°.14' W, altitude 772 and the sum of direct normal irradiation is 2417 kWh/m^2/year), The overall mean temperature is about 20.9°C. The overall mean value of wind speed is about 4.4 m/s.
- **Ghardaia** (semi-arid region): located in the middle southern region (latitude 32°.4' N, longitude 3°.08' W, altitude 468 and the sum of direct normal irradiation is 1800 kWh/m^2/year), The overall mean temperature is about 21.3°C. The overall mean value of wind speed is about 3.7 m/s.
- **Algiers** (Mediterranean climate)**:** located in the coaster region of Algeria (Latitude 36°.45' N, longitude 3°.00'E, altitude 116 and the sum of direct normal irradiation is 1517 kWh/m2/year). The overall mean temperature is about 17.8 °C. The overall mean value of wind speed is about 2.5 m/s.

Figure 2 presents the average daily Direct Normal Irradiation (DNI) by months for a typical year of these four sites. From this figure, we can see clearly that the irradiation level is high (> 5 kWh/m^2/d) over the year at Tamanrasset and Bechar. The peak is reached in February and March, respectively. Concerning Ghardaia site, the irradiation level is high during only five months; May, June, August, September and October. Algiers site is characterized by high level of irradiation during four months; June, July, August and September. The daily average DNI was found 7.56 kWh/m^2, 7.04 kWh/m^2, 4.68 kWh/m^{2}and 4.12 kWh/m^2 at Tamanrasset, Bechar, Ghardaia and Algiers, respectively.

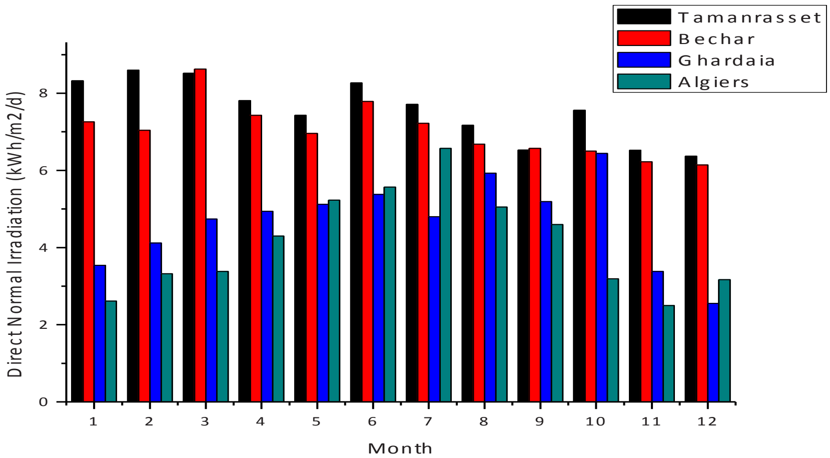

Fig.2 Average Direct Normal Irradiation per month at the four sites

4.1. Characteristics of the proposed plant of parabolic trough technology

The parabolic trough plant subjected to this study is consisting of 915,600 m^2 of solar field reflector based on the one of LS3 (LUZ solar collector, third generation). The plant uses 210 loops, each one has an aperture of 4360 m^2 with a solar multiple of 2. These collectors are fitted with a vacuum tube receiver of Schott PTR70 2008 type which has a heat loss of 166.25 W/m. Various design parameters of these collectors are given in table 2. The alignment of the collectors is in the north-south direction and its axis of direction is parallel to the horizontal plan. The heat transfer fluid (HTF) used in this plant is the Therminol VP-1. The thermal storage is able to store thermal energy for six hours using solar salt. The plant's baseline parameters are summarized in table 3.

Table 2, LS3 collector characteristics

Parameter	Value
Aperture width	5.75 m^2
Reflective aperture area per SCA	545 m^2
Length of collector assembly	100 m
Number of modules par assembly	12
Length of single module	8.33 m
Focal length	2.1 m
Mirror reflectivity	0.94

4.2. Estimation of the plant's energy output

The Analysis of energy yield and economic feasibility of the plant proposed have been carried out using National Renewable Energy Laboratory's (NREL) SAM software [16]. SAM provides modelling capability for several technologies including the CSTPP technologies [17]. SAM combines an hourly simulation model with performance, cost and finance models to calculate energy output, energy costs and cash flows [8].

Table 3, Design Characteristics of the proposed parabolic trough power plant

Characteristics	Value
Total plant capacity	100 MWe
Total land area	3,103,900 m2
Condenser type	Air-cooled
Collectors and Solar field	
Total field reflector area	915,600 m2
Number of loops	210
Single loop aperture	4360 m2
Solar multiple (for 6 hours of thermal storage)	2
Water usage per wash	0.7 L/m2 aperture
Number of washes per year	63
Row spacing	15 m
Number of field subsections	2
Thermal receiver and HTF properties	
Receiver type	Schott PTR70 2008
Absorber tube inner diameter	0.066 m

Absorber tube outer diameter	0.07 m
Receiver diameter	13.33 m
Absorber material type	304L
HTF type	VP-1
Design loop outlet temperature	391 °C
Design loop inlet temperature	293 °C
Thermal Energy Storage(TES)	
Full load hours of TES	6 hours
Storage type	Two tank
Storage fluid	Solar salt
Storage volume	27941.9 m3
Tank diameter	29.8 m
Estimated heat loss	0.66 26 W/m2-K

In order to evaluate the performances of the plant considered in this work, a typical meteorological year (TMY) data set of the three sites considered has been used, which contains hourly values for the DNI, ambient temperature, wind speed, sun angle, atmospheric pressure and solar azimuth angle for one complete year. About the plant's energy yield calculation, the SAM use a global mathematical model composed of four sub-models, each of them representing a stage of the conversion cascade, solar-electricity. It's to note that each stage of the plant performances calculation requires some parameters and data. The details of these calculations as various mathematical equations can be found in Ref. [17].

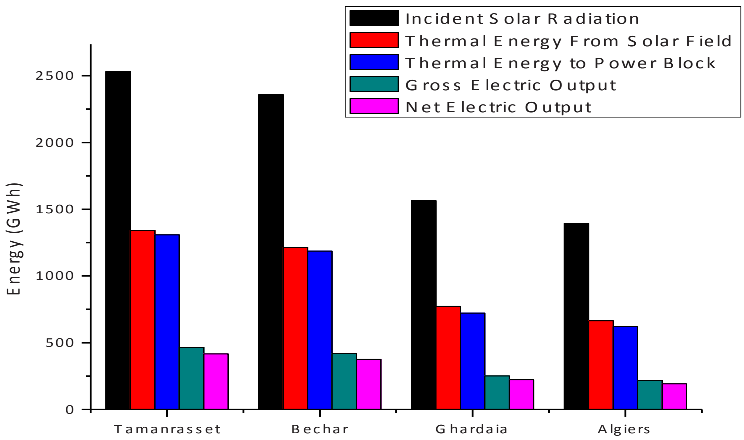

Fig. 3, The parabolic trough power plant Waterfall Chart

The plant waterfall chart from solar energy to net power output which shows the performance of each system component as power flows through the system is shown in Fig. 3. The first bar shows the amount of solar radiation collected by the solar field in the proposed sites. Each other consecutive bar shows losses associated with the following sequential transfers of solar energy and heat into electrical power, such as optical errors in the heliostats, heat losses in the receivers, thermal and mechanical losses in the power block and last the parasitic power which is required to operate pumps and fun of the plant. Each vertical bar shows a step of conversion while showing the optic, thermal, mechanic and electric losses in the solar tower system, as shown in figure 3. The annual energy produced by the tower plant is about 415 GWh, 376.6 GWh, 223 GWh and 261.8 GWh at Tamanrasset, Bechar, Ghardaia and Algiers, respectively. The high annual efficiency of solar- net electric conversion was recorded at Tamanrasset and Bechar with 16.4% and 16 % and the lower was at Algiers with 13.8%. It can clearly be seen the difference between the annual energy production which is very important between Tamanrasset and Algiers sites, which is about 1.6 time. These and other annual performances such as the capacity factor and the annual water used are calculated and summarized on table 4.

Table 4- Annual Simulation Results

Simulation results	Value			
	Tamanrasset	Bechar	Ghardaia	Algiers
Gross electric output (GWh/y)	465.3	419	251	237
Capacity factor (%)	44.2	39.6	24.5	21.1
Global efficiency (solar to electricity (%)	16.4	16	14.2	13.8
Annual water usage (m3)	84,863	79,830	65,576	62,030

The values of electric output of the parabolic trough power plant every one hour were obtained from the simulation and the results in term of monthly production are shown in figure 4. It can be seen that the monthly variation of the net energy production, for each site, almost follows the monthly variation of the direct normal irradiation. The results show that very high power values are reached over the year in Tamanrasset and Bechar, while Algiers presents the lower monthly energy production during most months of the year and Algiers in the other months. The results show also that the high energy values were reached over the year in Tamanrasset and Bechar and between May and August in Algiers. The peak power reaches 41.8 GWh and 41.5 GWh in Bechar and Tamanrasset in Mars and June, respectively. The months of June and July are characterized by the highest value in Ghardai and Agiers, they are about 26.5 GWh and 37.3 GWh, respectively. The most important remark is that the monthly power production is almost the same in Tamanrasset and Bechar in the most months of the year (7 months).

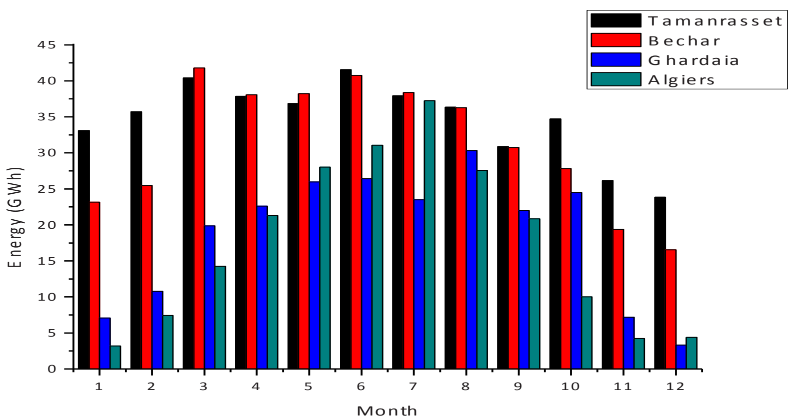

Fig. 4, Power Output versus Months of a Year

4.3. Economic feasibility study

To study the economic feasibility of a solar power system, different methods could be used to evaluate different figures of merit of the systems. Each method has its own advantages, disadvantages, limitations and some conditions to be satisfied so that it can be applied [18]. In this study, the calculation of both real and nominal Levelized Cost of Energy (LCOE) were performed, using the annual project cost incorporating both direct (heliostats, receiver and storage costs) and indirect cost (Engineering, Procurement and Construction costs). For an analysis from the point of view of a public service, calculation is simplified by omitting the different taxes (insurance…) and the land is offered by the state. The details of equations used for calculating the LCOE can be found in [15, 17]. The economical assumptions and data made for making simulations on SAM software are presented in Table 5.

Table 5, Assumptions and Data

Assumptions and data	Value
Life time	30
Real discount rate (%)	8
Nominal discount rate (%)	10.7
Inflation rate (%)	2.5
Direct costs	
Solar field cost ($\$/m^2$)	200
HTF system cost ($\$/ m^2$)	68
Storage cost ($/kWht)	50
Power block ($/kWe)	870
Contingency (% of direct costs)	10
Indirect costs	
Engineering, Procurement and Construction (% of direct costs)	13
Other costs (% of direct costs)	3.5
Total installed cost per capacity ($/kW)	5,940
Operation and Maintenance costs	
Fixed ($/kW-year)	70
Variable ($/MWh)	3

Figure 5 illustrates both real and nominal Levelized Cost of Energy (LCOE) of the power tower plant studied in each of the three locations. The simulation results indicate that Tamanrasset site yields the best LCOE. The real LCOE is found to vary between 11.93 c$/kWh at Tamanrasset, 13.3 c$/kWh at Bechar, 21.3 c$/kWh at Ghardaia and 29.58 c$/kWh at Algiers, while the nominal LCOE can reach 15.09, 16.82, 26.93 and 37.4 c$/kWh in Tamanrasset, Bechar, Ghardaia and Algiers, respectively.

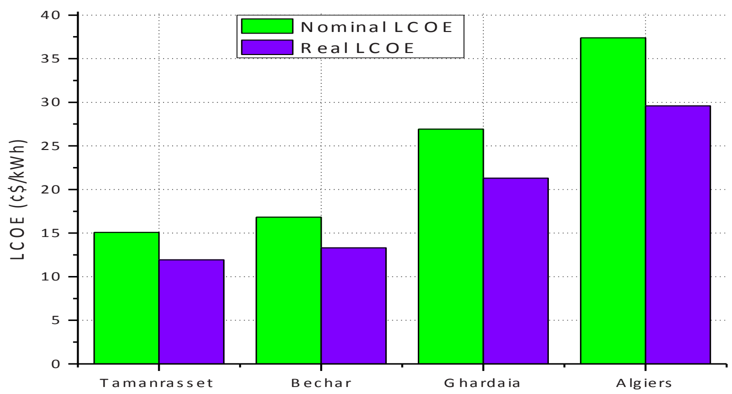

Fig.5, LCOE for the Power Plant Studied

In order to determine the dominant cost fraction of the whole plant, figure 6 exhibits the relative contribution of each project cost on the real LCOE. From this figure, one can see that the project cost is as a majority made up of solar field cost which represents 36.75% of the total cost, the power block 16.43%, and indirect cost also being big contributors with 15.97%.

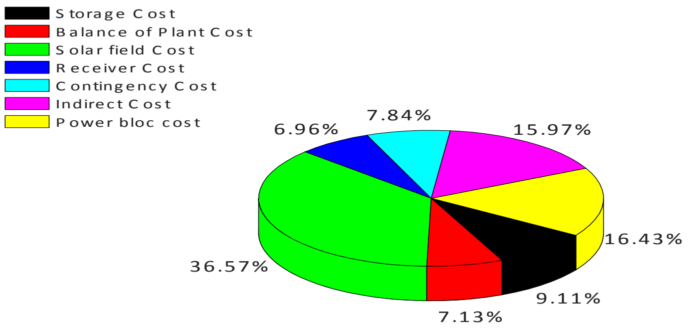

Fig. 6, The Relative contribution of each project cost for the proposed plant at Tamanrasset

5. Conclusion

A preliminary investigation for the techno-economic evaluation of CSTT at four representative sites at Algeria has been made in this assessment. In order to analyze the economic feasibility of these technologies, a 100 MW power plant based on parabolic trough system has been taken as reference case for this work. The SAM software has been used to simulate the plant considered in four locations. It's obvious that CSTT offer interesting opportunities for Algeria which is characterized by inexhaustible solar radiation, notably in the Sahara. It's indispensable to exploit its abundant solar energy resources through different ways like implementing a number of CSTT in order to diversify its energy sources and protects the environment.The Levelized Cost Of Energy generated by the solar parabolic trough plant at Tamanrasset (11.93 c$/kWh) is lower than those of ECOSTAR study of [19]. In the other hand Bechar site yields a very encouraging value of LCOE 13.3 (c$/kWh). These results confirm some previously studies which have shown that Tamarasset is the most favorable site for electricity generation via solar systems [20, 21, 22, 23]. It is evident that the suggested power plant needs considerable capital investment. Economically, this project can be classified in the large scale projects yielding long term return favored by the Algerian state. Finally, it is obvious that a series of sensitivities study is indispensable in order to determine the conditions which make this technology profitable and more economically feasible.

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