Parametric Study of the installation of a Solar Power Tower plant under Saharan Climate of Algeria: case study of Tamanrasset

Mohamed Abbas*

Nachida Kasbadji Merzouk**

Zoubir Belgroun

Zahia tigrine

Hanane Aburidah

Unité de Développement des Equipements Solaires (UDES), EPST/CDER
Route Nationale N° 11, BP 386 Bou Ismail, Tipaza
*abbasdreams@gmail.com
**nkmerzouk@gmail.com

Abstract— **The Concentrating Solar Power plants (CSTP) represent 70 % of the total power to be installed in the framework of the Algerian 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. These technologies incorporates three essential and different designs the parabolic trough, the Dish Stirling System and the power tower. The aim of this work is to carrier out a feasibility study of a solar tower plant in the Saharan climate of Algeria in order to study whether the installation of this kind of power generation is economically feasible. In this way, a parametric study of several parameters is carried out to investigate the least cost feasible option of the implementation of this technology. The site of Tamanrasset has been chosen and the NREL's SAM software (Solar Advisor Model) was used to simulate the proposed plant.**

Keywords-Concentrating Solar Power, Solar Energy, Electricity, Power tower, Receiver, Economic feasibility, DSG

I. INTRODUCTION

The search for a substitute to replace conventional energy sources has increased the importance of concentrated solar thermal power technologies (CSP) notably in the countries situated in the solar belt, such as Algeria. The CSP plants can play a prominent role in the future Algerian energy mix notably with the National Plan of Renewable Energies Development and Energy efficiency. In this ambitious program, CSP plants represent about 70% of the total power to be installed [1], see table 1.

In this purpose, this article presents a preliminary attempt towards the conditions and configurations making the solar tower power as a technical feasible and economic viable technology for electricity production under Algerian climate. In this study, Two configurations have been considered; the molten salt and the direct steam generation. Two representative sites covering climatic zones of Algeria have been chosen to simulate the proposed solar tower power plant configurations. An output of 30 MW has been taken as reference case.

The NREL's SAM software (Solar Advisor Model) is used to evaluate the energetic performances two plant configurations in the two sites proposed and also to study their economic feasibility in the second section.

TABLE I. NEW PROJECTS OF CSP PLANTS IN THE ALGERIAN INVESTMENT PLAN

Data	Location		
	Meghair	*Naama*	*Hassi R'Mel II*
technology	Solar-gas hybrid	Solar-gas hybrid	Solar-gas hybrid
Name	SPPII	SPPIII	SPPIV
Capacity (MW)	80	70	70
Estimated cost 106 US$	322	285	285

II. SOLAR POWER TOWER TECHNOLOGY DESCRIPTION

A. Basic concept

Solar power tower is characterized by the centrally located large tower. This kind of CSP technologies uses a thousand of two axis tracking mirrors called heliostats to reflect the solar radiation onto a receiver located on top of a tall tower, where the solar energy is absorbed by a heat transfer fluid (molten salt, water, liquid sodium or air) which is heated up to temperatures of 500-1000 °C, then used to generate steam to power a conventional turbine which converts the thermal energy into electricity as shown in figure1. A power tower system is composed of five essential components: heliostats, receiver, heat transport and exchange, storage and controls [2].

The heliostats design must ensure that radiation is delivered to the receiver at the desired flux density at minimum cost. Receivers are made of ceramics or the metals stable at high temperature. A variety of receiver shapes has been considered, including cavity receivers and cylindrical receivers [3].

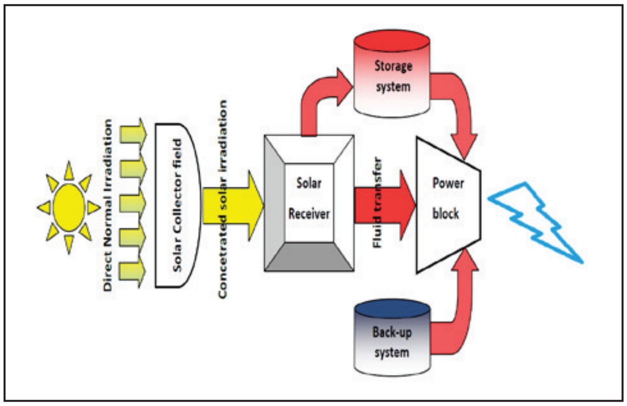

Figure 1. Flow diagram for a typical power tower plant

The average of solar flux impinging on the receiver is between 200 and 1000 kW/m^2 which facilitate the high working fluid temperature [4], without significant thermal losses and yields very high concentration ratio (300-1500 suns). Thank to these high operation temperatures, it is easy to integrate hybrid operation in these power plants, as well as thermal storage, at a lower cost in order to enhance performance and increase capacity factor [5].

B. Molten salt power tower concept

This concept has the same components as described previously. The molten salt is used as working fluid as indicated on figure 2.

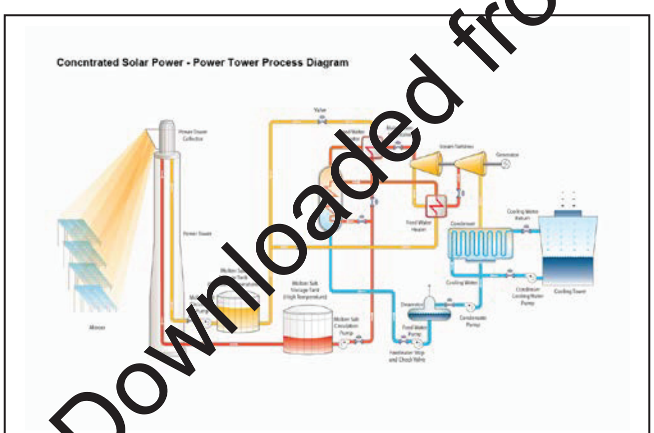

Figure 2. Molten salt power tower diagram

C. Direct Steam Generation power tower concept

The direct steam power tower consists of the same components and functionality of the molten salt power tower, with two important differences. First, the steam flowing through the tower is both the heat transfer fluid that transfers energy from the receiver and the working fluid of the power cycle (a "direct" system). Secondly, the steam tower is composed of three individual receivers: a boiler, superheater, and reheater; each with a defined role.

D. Power tower prototypes, in operation and under construction plants

The large scale power production with solar tower technology was proven to be feasible by Solar One plant. The 10 MW Solar One plant is the first large-scale demonstration solar power tower which was built in the early 80’s in the desert of California. In this period, there were also efforts to establish solar tower technology in some countries such as Italy, France, Japan, Spain and Russia. In order to validate nitrate salt technology [6] and give solution to the technical problems occurred during the operation period of Solar One plant in terms of storage and continuous turbine operation, Solar Two was implanted and operated between 1996 and 1999.

At the time being, there are some solar tower plants in operation. In Spain, the first commercial solar power tower plant is named “PS10” it has a capacity of 11 MWel with a capacity of 20 MWth of thermal storage. PS10 plant situated in Sevilla, and is on line since 2007.

The second power tower plant in commercial use is PS20, constructed on the same site, is an upgrade of PS10 plant (figure 3) in terms of efficiency receiver, control and thermal storage system. The plant has 20 MW of power output, a land area of 900,000 m^2 and 1255 sun tracking heliostats each with a surface area 120 m^2.

Solar Tres renamed Gema solar is the first commercial solar tower plant using molten salt heat storage technology. It consists of a 304,750 m^2 solar field, from 2,650 heliostats, each 120 m^2 and situated in concentric rings around a 140 m high central tower. Gemasolar, with its 19.9 MW of power, can supply 110 GWh per year [7]. The most innovative aspects of the plant are its molten salt receiver, its heliostats aiming system and its control system. The Gemasolar power tower, equipped with 15 hours of storage, was the first solar plant to generate electricity for 24 consecutive hours. In addition, this power station is expected to reach a yearly capacity factor of 80-85%, which is comparable to most fossil-fuel power stations [8].

In Germany, a 1.5 MWel demonstration plant is operational since December 2008 and started production of electricity the spring of 2009. China established a 1MWe demonstration solar power tower plant named “DAHAN”[9].

In south Africa, a solar power tower plant is planned with 4000-5000 heliostats mirror, each having an area of 140 m^2 [10]. Algeria also plans to implant its first demonstration solar power tower in the few next years.

Nowadays, more than 427 MW are underway in USA, South Africa and China.

Figure 3. The PS10 solar tower power plant

III. Parametric Study Procedure

A. Site Selection

The proposed plant is to be located at Tamanrasset situated in the south extreme of Algeria (latitude 22°.47' N, longitude 5°.31' E, altitude 1377m). The sum of direct normal irradiation is greater than 2691 KWh/m2/ year. The average monthly direct irradiation varies between 271kWh/m^2 and 359 kWh/m^2 in November and February, respectively. The overall mean ambient temperature is 23°C and the overall mean value of wind speed is about 3.2 m/s. Figure 1 presents the monthly Direct Normal Irradiation (DNI) for a typical year of Tamanrasset site. From this figure, we can see clearly that the irradiation level is high over the year notably between 9 a.m and 16 p.m. The peak is reached in January and February with more than 980 W/m^2 and the monthly average DNI was found to be 449.6 W/m2.

The monthly average of daily DNI was found 7.56 kWh/m^2 at Tamanrasset. The most important remark that the most of these values are higher than yearly average DNI in some locations were CSP technologies are in use today such as California where it reach 5.86 kWh/m^2, Almeria in Spain with 4.8 kWh/m^2 per day or Morocco where these values reach 4.84 and 5.86 kWh/m^2 [11].

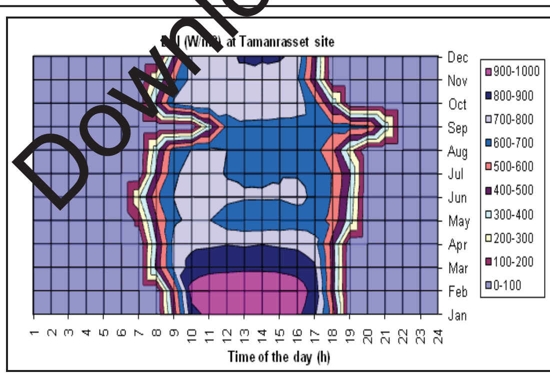

Figure 4. Variation of DNI at Tamanrasset

B. Assumptions

To identify the least cost feasible option for the implementation of such solar power plant, the following parameters were varied:

- Plant's configuration
- Thermal storage,
- Receiver configuration,
- Heliostat shape,
- Plant capacity

For all these cases, the energy's plant output is estimated, the Levelized Cost of Energy (LCOE) is also calculated. The technical parameters and the economical assumptions used in the simulation for the base case of the plant investigated are indicated on Table 2 and Table 3, respectively.

TABLE II. Design Parameters Of The base case of the Power Tower Plant

Characteristic	Value
Total plant capacity	100 MWe
Total land area	3,775,717 m^2
Condenser type	Evaporative
Heliostat and Solar field	
Total field reflector area	967,888.7 m^2
Number of heliostats	6704
Heliostat area	144 m^2
Mirror reflectivity	0.94
Solar multiple (for 6 hours of thermal storage)	1.9
Water usage per wash	0.7 L/m^2 aperture
Maximum distance from tower	1375 m
Minimum distance from tower	137.5 m
Thermal receiver and HTF properties	
Receiver type	External
Tower height	183.3 m
Receiver height	20.15 m
Receiver diameter	13.33 m
Receiver material type	Stainless_AISI316
HTF type	Solar salt
Required outlet HTF temperature	574 °C
Receiver coating absorptivity	0.94
Receiver coating emissivity	0.88
Thermal Energy Storage(TES)	
Full load hours of TES	6 hours
Storage type	Two tank
Storage fluid	Solar salt
Storage HTF volume	7553 m^3
Tank diameter	21.9 m
Max fluid volume	7,175.52 m^3
Min fluid volume	377.659 m^3

This investigation has been carried out using the National Renewable Energy Laboratory's (NREL) SAM software [12]. SAM provides modelling capability for several technologies including the CSP technologies [13]. SAM combines an hourly simulation model with performance, cost and finance models to calculate energy output, energy costs and cash flows [4]. Typical meteorological year (TMY) direct normal irradiation, ambient temperature, wind speed, sun angle, atmospheric pressure and solar azimuth angle and data for Tamanrasset were used as inputs to simulate the thermodynamic operation of the plants.

It should be noted that this software (SAM) and others such as DELSOL and WINDELSOL have been used within previous studies of CSP technologies [14, 15, 16].

TABLE III. PLANT'S ECONOMIC ASSUMPTIONS AND DATA

Assumptions and data	Values
Life time	25
Real discount rate (%)	8.2
Nominal discount rate (%)	10.9
Inflation rate (%)	2.5
Direct costs	
Heliostats cost ($/m2)	180
Receiver cost ($/ m2)	69189
Power block ($/kWe)	1200
Contingency (% of direct costs)	07
Indirect costs	
Engineering, Procurement and Construction (% of direct costs)	11
Total installed cost per capacity ($/kW)	5,384
Operation and Maintenance costs	
Fixed ($/kW-year)	80
Variable ($/MWh)	3

IV. RESULTS

In this section, only the following parameters are taken into account:

A. Influence of heliostat shape

There are two shapes of heliostats; rectangular (glass/metal) and circular shape (stressed membrane). The glass/metal heliostat is usually rectangular and is made of flat float glass in a sandwich design, silvered glass, backed by float glass for support. Membrane heliostats have a stressed membrane supporting a reflecting film with a circular shape. Heliostat's shape has a significant impact on the results as shown in table 4. This is mainly due to the properties and lower cost of the second heliostat technology.

TABLE IV. EFFECT OF HELIOSTAT SHAPE ON PLANT'S PERFORMANCES

Simulation results	Rectangular heliostat shape	Circular heliostat shape
Number of heliostats	6704	8728
Power output (GWh/y)	416.4	444
LCOE (c$/kWh)	11.71	11.04
Total installed cost ($/kW)	5,699	5,720

B. Influence of receiver configuration

There are two main receiver configurations: external and cavity receivers. External receivers have heat absorbing surfaces that are either flat, often called a billboard, or convex toward the heliostat field. For a large plant, an external receiver is typically a multipanel polyhydron that approximates a cylinder, with a surround heliostat field. The effect of receiver configuration on plant's performances is given in table 5. The results show that the performances increase for external receiver configuration.

TABLE V. EFFECT OF RECEIVER CONFIGURATION ON PLANT'S PERFORMANCES

Simulation results	External receiver	Cavity receiver
Power output (GWh/y)	416.4	411
LCOE (c$/kWh)	11.71	12.84
Total installed cost ($/kW)	5,699	6,653

C. Impact of thermal storage

The thermal energy storage (TES) unit is integrated into the air cycle, through which the operation of the power plant can be held for a certain time at constant power, depending on the storage dimensions [17]. There are several possible configurations to implement thermal energy storage. The most common configurations are the two-tank system and the thermocline. In principle, when the plant has storage, the solar field is larger in order to increase its generation hours. The relative size of the solar field is measured by the Solar Multiple, a dimensionless parameter, which is the ratio of the actual size of CSP plant's solar field compared to the field size needed to feed the turbine at design capacity when solar irradiance is at its maximum.

The two technologies of TES are considered in this study; the two tanks and thermocline systems were investigated for seven cases with 0, 3, 6, 9, 12, 15 and 18 hours storage, respectively. Figure 5 and 6 show the influence of full load hours of TES on LCOE and power output of the power tower plant for both storage configurations. The storage optimum size is 4 and 8 hours for two tank and thermocline technology, respectively.

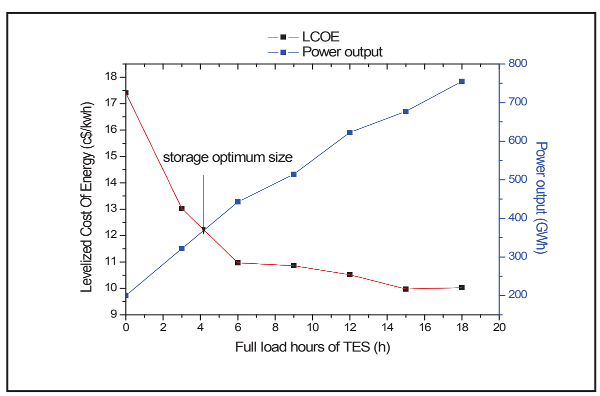

Figure 5. Effect of two tank storage technology for seven cases on plant's performances

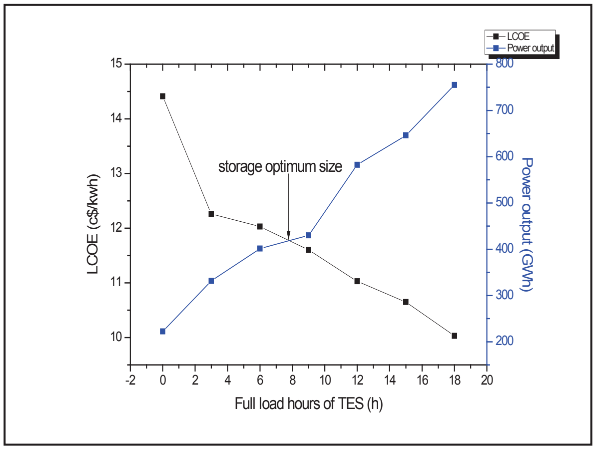

Figure 6. Effect of thermocline storage technology for seven cases on plant's performances

D. *Impact of plant's configuration*

In this section, two configurations are discussed; the molten salt and the direct steam generation (DSG) plant. This concept has the same components as described previously (section II, B and C).

The molten salt is used as working fluid by the molten salt plant while the water is used by the second concept (DSG plant).

Annual simulation results are presented in table 6, showing annual performances of the two configurations discussed above. The annual power output is 293 GWh for the DSG and 209 GWh for the molten salt plant.

This shows the about 28.66% higher gross to net efficiency of the DSG concept. Capacity factor is significantly higher for DSG than molten salt (33.5%) because the good performance of DSG plant and the same case for the annual water consumption.

TABLE VI. ANNUAL PERFORMANCES FOR TWO PLANTS LAYOUT

Annual performances	DSG	Molten Salt	DSG to Molten salt (%)
Annual net Energy output (GWh)	293	209	28.66
Capacity factor (%)	33.5	23.9	28.65
Annual water usage (m3)	65064	37144	43

Based on the annual yield simulation, the costs dada and the prediction of operating and Maintenance (O&M), the economic indicators above described are calculated.

The LCOE of the DSG plant is 5% about lower than the molten salt plant. The second economic indicator considered is the NPV.

The results show that this indicator is around 60 million US$ at the end of plant life time for DSG plant and about 44 million US$ for Molten salt plant. The other economic indicator in the IRR, it's almost the same for both plants (table 7).

TABLE VII. ECONOMIC RESULTS OF THE TWO PLANTS

Economic indicators	DSG	Molten Salt	DSG to Molten salt (%)
LCOE (ç$/kWh)	14.82	15.56	-4.99
NPV (M$)	60.0	44.0	-26.6
IRR (%)	20.50	20.96	-2.24

E. *Impact of plant size*

It's obvious that the electric power output of the solar plants is proportional to the solar sources (DNI) and the plant's efficiency. The annual electric power generated from the proposed plant versus plant size is presented on figure 7. Figure 8 illustrates the capacity factor versus the same parameter.

A plant of 20 MWe generates 70 GWh per year with a capacity factor of 39.6 % when a tower plant with a capacity of 50 MWe produces 200 GWh with a capacity factor of 44.8 %. In the case of tower plant of 100 MWe of capacity, the annual power generation is about 400 GWh with capacity factor of 45.5%.

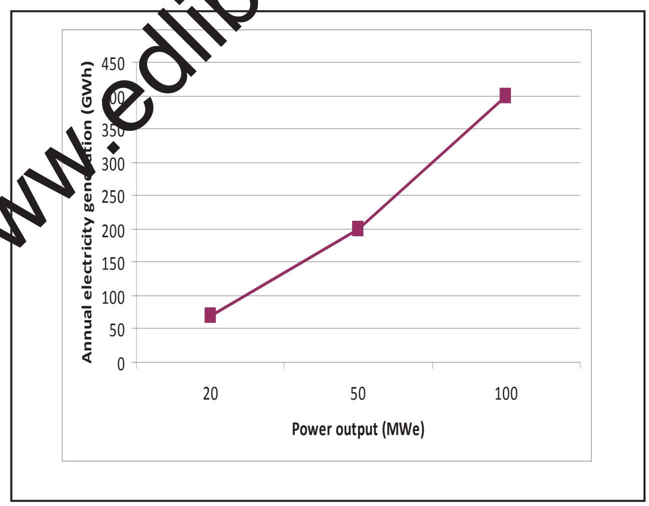

Figure 7. Effect of tower power output

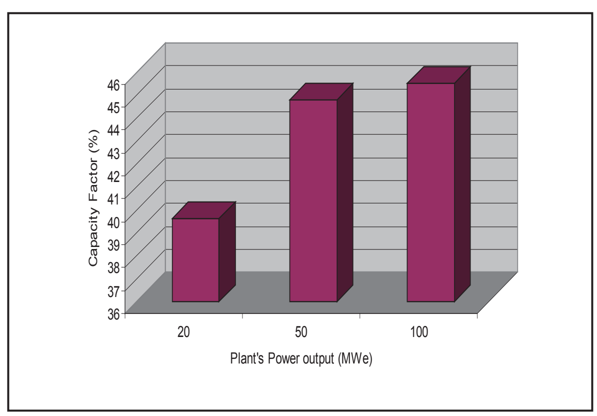

Figure 8. Capacity factor versus plant's power output

V. Conclusion

This paper intends to remark the importance of the parametric study in the same conditions in order to select the best configuration of solar tower power plant for an optimum use of the solar resource.

The aim of this work was to carrier out a feasibility study of a solar tower power plant in the Saharan climate of Algeria in order to study whether the installation of this kind of power generation is economically feasible. A parametric study of some parameters is carried out to investigate the least cost feasible option of the implementation of this technology.

From this study, it's evident that the installation of solar tower power plant in Tamanrasset site is economically with some configurations.

Finally, more detailed analysis is required before concluding about the best plant configuration to be adopted in the solar power plants. On the other hand, others economic parameters merit to be discussed in details.

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