Solar Tower Plant Implementation in Northern Algeria: Technico Economic Assessment

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Abstract— The present work deals with the technical feasibility of central receiver system using solar tower technology. This technology is based on solar concentration ratio of up to 1000 suns that can supply solar process heat at higher temperatures of about 800°C.
This technology has been under development since 1980s after the pioneering experience of Solar I and Solar II in USA and the Plataforma de Almeria in Spain during the period of 2000-2010.
It has reached the commercial maturity and is full expansion.
Algeria is very rich in solar energy resources. It possesses large unpopulated and unproductive land in the Sahara which represents 80% of the total country area. This makes the country an ideal place for the implementation of the concentrating Solar Thermal Power Plant technologies (STPP). Algeria has expressed a high interest in developing its solar energy resources. To this end, it has introduced a program where solar thermal energy plays a central role.
In order to study the viability of STPP under Algerian climate, we present here a technico economic assessment of a solar tower power pilot plant located in Tipaza near Algiers.
Using the economical, technical, meteorological and radiometric data, we have carried a simulation of the STPP under SAM Advisor Software.

The results show that for a net annual energy of about 1 MW, the levelized cost of electricity (LCOE) is about 0.1$/kWh which is relatively high in comparison with the LCOE of fossil power plant (0.04 $/kWh). However by increasing the plant power from 10 to 100 MW, the results indicate that the LCOE is drastically reduced. This suggests that, at high power, STPP can be competitive with conventional power plant.

Keywords— Technical Feasibility, Central Receiver System, STPP, SAM Advisor, LCOE

978-1-4673-5814-9/13/$31.00 ©2013 IEEE

I. Introduction

The world has been experiencing for more than a century a significant economic growth. The industrial developments, the increase in the automobile park and the multiplication of the domestic equipments have lead to a significant growth of the energy demand.

In Algeria, this growth in the energy has been mainly covered by the construction of new power plant whose source is in fossil energies (natural gas), stimulated by technico-economic factors.

With 2.381.741 km² of land area, Algeria is by far the largest country of the Mediterranean. Over 70% of its area are South of 20° latitude. According to a study of the German Aerospace Agency, Algeria has with 1'787'000 km² the largest long term land potential for concentrating solar thermal power plants [4].

The Renewable Energy Development Center (CDER) summarized the available insolation measurements in Algeria. According to the irradiation maps presented in fig.1, total annual direct normal irradiation ranges from 2100 kWh/m²yr to over 2700 kWh/m²yr and is counted among the best insolated areas in the world [4].

Algeria's solar potential and land resources are optimal for the implementation of solar thermal power technologies thus:

- Most desert areas in Algeria's offer direct normal insolation above 2100 kWh/m²yr
- The best sites, in the southern part of the country, exceed 2500 kWh/m²yr

It is estimated that within 50 km from required infrastructure (roads, grid) accessible sites have huge potential far in excess of present consumption.

Within its policy of climate and environment protection, the Algerian Ministry for Energy and Mines fully supports the objective of the Concentrated Solar Power (CSP) within the Global Market Initiative (GMI) that facilitates and expedites the realization of 5,000 MW_e of CSP worldwide over the next ten years. Algeria has committed itself to develop solar energy as its main renewable energy source, to cover 5% of the national electricity needs by 2010.

Opportunities of combining Algeria's richest fossil energy source - the natural gas - with Algeria's most abundant renewable energy source - the sun - is the actual transition model between fossil and renewable source using Integrated Solar Combined Cycle System (ISCCS).

II. SITE SELECTION CRITERIA FOR PRE-FEASABILITY STUDY FOR CSP PLANT

II.1 ENERGY RESSOURCES

The first parameter considered in site assessment in term of energy resource is the direct normal irradiance (DNI), which is defined as the radiant flux density in the solar spectrum (0.3 μm to 3 μm) incident at the earth's surface perpendicular to the direction to the sun integrated over a small cone tracing the sun. The available DNI is affected by absorption and scattering of the solar radiation at air molecules, ozone, water vapor and aerosols. As we can see in fig.1, the available DNI is very high in southern of Algeria while it reduces gradually when getting to the north side.

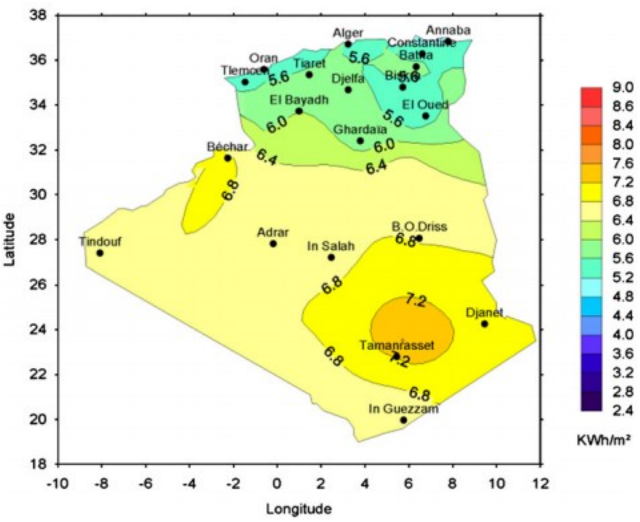

Figure 1: Daily direct normal irradiation in kWh/m²/day.[07]

As reported in Table 1, Algeria can be divided into three regions in terms of average sunshine duration and the amount of energy received by square meter. We can assume that Algeria has the most important solar energy potential in the world and has over 2000 hours of sun exposure by year.

Table 1: Average energy resource received in Algeria.

Regions	Coastal regions	Highlands	Sahara
Area (10^6 km²)	0.095	0.238	2.048
Mean daily sunshine duration(h)	7.26	8.22	9.59
Average energy density (kWh/m²/day)	4.80	5.20	7.26

II.2 LAND AVAILABILITY

CSP plants need large land area compared to conventional power plants. The specific surface area for a solar tower power plant is about 0.02 km² to 0.025 km² per $MW_{The.}$ This is slightly high comparing to parabolic trough power plant which requires specific area in the range of about 0.015 to 0.02 km² per MW_{The}. The availability of land to build large CSP collector fields is therefore an important site criterion.

In the case of Algeria, there are large unproductive and poorly populated areas in the south that are very suitable for CSP installation.

II.3 WATER AVAILABILITY

Water requirements for solar thermal power plants are similar to conventional thermal power plants of equivalent output. However, there is additional need for water that is necessary for solar reflector cleaning. For a wet cooled system the total water consumption would be around 276.10^6 l/year, while if dry cooling was introduced this could fall to around 36.10^6 l/year [06].

Concerning the water resources, there is the Mediterranean sea and a dense hydraulic network linked to several big dam in the north of Algeria. In the region of the highland and south of Algeria, there exists also a great water table which is important for economical investment such as new power plants far from urban cities.

II.4 NATUREL HAZARD POTENTIAL

Natural risks include phenomena such as earthquakes, storms. These risks can affect the operating safety of a CSP plant. In order to resist the impacts of these phenomena, the design of the solar field and of the power block must be adapted, which may imply higher construction costs. Additionally, insurance costs may rise at sites with higher damage risks.
In the case of Algeria, the southern part of the country has no history of earthquakes and storms are rare. Geological studies indicate that the region is stable with no risks of earthquakes.

II.5 Infrastructure convenience

CSP plants need certain infrastructure for their operation. Existing infrastructure is, hence, an important site criterion. Missing infrastructure requires higher investment. A power plant needs access to roads or other transportation ways (navigable waterways), to high or medium voltage power grids and to water resources if wet cooling is planned. Additionally, pipelines may be favorable for water transport or fuel transport for hybrid plant operation.

In the case of Algeria, there has been a large investment in setting up highway through the country. This is the case of the east west highway that links the eastern part of the country to its western part by crossing its central part. Other important highway projects such the north south highways are under way.

II.6 Political and economic frameworks

Political and economic conditions are also important site criteria. Promotion measures for renewable energies are especially decisive. There are different promotion strategies. The most important strategies are special feed-in tariffs or premiums for electricity generated on the basis of renewable energy sources, quotas for the renewable energy share and tax incentives. The politically controlled promotion of CSP is still necessary because of the currently higher levelized electricity cost of CSP plants in comparison to fossil fired power plants and some other competitors. Political promotion has the aim to help CSP plants until they get competitive on their own.

Incentive premiums for CSP projects are granted within the framework of Algeria's Decree 04-92 of March 25th, 2004 relating to the costs of diversification of the electricity production. The incentive premiums of this decree shall attract private investors to implement integrated solar combined cycle plants in Algeria. According to the current power expansion planning of the ministry for energy and mines, the capacity targets for CSP power implementation in Algeria are 500 MW of new ISCCS plants until 2020. With these CSP targets and the new decree 04-92, Algeria has established the necessary GMI commitment on national solar thermal power market implementation. As the next GMI step that has been agreed at the renewables conference in Bonn, the government of Algeria has pledged to develop a framework for solar thermal electricity export from north-Africa to the European Union.

III. Central Receiver thermal power plant descriptions

Central Receiver System with large heliostat fields and solar heat exchanger located on top of a tower are now in a position for deployment of the first generation of grid-connected commercial plants. The Central Receiver System (CRS) power plant technology can be considered as sufficiently mature after the pioneering experience of several 0.5 to 10 MW pilot plants in the early 1980s. A schematic representative of CRS is shown in fig. 2

Incident sunrays are tracked by mirrors called heliostats, which concentrate the energy flux to the receiver. The heliostat field performance is defined in terms of the optical efficiency, which is equal to the ratio of the net power intercepted by the receiver to the product of the direct insolation and the total mirror area. The different losses affecting the system are the cosine effect, shadowing, blocking, mirror reflectivity, atmospheric attenuation and spilling effect.
The typical optical concentration ratio ranges from 200 to 1000 suns. The high solar flux incident on the receiver (averaging between 300 and 1000 kW/m^2) enable operation at relatively high temperatures of up to 1000°C.
Different type of thermal fluid system, such as air, steam, molten nitrate salt and liquid sodium, are used to transfer thermal energy from solar receiver to power bloc via heat exchanger system.

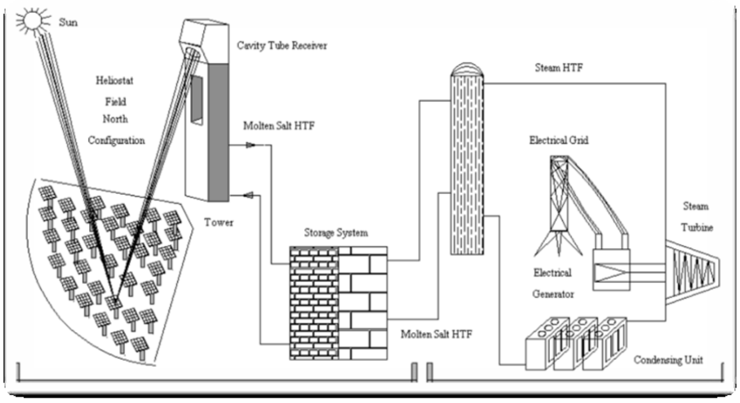

Figure 2: Solar central receiver power plant main components.

IV. Central receiver system design and modeling

The design and modeling of each component entering in the constitution of the solar central receiver power plant involve an interactive process which gives at each level the physical state and governing equation of each part.

IV.1 HELIOSTAT FIELD LAYOUT

The optimization method used to tradeoff between cost and performance of the heliostat field is established using computer codes such as DELSOL3 and SOLERGY [9] to provide relationship between tower height, receiver dimensions and the radially staggered field layout. This configuration is showed in fig.3

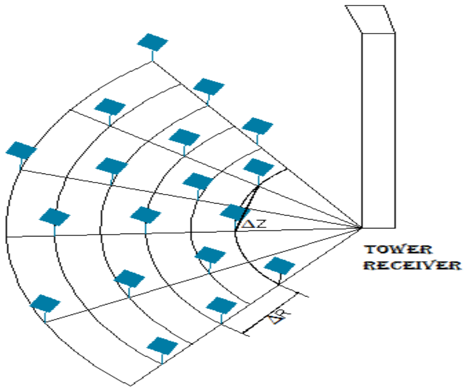

Figure 3: Radially staggered field layout.

In case of north configuration shown in fig.4, the correlation between the radial (ΔR) and azimuthal (ΔAz) spacing is given by the equation (1) and (2) [16]

$$\Delta R = [63.0093 - 0.587313.\theta l + 0.0184239.\ \theta l^2 + \cos\varphi(2.80873 - 0.14805.\theta l + 0.0014892\ .\theta l^2)].H_{helio} \quad \ldots(1)$$

$$\Delta Az = [2.46812 - 0.040105.\theta l + 9.2359\ 10\text{-}4.\ \theta l^2 + \cos\varphi(0.17345 - 0.009113.\theta l + 1.276110\text{-}4\ .\theta l^2)].W_{helio} \ldots(2)$$

Where:

φ: heliostat azimuth angle, 0° in south.
$\theta l = \frac{\pi}{2} - \theta$, θ the angle between the vector from heliostat to tower and vertical.

H_{helio}: height of the heliostat mirror,
W_{helio}: width of the heliostat mirror.

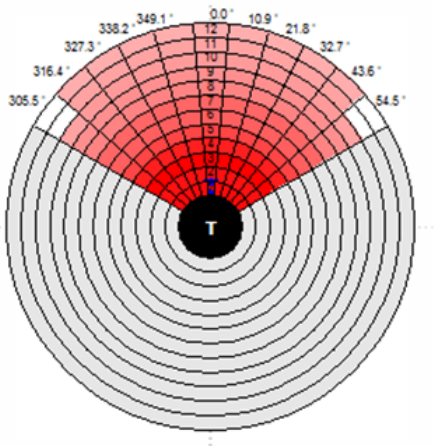

Figure 4: Representation of optimized fields with north configuration using SAM Advisor software.

IV.2 CAVITY RECEIVER GEOMETRY

In our model, we have used a cavity receiver type which consists of a cavity with a small opening (inlet aperture).

The concentrated solar radiation is aimed at the small opening where inside it impinges on tubes carrying the working fluid as represented in fig.5.

The idea behind the cavity receiver is to minimize the radiation losses. From the radiation entering the inlet aperture, only small amounts are reflected back into the atmosphere through the inlet aperture.

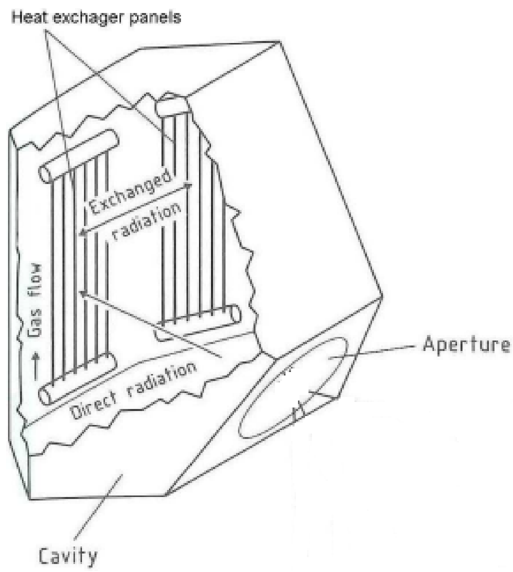

Figure 5: Cavity receiver geometry.[13]

IV.3 THERMAL STORAGE SYSTEM

There are different storage techniques. Among these techniques, there is the direct storage system which has been successfully applied in the solar tower technology. In this case, the HTF, which is heated in the receiver, is used directly as a storage medium. The HTF/storage medium can be stored either in a single or dual tank. In this simulation, we have used a two tank model (hot and cold tank).

IV.5 HEAT TRANSFER FLUID SYSTEM (HTF)

In the present study, molten salt is considered as the HTF. This section describes the operation of the molten salt in the plant. It is composed of 60% sodium nitrate and 40% potassium nitrate salt. It is heated while travelling in upward direction though the receiver tubes. From the receiver, the molten salt is pumped and fed into a hot-salt storage tank where it reaches a temperature of approximately 565°C.

From there the molten salt goes through a steam generator where the heat is transferred onto the steam cycle. After the molten salt has transferred its heat to the steam, it is still at a temperature above 290°C at which it is pumped into a cold-salt storage tank. It is kept to a minimal temperature of 290°C at all times to prevent the salt from solidifying.

IV.5 SIMULATION DATA

We have carried out a simulation using SAM advisor which makes performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters that we specify as inputs to the model.

The main parameters used in this study are represented in Table 2:

Table 2: Parameters introduced in simulation

Parameter definition	***Input value***
Direct Normal Irradiance (DNI)	1446.4 kWh/m²
Analysis period	30 years
Inflation rate	2.5 %
Debt fraction	40 %
PPA escalation rate	1.4 %
Heliostat area	8 m²
Solar multiple	1.2
Heat Transfer fluid	Molten Salt
Cavity aperture	22.5 m²
Turbine gross output	2 MW
Temperature of hot Tank	565°C
Temperature of cold Tank	290°C
Capacity storage	2 h

V. RESULTS AND DISCUSSION

The financial evaluation of each part of the plant is given by the diagram bar in fig.6. It can be seen that in a solar tower power plant, the solar field is the most critical part in terms of investment with a cost of 33 cents$/kWh. It represents about 35% of the total direct cost.

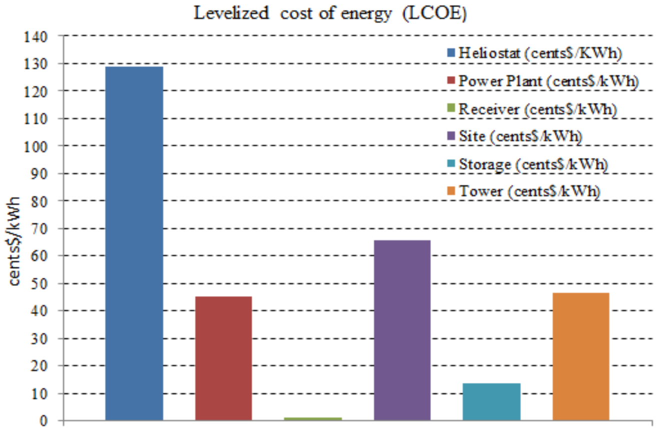

Figure 6: The levelized cost of energy of the main power plant component.

For the base case, the annual energy flow is reported in figure 7. With an annual thermal energy output of about 16 KWh_{th} as an energy resource from solar field, the electrical energy outlet of the turbine does not exceed 1.9 KWh_{th} . This results in a global efficiency of about 12% (base case). This is due to different losses (optical losses of the heliostats field, receiver losses (convective, conductive and radiative), the thermal losses in storage in tanks, thermal conversion efficiency of the Rankine cycle, the control and supervision of the plant and the cooling system.

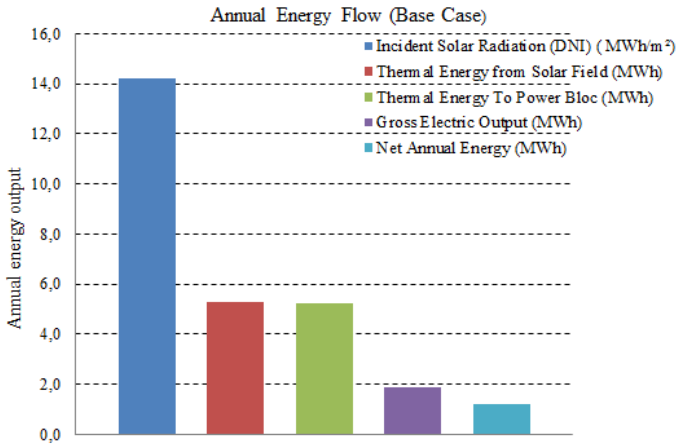

Figure 7: The annual energy output flow diagram.

For a net annual energy production of 1 MW_e, the levelized energy cost is about 0.128$/kWh which is very high comparing to LCOE of fossil energy (0.04$/kWh). For a power plant with a10 to 100MWelect, the land area needed is about 285 000 m² and an annual need of water about 6600 m^3. For instance, the solar tower power plant will be competitive for higher power production level.

As the energy resource is intermittent within the day and along the year, we have estimated the best solution relative to the capacity of the thermal storage system given a solar multiplier value suggested by economical consideration. Fig.8 shows that the optimal value for energy storage system is about 2.5 hours regarding to LCOE which remains constant (0.128$/kWh) and a maximum net annual energy output (AEO) is about 953 kWh.

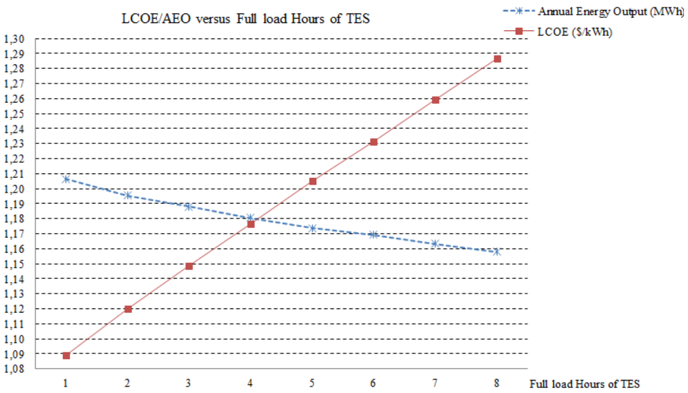

Figure 8: Optimal hour value for thermal storage system TES.

The future research work focuses on reducing the cost of the heliostat field to be competitive with conventional power plant

VI. CONCLUSIONS

In this study, SAM Advisor software is used to perform a technico-economic examination of the solar tower power plant of 2 MW_e. The simulation has been applied to the project ALSOL1 the future central receiver power plant which will be held at Tipaza state near Algiers.

We assume that:

- In this type of concentrating solar plant, the biggest investment is critical in the heliostat field and all associated operating and Maintenance costs during the life time cycle;

- The levelized cost of electricity LCOE is inversely proportional to the capacity of the plant, more high the capacity of the power plant less the LCOE value;

- In the central receiver plant at Tipaza which have a capacity of $2MW_e$ electrical output, the LCOE is about 0.128 $/kWh which is relatively high, thus increasing the capacity of the power plant will be more competitive.

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