The Impact of Direct Normal Irradiation on the Solar Tower Power Plant Performance based on Real and Satellite Data: Analysis on Algerian Regions

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Abstract

The present paper presents a deep study on the possibility of implementing Concentrated Solar Power (CSP) plants in Algeria for the production of the electrical energy. Indeed, this paper focusses mainly on the main parameters, which can have an important impact on the choice of the location, the dimension and the available thermal energy storage system. In this study, three main parameters are investigate such as the solar Multiple (SM), the thermal energy Storage (TES) capacity and the Capacity Factor (CF),where the main challenge is to find their optimal values based on the available solar energy deposit and the different constraints of the four considered region of Algeria presented in this paper. These optimal values will be used in the implementation and the management of the considered CSP to ensure the maximal probability of the location in terms of balance between the production and the demand of energy. This paper benefits from the onsite real data and the satellite data for finding the optimal values of the aforementioned parameters, where it has been proved that the satellite data can ensure more precise profitability of the available solar energy to ensure more produced electrical power. The obtained results allow to obtain optimized configuration of the implemented CSP and demonstrate that the use of such solar power plant can be of great interest to ensure more times production of the national electrical energy demand, especially in the large Sahar of Algeria which can power several part of the world and neighbour countries.

Keywords: Solar energy, solar tower power systems, direct normal irradiation, heliostat field, energy projects.

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1. Introduction

In the last decade the global world demand of energy has increased with the expectation of its growth within the coming years due to the actual growth of population and industries plants. On the other side, the fossil or even fissile energy resources, which are the more used energy sources, are gradually decreasing over time and their huge exploitation is leading to drastically long-term environmental damage and global warming. Therefore, a lot of scientific research has been carried out in order to find an unlimited, economical and low-polluting sources of energy such as those based on solar and wind, which aim in fulfilling the main important goals of environmental protection and rationalized use of energy. Indeed, thermodynamic solar energy can offer relevant solutions, especially in regions with strong solar irradiation for the production of electrical energy at relatively average cost.

However, in solar power plants, the solar energy being insufficiently dense, it is necessary to concentrate it via reflective mirrors in order to obtain exploitable temperatures for the production of electricity. Solar radiation can be concentrated on a linear or point receiver, from where the receiver absorbs the energy reflected by the mirror and transfers it to the thermodynamic heat transfer fluid. Therefore, the performance of the solar thermal system is characterized by its concentration factor, this coefficient makes it possible to evaluate the intensity of the solar concentration. It is obvious that with a higher concentration factor, a higher temperature can be obtained, in the same time it is well know that the linear concentration systems generally have lower concentration factor than the systems based on point concentrators.

In order to better adapt to the variation of the solar irradiation and to improve the efficiency of the solar power plant based on the maximization of the power delivered by the used solar concentrator, several criteria for optimizing the efficiency of the system were applied as have been discussed in several previous works [1]-[8].

The main aim of this work is to analyse the normal direct irradiation on the performance of the power plants with solar tower of external receiver based on molten salts in different regions in Algeria. In order to optimize the configuration of the concentrated solar power plant presented in this paper, a comparative study between two regions based on real data (the regions of Bechar and El-oued) and two regions based on satellite data (the regions of Djelfa and Batna) will be presented and analysed. In this context, an approach to estimate the parameters of the model of solar tower power plant as a function of irradiation and temperature is be presented, these parameters are determined based on the real data obtained on site from these two solar tower power plants. Each installation is equipped with a thermal storage system (TSE) based on molten salts, the receiver is of the external type and the location of the heliostats field is expected to ensure an annual production of 20 MW.

This study is useful for prioritizing, sizing and locating new installations and hence for determining the technical parameters to be taken into account the design and implementation of the projects of solar tower power plants using external molten salt receivers. It will also be useful to define the ideal location according to the solar radiation which maximizes the efficiency of the installation of the solar tower power plant.

2. Solar irradiation

The solar energy is the most dominant energy among all the used renewable energies due to its important potential of energy and its ease exploitation. Hence, the exact determination of the position of the sun in the space within the earth celeste during the daylight, is very important for the study and evaluation of the captured energy from the sun. The trajectory of the sun in the space during a day from sunrise to sunset makes it possible to evaluate certain quantities such as the maximum duration of daily sun hours and the global irradiation where its direct component plays an important role in the solar concentration system. Indeed, there is a variation of the day length along the whole year. This variation is due essentially to two main features of the motion of the earth globe around itself and around the sun such as:

- The elliptical form of the earth rotation trajectory around the sun which is completed in each year;
- The tilt angle of the equator of the each with the elliptical plan of the sun-earth plan.

This variation presents by the difference between the mean solar time (MST) and the true solar time (TST) according to the considered day of the year which can be defined as follows [7], [9], [10]:

$$ET = TST - MST \quad (1)$$

This variation is known as the equation of time which is measuring the variation in the length of each day through the course of the year, it can be calculated by using the following equation:

$$ET = a_1\cos(\gamma) + a_2\sin(\gamma) + a_3\cos(2\gamma) + a_4\sin(2\gamma) \quad (2)$$

where:

$a_1 = 0.258$

$a_2 = -7.416$

$a_3 = -3.648$

$a_4 = -9.228$

γ is an angle which is defined according to the number of the day (n). The count starts from January 1st which corresponds to n = 1 and it can be caluclated as follows:

$$\gamma = \frac{360(n-1)}{365.25} \quad (3)$$

The effective time of irradiation is the time during a day in which direct solar radiation can reach the surface of the earth of the considered place. The direct radiation which is also called the “beam” is the part of sun radiation arriving the external side of the atmosphere and which reaches directly the surface earth without any kind of deviation along the atmosphere layers. In clear cloudless skies, the ground receives direct solar radiation along the duration of the day, or more precisely during the maximum period of day sunshine hours SS_0. The ratio between the effective duration and the maximum duration of sunshine per day is called sunshine rate or insolation rate and it is expressed as follows [11]-[14]:

$$\sigma = \frac{SS}{SS_0} \quad (4)$$

The maximum duration of sunshine SS_0 for a clear sky site neglecting the atmosphere can be taken equal to the duration of the day measured in hours which depends only on the latitude φ and the declination δ, and it is calculated by the following formula [15]-[18]:

$$S = \frac{2}{15}.cos^{-1}(-\tan(\varphi).\tan(\delta)) \quad (5)$$

An important factor on which depends the received radiation on the earth surface is solar constant. Indeed, its value at any point at the external side of the atmosphere is constant. However, it value is related to a correction factor, this factor is function only of the number of the day of the year n. Hence the value of the solar constant can be estimated based on the following equation (7), (8), (19), (20), (21):

$$I_0 = I_{sc}\left(1 + 0.034 * \cos\left(\frac{360}{365.25} * n\right)\right) \quad (6)$$

where I_{CS} is the solar constant which is equal to 1367 W/m^2 . More precisely, based on the collected real data of the irradiation which presents nearly a periodic behaviour, the Fourier series can be applied for the estimation of the corrected solar constant, here only the second term of the series is taken into account where it seems that the other terms have not important effect on the estimated value. Hence the corrected solar constant can be estimated as follows:

$$I_0 = I_{CS}\big(b_1 + b_2\cos(\gamma) + b_3\cos(\gamma) + b_4\cos(2\gamma) + b_5\sin(2\gamma)\big) \quad (7)$$

where:

$b_1 = 1.000110$

$b_2 = 0.034221$

$b_3 = 0.001280$

$b_4 = 0.000117$

$b_5 = 0.000077$

Global solar radiation have mainly three component, the direct radiation or the beam, the diffused radiation and the reflected radiation. The last component can be useful only if we consider the tilt of the surface receiving the radiation.

Hence in case of horizontal receiver this component has no effect on the received power, and it is equal to zero. Whereas, the diffused component is due to the nature of the atmosphere content such as the cloud, the aerosol, the humidity and others, which are distributed in the atmosphere. In the general case of tilt surface, the global solar radiation is the sum of the three aforementioned components which is present by the following equation

$$I_{g\beta} = I_{b\beta} + I_{d\beta} + I_{r\beta} \quad (8)$$

where

β: is the tile angle.

$I_{g\beta}$: is the global radiation.

$I_{b\beta}$: is the direct radiation component (the beam).

$I_{d\beta}$: is the diffused radiation component.

$I_{r\beta}$: is the reflected radiation component.

In the case of a horizontal received the global radiation can be expressed as follows:

$$I_{gh} = I_{bh} + I_{dh} \quad (9)$$

where

I_{gh}: is the global radiation on horizontal receiver.

I_{bh}: is the direct radiation component on horizontal receiver.

I_{dh}: is the diffused radiation component on horizontal receiver.

It is important to clarify that other factors can affect the amount of the global radiation such the number of the day, the declination, the azimuth, the latitude, the orientation of the considered surface, etc.

2.1 Solar potential in Algeria

Regarding its geographic location, Algeria has one of the highest solar fields in the world. The duration of sunshine hours on almost the entire national territory exceeds 2000 hours annually and can reach 3900 hours (162.5 days) for the highlands and the Sahara, as presented in Table 1.

Table 1. Solar Potential in Algeria [23]Region

	Coastal	Highlands	Sahara
Area (%)	4	10	86
Average duration of sunshine (hours / year)	2650	3000	3500
Average energy received (KWh / m² / year)	1700	1900	2650

The daily energy received on a horizontal surface of $1m^2$ is of the order of 5 KWh over most of the national territory, i.e. almost 700 KWh/m^2/year in the North and 2263 kWh/m^2/year in the South of the country [22]. The total energy received is estimated at 169,400TWh / year, or 5,000 times the actual country's annual electricity consumption. This potential can constitute an important factor of sustainable development, if it is exploited in a rational way.

The study of solar radiation is necessary to choose the best site for the installation of a solar collector system. The radiation received by a solar collector also depends on the level of radiation of the site considered and its orientation relative to the sun. A fixed solar collector receives the maximum energy when it is oriented towards the south and is inclined at an angle practically equal to the latitude of the place. So that the solar radiation is mostly perpendicular to the solar panel, and in order to optimize the entire solar collector system, it is necessary to use the technique of tracking the sun (heliostat, sensor).

3. Modelling of a tower solar power plant

The tower solar power plants are made up of many mirrors concentrating the solar rays towards a boiler located at the top of a tower. The uniformly distributed mirrors are called heliostats, each heliostat can adjust its position and track the sun individually and hence it reflects the received radiation precisely towards the receiver at the top of the solar tower. The concentration factor can exceed 1000, which allows significant temperatures from 600 °C to 1000 °C to be reached. The energy concentrated on the receiver is then either directly transferred to the thermodynamic fluid ensuring the direct generation of steam driving a turbine or heating of air supplying a gas turbine, or indirectly by heating an intermediate heat transfer fluid which can be used in an intermediate secondary cycle like molten salt . This heat transfer liquid is then sent to a boiler where the generated steam will be used to ensure the driving of the turbines, which are used for producing the mechanical energy required by the alternators for producing the electrical energy at the end of the whole process [24], [25]. Optimizing the design of the heliostats field is based on a techno-economic analysis which is a compromise between the optical performance and the cost [26], [27].

The implementation of the solar collection system is shown in Figure 1 can be performed by determining the optimal values such as the radial distance ΔR between two heliostats centres and the azimuthal distance ΔA_Z between two heliostat centres at the same defined radial distance .

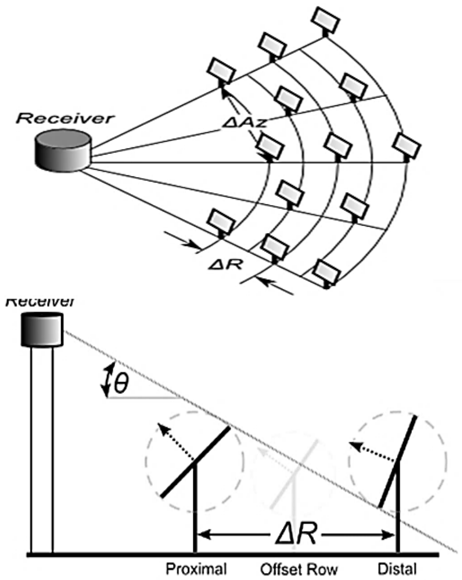

Figure 1. Mirror position receiver

Indeed, these two parameters are function of the heliostat azimuth angle θ (0' at the south) and the receiver elevation angle from heliostat α in degrees. These two parameters can be estimated using empirical expressions as follows: [28], [29]

$$\Delta R/HM = 63.0093 - 0.5873130\theta + 0.0184239090\theta^2 + \cos\left(\alpha(2.808733 - 0.1480498\theta + 0.0014892010\theta^2)\right) \quad (8)$$

$$\Delta A_Z/WM = 2.46812 - 0.0401054\theta + 0.0009235940\theta^2 + \cos\left(\alpha(0.173444593 - 0.0091125900\theta + 0.0001276100\theta^2)\right) \quad (10)$$

where *HM* presents the heliostat height in meters and *WM* is the heliostat width in meters

3.1. Modelling of energy parameters

The size of the heliostat field influences the optical performance and it depends on the desired power and the temperature of the heat transfer fluid at the outlet. As the optimized heliostat of the studied field is obtained, we can then estimate the efficiency of each heliostat in the field separately. The total incident thermal energy is given by the following equation [30], [31]:

$$Q_h = I_b \times A_h \times N_h \quad (11)$$

with I_d is direct normal irradiation (DNI), A_h is the heliostat surface, N_h is the number of heliostats.

The efficiency presents the ratio between the power that effectively transferred to the receiver surface and to the total incident energy produced by the direct component of the radiation. Therefore, the efficiency of the field layout is defined by the following equation:

$$\eta_h = \frac{Q_{rec}}{Q_{inc}} = \frac{Q_{rec}}{I_b \times A_h \times N_h} \quad (12)$$

with Q_{rec} is the heat flow from the receiver, Q_{inc} is the heat flow from the incident.

The global or total efficiency can be calculated by considering the losses due to the different effects (cosine, shading, blocking, overflow, reflection, dispersion) as follows [27]:

$$\eta_h = \eta_{\cos} \cdot \eta_{omb} \cdot \eta_{bloc} \cdot \eta_{deb} \cdot \eta_{ref} \cdot \eta_{disp} \quad (13)$$

where $\eta_{\cos}$, η_{omb}, η_{bloc}, η_{deb}, η_{ref}, η_{disp} are the losses due to cosine effect, shading effect, blocking effect, overflow, reflection and dispersion respectively.

The cosine effect is defined as the reduction of the receiving area caused by the cosine angle formed between the solar radiation and the normal line to the mirror. This effect is an extremely important concept as it is one of the main reasons that causes the energy loss in solar energy concentration system. The cosine efficiency of a heliostat equals to the cosine of incidence angle θ of the direct radiation relative to the heliostat centre and is given as follows [32], [33]

$$\eta_{\cos} = \frac{\sqrt{2}}{2}\left(\sin(\alpha)\cos(\lambda) - \cos(\theta_H - A)\sin(\lambda) + 1\right)^{0.5} \quad (14)$$

where, α is the solar altitude angle, A is the solar azimuth angle, λ is the angle between the reflected ray incident on the heliostat centre and the vertical direction, θ_H is the azimuth angle of the heliostat relative to the tower base.

The interception efficiency is estimated by [27], [34]:

$$\eta_{intrecept} = \frac{1}{2\pi\sigma_{tot}^2}\int(x)\int(y)\exp\left(\frac{-x^2+y^2}{2\sigma_{tot}^2}\right)dxdy$$
$$\sigma_{tot} = \left(\sigma_{solaire}^2 + \sigma_{miroir}^2 + \left(2\sigma_{track}^2\right)^2\right)^{0.5} \quad (15)$$

σ_{tot} is the total tracking error, $\sigma_{solaire}$ is the interception error of the sun's rays, σ_{miroir} is the reflectivity error of the mirrors and σ_{tract} is the error linked to the motor mechanism of the reflector.

The atmospheric transmission efficiency depends on the ambient conditions, and the distance between the heliostats and the receiver. It is expressed as follows:

$$\eta_{Atoms} = \begin{cases} 0.99321 - 0.000176S_0 + 1.97 \cdot 10^{-8}S_0^2; S \leq 1000m \\ \exp(-0.0001106S_0) \quad ; S \geq 1000m \end{cases} \quad (16)$$

where S_0 is the distance between the heliostat and the receiver.

3.2. Receiver modelling

In our study, the receiver model is of the external type. It consists of a large number of vertically arranged tubes through which a heat transfer fluid is pumped in the vertical direction. Inside the tube, three types of heat transfer can be occurred such as radiation, convection and conduction. Whereas, the heat transfer with the outside environment of the tube causes several loses such as the radiation losses (solar losses), convection losses (losses to the body of the receiver) and the conduction (losses by thermal bridges).

The heat flux of the receiver can be expressed by the following equation [18]:

$$Q_{rec} = q_{htf} + q_{conv} + q_{rad} + q_{ref} \Rightarrow Q_{rec} = S_i \cdot I_d \quad (17)$$

where q_{htf} is the heat flux of the molten salt, q_{conv} is the loss of convective heat flux, q_{rad} is the loss of radiant heat flux, q_{ref} is the loss of reflective flux and S_i is the total area.

The energy absorbed by the heat transfer fluid (q_{htf}) is given by the following equation:

$$q_{htf} = m_{htf} \cdot C_{htf}\left(T_{htf(x+dx)} - T_{htf(x)}\right) = US_i \times \left(T_{st} - T_{htf}\right) \quad (18)$$

with:

$$US_i = \frac{1}{R_{cond}+R_{conv}}, \; R_{cond} = \frac{\ln\left(\frac{D_{ot}}{D_{it}}\right)}{2\pi \cdot L_t \cdot K_t \cdot N_t \cdot D_t}$$

and

$$R_{conv} = \frac{2}{\pi \cdot h_{htf} \cdot L_t \cdot K_t \cdot N}.$$

where T_{htf} is the inlet temperature of the molten salt at *x* position, m_{htf} is the molten salt flow rate, C_{htf} is the heat capacity of the molten salt fluid, T_{st} is the surface temperature of the receiver, D_{ot} is the outer diameter of the tube, D_{it} is the inner diameter of the tube, L_t is the length of the tube, K_t is thermal conductivity of the receiver tube, N_t is the total number of the receiver tube, and D_t is the diameter of the tube.

The convection losses are expressed by the following equation:

$$q_{conv} = S_i \cdot h_{conv} \cdot (T_{st} - T_{ic-air}) \quad (19)$$

where h_{conv} is the convection heat losses from each receiver tube (W/m^{2}K), T_{st} is the receiver temperature at the surface (K), and T_{ic-air} is the temperature of the air in the inner cavity (K).

The losses of radiation q_{rad} have a negligible value because the absorber has a strong absorption of the short waves of the solar radiation. As well as the reflection losses q_{ref} which is neglected due to the lower emissive of the long thermal waves.

3.3. Modelling of the solar power plants performance

The performance of an adequate conception of the solar tower system depends on several parameters such as the production of energy injected into the electrical power system network, the incident solar radiation and the thermal storage capacity.

Whereas, for the analysis of the performance of the studied concentration solar power plant some factors are considered such as, the capacity factor and solar multiples are the most important factors characterizing the performance of a central solar tower system, which are defined as follows:

- The capacity factor (CF) is defined as the ratio between the energy generated by the system in part time E_{gp} and the energy generated in full time E_{gf}, it is given by the following equation [22], [23]:

$$CF = \frac{E_{gp}}{365.24 \cdot E_{gf}} \quad (20)$$

- The solar Multiple (SM) is defined as the ratio between the thermal power produced by the heliostats field at different DNI values (q_{sf}) and the thermal power required by the Power Block under nominal conditions (q_{pb})). It is expressed as follows: [8], [18]:

$$SM = \frac{q_{sf}}{q_{pb}} \quad (21)$$

For a system without storage mode, SM will be equal to 1.

In this work, we have reviewed the modelling tools existing in the concentrated solar domain starting with brief reviews, definitions and general laws relating to the analysis of energy and geometric parameters.

The analysis of the thermodynamic solar system allows understanding the main factors, which influence the performance of the installation. We have found two categories of factors that are directly influencing on the performance of the installation and which have been aforementioned such as the capacity factor (CF) and the solar multiple (SM).

4. Results and comparative analysis of solar zones in Algeria

The advantage of solar-powered thermal reflector plants is that they initially produce heat and therefore this heat can be stored to produce electricity day and night, even after sunset.

Algeria has one of the highest deposits in the world, where average annual sunshine durations range from 2,600 hrs/year in the North to 3,500 hrs/year in the south. So concentrated solar technology remains a major challenge in Algeria.

According to numerous technical and economic studies, a direct irradiation threshold (DNI) makes it possible to claim the profitability of a concentrated solar power plant in Algeria which can supply Algeria with electrical energy. However, the establishment of concentrated solar power plants to produce electricity appears to be one of the most suitable solutions for future energy in Algeria.

Algeria possesses an abundant solar potential along the whole year, it is a country where the humidity and precipitation are low, and there are a plenty of unused flat lands especially in the Sahara region which occupied around 1.787.000 km^2.

It is considered as one among of the world countries that has an important solar deposit with a duration of useful irradiation up to 3500 hours/year, and the average energy received on a horizontal surface is estimated to be around 1700 kWh/m^2/year on the North of the country, and 2263 kWh/m^2/year in the other regions of the country [35].

According to the study of the German Aerospace Centre, Algeria has the largest long term land potential for concentrating solar thermal power plants (CSP) [36]-[38].

In this paper, two different regions in Algeria are studied such as the region of Djelfa based on read data obtained onsite and the region of Bechar based on satellite data.

The obtained results for these two regions are compared to other two similar regions in Algeria such as the region of El-Oued based on satellite date and the region of Batna based on real data obtained onsite these last region results are used for the validation of the results obtained in this work.

4.1. Results obtained onsite at Djelfa region

The results presented in this section are based on real onsite date obtained in the region of Djelfa, which is located in the south of the capital Algiers at (latitude 34.41°N, Longitude 3.15°E).

Figure 2 shows the effect of thermal energy storage capacity (TES) measured in hour on the electricity production under different values of solar multiple such as SM={1, 1.2, 1.4, 1.5, 1.6, 1.8, 2, 2.2, 2.4}.

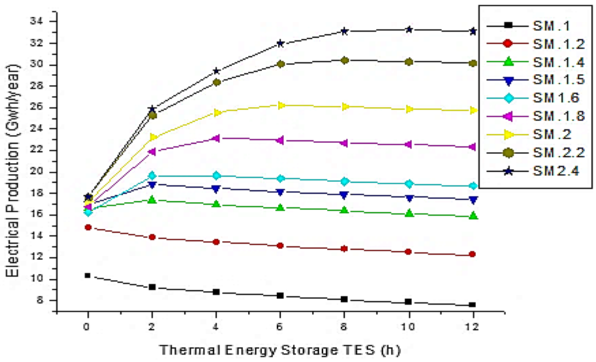

Figure 2. Effect of TES on the production of electricity under different values of solar multiple in the region of Djelfa, Algeria

In Figure 2, the level amount of the produced electrical energy increases with the increase of the solar multiple (SM) within the aforementioned values. It can be seen also that at TES equal to zero the produced energy from solar tower power plant without using storage system is more important with the increase of the value of SM.

However, as the SM is lower the produced energy decreases faster with the increase of the TSE, contrary with high values of SM within the range [2 to 2.4] the produced power is kept nearly constant even with increased values of TSE, which means that for stable balance between the required power or the demand consumption and the produced power from the solar tower power plant at the selected location the best values of SM should stands with high range such as [2 to 2.4].

These results clearly demonstrate the need to the use of the storage energy system for support the solar power production, especially during the period of low radiation due to weather conditions and during the night where it is important to ensure a constant production of the electrical energy.

On the other hand, it can be said that the choice of an optimized value of the SM according to the required electrical energy to be produced power, plays an important role for ensuring the good compromise between the solar production, the management of the thermal energy storage system and the required electrical energy.

To clearly understand the effect of the TES capacity versus the values of the SM within the afore mentioned range, it is mandatory to study the behaviour of the electrical energy production function of SM. Indeed, TES does not only reduce the unbalance and disharmony between the demand and supply by conserving energy, but also improves the performance and thermal reliability of the system, especially when the power system to which the power plant is connected does not support power production disturbances or breakage. Therefore, designing efficient and economical TES systems is of high importance.

High-energy storage density and high power capacity for charging and discharging are desirable properties of any storage system considering this issue and based on Figure 2 (*supra*), it can be said that this constraint can be achieved for the studied region under optimized design and optimized values of TES.

Another very interesting aspect which can be considered when choosing the exploitation of solar energy in Djelfa region, is whether using the photovoltaic systems or the solar thermal system to produce electrical energy within important amount, is the temperature effect. In this region the solar cells are generally exposed to operating temperatures ranging from 10 to 50° C.

This issue does not have any kind of effect on the thermal solar power plant hence this kind of solar exploitation can be of great advantage and importance in ensuring a reliable source of electrical energy.

It is important to clarify that for low values of SM the produced power is low and it can be mostly less than the required power, to overcome this issue while keeping the same value of SM, a large dimensioning of the solar tower, an important number of the mirrors and a large area.

Therefore, this thermal solar power plant system configuration becomes unprofitable. On the other hand, the starting power of the power station is much better for SM=1.5 where it remains almost stable from TES=4h.

Figure 3 illustrates the produced electrical energy versus the variation of the SM value within the range of [1-2.4] for difference thermal energy storage capacities.

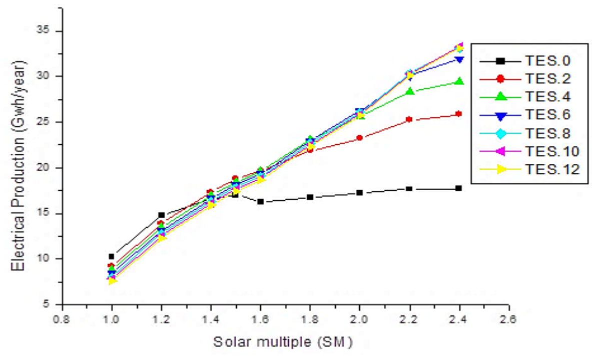

Figure 3. Multiple solar effect (SM) on electricity production under different TES values in the Djelfa region, Algeria

It can be seen clearly that the variation of the produced power is nearly the same for all cases for SM within the interval [1-1.4] and the produced energy is slighter increased with decreased value of TES. Whereas, within the range [1.4-2.4] of SM, in the case of TES.0, the produced electrical energy remains almost constant. In the case of TES.2 and TES.4, the produced energy increases with the increase of SM, however the increase of TES.2 is less than TES.4, but both of them tends to reach limits value. For the other cases, the increase of the produced energy is the same in a nearly linear way, where high value is reached at SM=2.4.

The obtained results show that the energy storage in the form of heat is much better, reliable and can be less expensive than in electrical form, furthermore it allows ensuring the storage of a huge amount of energy compared the electrical form.

At the same time, its conversion to electrical energy can be managed and performed easily, thanks to the available technologies.

Due to the important potential solar energy in the region of Djelfa and the availability of thermal energy storage systems, it can occupy in future an important source of electrical energy. However, research efforts should be directed to improve the storage performance of existing systems and to find new storage technologies.

Figure 4 shows that the variation of the capacity factor (CF) versus solar multiple (SM), behaves in similar way as the produced electrical energy versus SM shown in Figure 3.

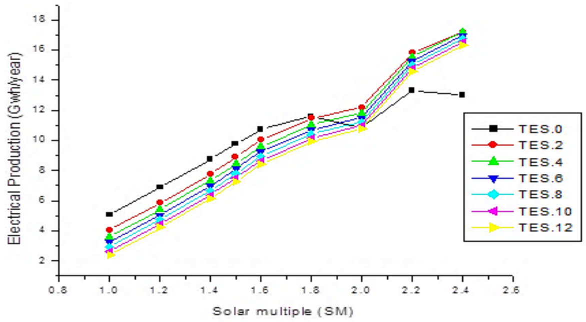

Figure 4. Multiple solar effect on the capacity factor (CF) under different TES values in the Djelfa region, Algeria

4.2. Result of Bechar region

The region of Bechar is a semi-arid region which is 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 [39].

Indeed, the region of Bechar has a 300 MW photovoltaic solar energy station which could be considered the first large scale in African. The produced electrical energy produced by this station is expected to reach 22,000 MW by 2030. In this region, electrical energy can be also produced by concentrated solar power plants where the option of using the thermal energy storage technology to ensure the continuity and reliability of electrical energy flow, can be an interesting advantage for supporting this kind of solar power plant. In this context, the results obtained in the study of this region have made it possible to identify and analyse the difference parameters, which can have major impact on the performance of the eventual concentration solar power plant.

Figure 5 shows the effect of the TES on the production of electricity under different values of SM of the Bechar region, on this figure we can observe that the electric production of the considered heliostats increases in proportion to each value of SM taken with a defined graduated set such as the same as the one considered in the case of the region of Djelfa.

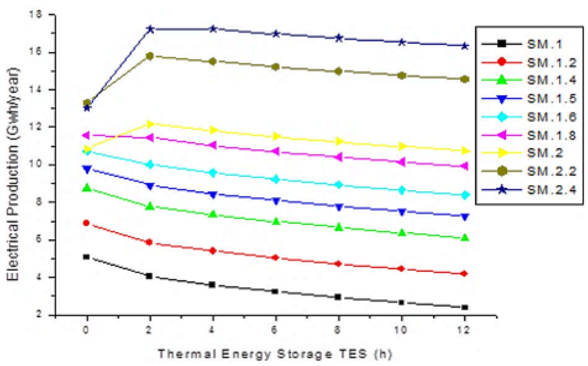

Figure 5. Effect of TES on electricity production under different values of solar multiple in the Bechar region, Algeria

On the other side, it can be noted from Figure 5 that as the SM increases the decrease of the produced energy versus the TES, decreases with lower slope which means that with high values of SM the thermal solar power plant produces electrical energy in a very smooth and nearly constant value even under the increase of the thermal energy storage capacity.

Figure 6 shows the variation of the produced electrical energy versus a limited range of the SM [1-2.4] for the same different values of TES, which were used in the case of the region of Djelfa.

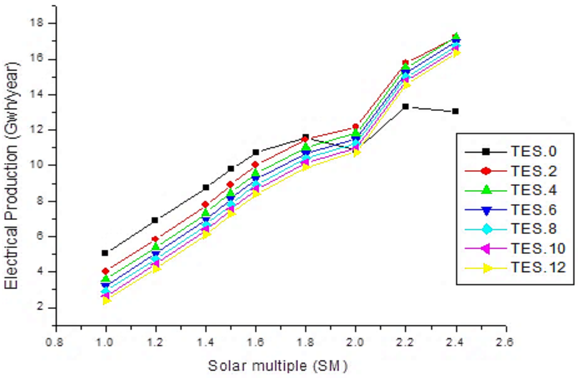

Figure 6. Multiple solar effect (SM) on electricity production under different solar TES values in the Bechar region, Algeria

It is clear that the produced electrical energy increases proportionally to the increase of SM for all the values of TES, whereas within the range of SM [1-1.8], it increases linearly with constant slope, however all the curves for the different values of TES are parallel with different initial values, which are corresponding to SM=1. On the same time, the produced electrical energy increased with decreased values of TES. This difference among the produced electrical energy is more remarkable compared to the case of Djelfa region. This issue can be explained by the higher intensity of the direct normal irradiation (DNI) which is in Bechar region is more than in Djelfa Region.

In the same figure, it can be seen clearly that starting from the value SM=1.8, the produced electrical energy corresponding to TES-0 becomes less than all the other produced electrical energy for different values of TES. On the other side the curves of different values of TES become more closed with more increase according to the increase of SM. It can be said that these results are similar to the once obtained in case of the region of Djelfa with difference of the values of the produced electrical energy which is due to the intensity of the NDI.

Figure 7 illustrates the multiple solar effect on the capacity factor (CF) under different values of solar TES of the region of Bechar.

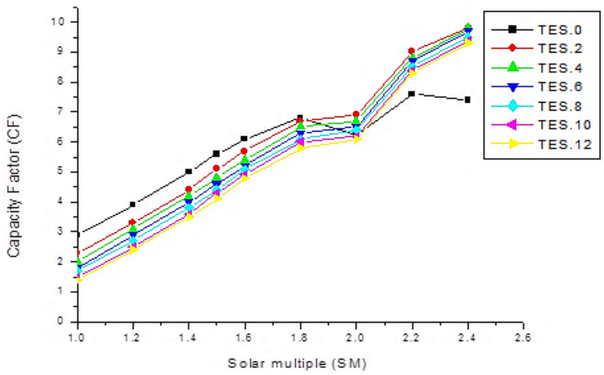

Figure 7. Multiple solar effect on the capacity factor (CF) under different solar TES values in the Bechar region, Algeria

It is obvious from Figures 6 and 7 that the variation of the capacity factor (CF) versus the SM for different values of TSE behaves in the same as the produced electrical energy versus SM. These results are similar to those obtained in Region of Djelfa and which are based on real data collected onsite.

The results obtained in this part of the work focused on the evaluation of global solar radiation in the Bechar region of Algeria and the estimation of the electrical energy produced by concentrated solar power plants. Hence, these solar power plants use a large quantity of mirrors which must follow the movement of the sun in order to collect and concentrate the radiations throughout the daily solar cycle. So, such a system does not seem to have been much studied in the literature.

The results obtained for the both regions of Djelfa and Bechar, which are based on the real date collected onsite and based on satellite data respectively, demonstrate the validity of the both studies for the evaluation of the performance of the proposed concentration solar power plant that is a promising renewable energy source in the future for the production of the electrical energy.

5. Validations of results

Actually, the production of electrical power from renewable energies sources have known an important growing trend in supporting the global need of electrical energy related to the power system, the autonomous gird, isolated sites and individual application. Among the main aims of using such source of electrical energy is the reduction of gas emissions, the environmental protection and the rational use of the existing energy potential at low costs. Indeed, the concentration solar tower power plants (CSP), have been used to produce solar thermal electricity almost everywhere in the world.

The regions studied in this work are the region of Djelfa, the region of Bechar, which are based on satellite and read data respectively. The obtained results have been compared with previous work obtained in other two regions in Algeria with similar solar deposit such as the region of Batna and of El-Oued where their results are obtained based on satellite and real data. The numerical study carried out in this paper on the afore mentioned regions in Algeria can be of great importance and very useful for the eventual building and implementation of the concentrated solar power plant in these regions, whether for ensuring adequate technical-economic optimization and design or for predicting their performances. On the other hand, the presented comparison of the results aims in understanding the influence of normal direct solar irradiation on the solar power plants and its efficiency.

The comparison brought in this paper is based on the parameters, which were presented and discussed in the case of the both studied regions such as the production of electricity and capacity factors considering different values of the thermal energy storage capacities and the solar multiples.

The present study in all the regions is using the thermal energy storage system which is based on the technology of thermal molten salt storage systems that is seems to be the best proposed solution among other technologies.

Table 2 presents the results obtained of the optimal values from the regions of Djelfa, Bechar, El-Oued and Batna in Algeria such as the solar multiple, thermal energy storage capacity, the produced electrical energy, the capacity factor.

Table 2. Results obtained from Bechar, El-Oued, Djelfa and Batna regions in Algeria

Region	DNI (W/m²)	SM	TES (h)	Prod-Elec (Gwh/yr)	CF	data
BECHAR	700	1.8	2	11.44	6.7	Real
EL-OUED	750	1.2	2	7.4	4.2	Real
DJELFA	1050	1.5	4	18.45	10.5	Satellite
Batna	1907.3	1.5	8	18.15	10.6	Satellite

These results are obtained under different available direct normal irradiation related to the region, it is clear that the solar deposit in Bechar and El-Oued from one side, and of the regions of Djelfa and Batna from other side are nearly similar. On the same time the data collected for the first two regions and the second two regions are obtained based on real onsite and satellite data respectively.

Figure 8 shows the histogram of different results presented in Table 2.

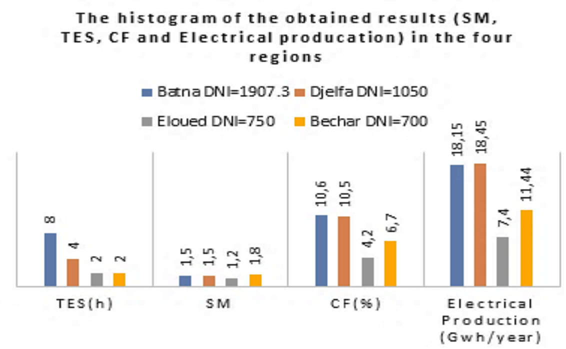

Figure 8. Explanatory histogram of results obtained

It can be seen clearly that the results for each of the two regions (Bechar with El-Oued and Djelfa with Batna) are matching and in agreement, however the difference in the produced energy is due to the difference of the used solar multiple in case of the first two regions and due to the values of the DNI, which require different TSE for the second regions.

Figure 9 shows the effect of TES on electricity production in different regions in Algeria taking into account the optimal values of SM which are presented in Table 2.

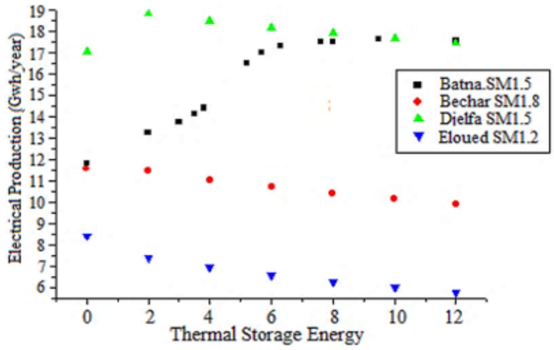

Figure 9. Effect of TES on electricity production in different regions in Algeria with optimal SM values

In this figure, the four curves are corresponding to the four regions respectively, where for each value of TES the corresponding optimal values of produced electrical energy in each region are presented. It is clear that the case of region of Djelfa can be the more profitable due to its important produced electrical energy even at low values of TSE. Whereas, the case of El-Oued is the less profitable case, surely this deduction is valid under the same requirement or demand of the generated power. Unless all the case can be profitable depending on the level of the required electrical power to be produced.

Table 3 summarize the above mentioned results, where the optimal produced power is presented for each value of TES, it is clear that the best value for the region of Djelfa is 18.817952 which corresponds to the value of TES=2h.

Table 3. Optimal SM values of electricity production obtained from Djelfa, Bechar and El-Oued regions in Algeria

TES	Betna_ SM=1.5	Bechar_ SM=1.8	Djelfa_ SM=1.5	El-Ouede_ SM=1.2
0	11.773	11.563929	17.018192	8.417862
2	13.21909175	11.448302	18.817952	7.399254
4	-	11.036597	18.455204	6.949821
6	-	10.704641	18.154252	6.592289
8	17.4816237	10.413588	17.890326	6.282661
10	-	10.150441	17.650414	6.002598
12	17.52328988	9.903687	17.425540	5.744309

For the case of Batna, some values are not presented due to the available real data.

Figure 10 illustrates the effect of the SM on the production of the electrical energy under the optimal values of TSE for each region, which are presented in Table 1.

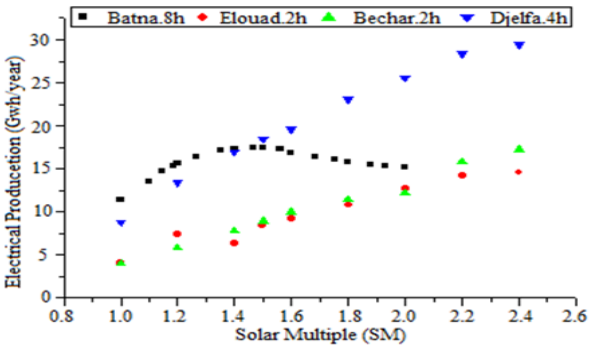

Figure 10. Multiple solar effect (SM) on electricity production in different regions in Algeria with the optimal values of TES

It can be seen clearly that for SM less than 1.4 the produced energy at the Batna region is better, however for the values of SM is greater than 1.4 the produced electrical energy at the region of Djelfa is higher. In the same time the production at the regions of Bechar and El-Oued are nearly the same compared to each other along the variation of the value of SM.

Table 4 presents the more details about the effect of SM on the production of electrical energy for the four regions taking into account the optimal values of TES.

Table 4. Results of electricity production (Gwh / year) obtained from Batna, El-Oued, Bechar and Djelfa

SM	Batna TES=8h	El-Oued TES=2h	Djelfa TES=4h	Bechar TES=2h
1	11.3898	4.02322	4.03816	8.773351
1.2	15.6102	7.39925	5.84442	13.44122
1.4	17.339	6.31265	7.76676	16.95465
1.5	17.4915	8.37139	8.90823	18.4552
1.6	16.8814	9.21429	10.0098	19.64232
1.8	15.7627	10.7966	11.4483	23.11568
2	15.1017	12.6612	12.1714	25.55931
2.2	-	14.2293	15.7923	28.35663
2.4	-	14.5646	17.2099	29.43686

It is also clear that the power production at the regions of Bechar and El-Oued are nearly the same, but in the case of Djelfa and Batna, it is clear that the region of Djelfa can little bit profitable.

Figure 11 shows the multiple solar effect on the capacity factor CF in different regions in Algeria with the optimal values of TES taken from Table 2.

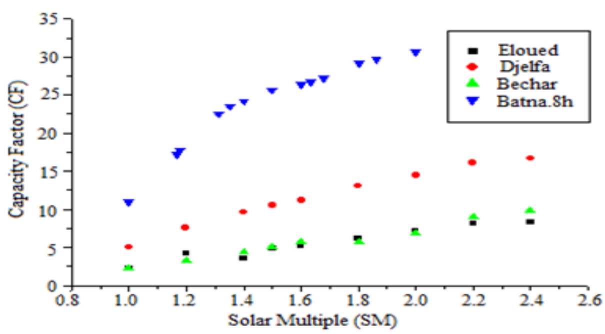

Figure 11. Multiple solar effect on the capacity factor CF in different regions in Algeria with the optimal values of TES

In this figure, a higher SM can lead to a larger storage system and a higher capacity factor of production which means a larger thermal energy storage system is required to ensure the stable operation of the concerned power plant. On the other side, the capacity factor of the regions of Bechar and El-Oued are nearly have the same behavior along the variation of SM, contrary to the region of Batna and Djelfa which have high capacity factor, however the region of Batna has a higher capacity factor. Just to clarify that the region which has high capacity factor requires large thermal energy storage systems, which means high investment charges.

Table 3 presents the optimal values of capacity factor obtained at the regions of Djelfa, Batna, Bechar and El-Oued.

Table 3. Influences of SM of the capacity factor (CF) at regions of Djelfa, Bechar, Batna and El-Oued regions in Algeria

SM	Batna TES=8h	El-Oued TES=2h	Djelfa TES=4h	Bechar TES=2h
1	10.963	2.3	5.0	2.3
1.200	-	4.2	7.6	3.3
1.4	24.157	3.6	9.6	4.4
1.5	25.653	4.8	10.5	5.1
1.6	26.405	5.2	11.2	5.7
1.8	29.186	6.1	13.1	5.7
2.000	30.691	7.2	14.5	6.9
2.2	-	8.1	16.1	9.0
2.4	-	8.3	16.7	9.8

These results allow finding the optimal configuration of a CSP-based thermal solar power plant, based on the obtained optimal parameters and the other factors, which are related to the studied location such as the solar field, the site's solar irradiation, and the time of full charge. It can be said that all the presented regions are the most favourable and profitable regions to produce electrical energy using CSP plants.

Finally, based on the obtained results, especially concerning the curves of the electrical produced energy from the concentrated solar power plant. It is important to notice that the electrical produced powers in the cases of the two regions which are based on satellite data, are nearly twice those in the case of two regions which are based on real data. This issue can be explained by the fact that the data based on satellite are more precise and they take into account all the atmosphere constrains. Hence, it can be said that the satellite date can be of great interest to be used in the design and building of the CSP.

6. Conclusions

The present paper deals with the possibility of using concentrated solar power plant in Algeria to ensure the production of the electrical energy along the whole day, even under worse case of bad weather. Indeed, the obtained results are very encouraging to go towards this choice, in the same time they are confirming that a high power CSP is able to replace the existing plants for the production of electricity in Algeria with high levels, which can cover the national electrical energy demand.

The presented study was based on a deep investigation on four regions in Algeria, which have high deposit of solar energy, where, two kinds of data have been used based on measurements onsite and satellite information.

On the other side, to solve the problem of dark periods a thermal energy storage system based on molten salt has been proposed and integrated in this study, where optimized parameters, especially the solar multiple (SM) and the thermal energy storage capacity (TSE), which have been identified in this work for the four studied regions.

The obtained results of the studied concentrated power plant (CSP), conduct us to the following point:

- The direct normal irradiation is the key factor of the selection of the profitable region;
- The satellite data can be a key decision on the real capacity of a region;
- There is a strong relationship between Solar Multiple (SM), electricity production and storage capacity;
- To avoid proceeding to an auxiliary source of energy to guarantee a permanent activity during all the day, the number of heliostats should be increased to increase the SM value and a thermal energy storage system with optimized TES should be installed.

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