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Estimation of Solar Radiation and Feasibility Analysis of a Concentrating Solar Power Plant in Birao, Central African Republic

Venant Sorel Chara-Dackou[1,2*], Donatien Njomo[1], René Tchinda[3], Yvon Simplice Kondji[2], Daniel Roméo Kamta Legue[1], Mahamat Hassane Babikir[4]

[1] Energy and Environment Laboratory, Department of Physics, Faculty of Science, University of Yaounde I, P.O. Box 812, Yaounde, Cameroon
[2] Carnot Energy Laboratory (CEL), Department of Physics, Faculty of Science, University of Bangui, P.O. Box 1450, Bangui, Central African Republic
[3] Department of Physics, University Institute of Technology, Fotso Victor of Bandjoun (IUT-FV), P.O. Box 134, Bandjoun, Cameroon
[4] Department of Physics, University of Ndjamena, P.O. Box 1117, N'Djamena, Chad

Corresponding Author Email: chav7@yahoo.com

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ABSTRACT

This study develops numerical models to estimate the solar radiation in Birao, Central African Republic and evaluates the feasibility of a concentrating solar power (CSP) plant. Three solar radiation estimation models are assessed using statistical performance metrics. The Capderou model shows the best accuracy with mean absolute deviation of 14% and root mean square deviation of 17%. The model is applied with three sun-tracking modes, with the north-south axis mode having the lowest RMSD of 7% in estimating direct normal irradiance. A techno-economic analysis indicates that the solar resource in Birao can support a CSP plant. The developed estimation tool can help optimize the siting and sizing of CSP systems to enable greater solar energy utilization.

1. INTRODUCTION

The exploitation of a resource in a given region requires the quantification of the existing potential [1]. For environmental protection and sustainable development [2], the use of renewable energy resources is important for the production of energy (steam, electricity) for industrial or local needs [3, 4]. Solar photovoltaic technology is widely used to produce electricity, sanitary water in private residences and also in solar power plants [5]. Due to its low overall solar-electricity efficiency, concentrating solar power technologies are increasingly being used on a large scale with good solar-electricity efficiencies. This requires first of all the information on the availability of solar resources satisfying the conditions of use of the chosen technology [6-11]. The quantification of the solar potential from good quality in situ measurements is ideal for any solar application project [12, 13]. However, in the absence of these, solar radiation estimation models are used [14, 15]. Theoretical and numerical models for estimating incident solar radiation have been developed in different climates for local applicability and sometimes according to climatic similarities [16]. Therefore, there are several types of so-called empirical models that use sunshine duration, meteorological parameters as input to determine the components of solar radiation and evaluate the energy potential in a given region [17-21]. The so-called semi-empirical models need geographic coordinates as input and some characteristics such as the state of the sky, the albedo to take into account the phenomena that solar radiation undergoes when crossing the atmosphere [22]. They have the advantage of estimating solar radiation on different planes and even adapt to the modes of tracking the sun for moving collectors [23]. In addition, there are estimation techniques from satellite images where the results are very close to those of measurements made in situ [24], then the prediction from artificial intelligence [25-27], and others [28-31]. Depending on the contexts of the study conducted, the choice of the solar radiation estimation model is very judicious. In his work on the study of the performance of a flat plate solar water collector in steady state, Brahimi [32] made a comparative study of three models for estimating solar radiation, a parameter on which the performance of the device strongly depends in order to choose the most suitable one for the study. The results showed that some models estimate better the direct component of the sun, other models estimate well the other components and according to the inclinations of the sensor. Mesri-Merad et al. [33], have developed theoretical models for estimating solar radiation on the ground in Algerian sites. These four models were compared to the measured data of the sites in order to validate the one whose estimation is the best in the different climatic conditions. Obukhov et al. [34], in order to predict the main characteristics of solar radiation for any geographical point in Russia have developed an original model of solar radiation arriving on an arbitrarily oriented surface. This model has as a particularity the initial data as the numerical values of the atmospheric transparency index and the surface albedo. The results clarify the applicability of the model wherever actinometric observations are not regular. A mathematical model for calculating global solar radiation with greenhouse effect was developed by Chena et al. [35], for use in buildings after analyzing six typical greenhouse shapes (same span, unequal span, ellipse, arch, sawtooth and winery) found in southern China in order to select the most suitable one, for maximum solar radiation capture. This model is applicable not only to different regions of the world but also to other types of buildings and that the sawtooth captures the most global solar radiation in winter at all latitudes. Tabet et al. [36], in their work, used isotropic models (Capderou, Liu & Jordan) to determine the solar radiation incident on a horizontal surface in Ghardaïa (Algeria). They are then associated with other anisotropic models (Klucher, Hay-Davies and Reindl) to determine the solar radiation on a tilted surface and the optimal tilt angle for each month, season for hybrid solar collectors in order to improve their efficiency. The statistical results show that these models used were well designed, and that the tilt angle of the collector used takes different values during the year. Also, this collector receives more solar energy compared to the collector without optimal angle. Comparative studies of the choice of estimation models similar to the latter have been carried out in order to propose an estimation model that responds to the variability of solar flux in the study area and its climatic specificities [37-39]. El Mghouchi et al. [40] evaluated four solar radiation models in the North of Morocco. Statistical analyses indicate that these models can be used to predict daily solar radiation data for the year. Babikir et al. [41] modeled and estimated the incident solar radiation in the city of Ndjamena in Chad using the Capderou model. Arim et al. [42] in their work made a comparative study of two radiation models in two cities of Chad under different angles of inclination to the ground. The results showed the limitations of these two models according to the angle of inclination and also according to the climatic seasons. These multitudes of comparative studies in the use of solar radiation estimation models are due to their level of adaptation and accuracy in modeling and estimating solar radiation in a region under its climatic variabilities and the search for the most adequate model. Refs. [22, 40-42], have shown that the models of Capderou, Perrin de Brichambaut and Liu & Jordan are the most adapted to the Sahelian desert climate. However, these models differ in the quality of their estimates depending on the periods or seasons of a given year [43-47].

Thus, in this work, a statistical evaluation of these three radiation models (Capderou, Perrin de Brichambaut and Liu & Jordan) is made with the aim of proposing the most accurate and adapted one, followed by a simplified techno-economic study of the project of implementation of a solar power plant with parabolic trough concentrator to develop the quantified solar potential.

The main contributions of this work are summarized as follows:

- A statistical evaluation with model validation was performed and the best model was obtained. The solar radiation components in the city of Birao were modeled and estimated for all months of the year.
- A statistical study was performed on the optimization of solar radiation for moving collectors and the most optimal tracking mechanism in Birao was obtained.
- The simplified economic analysis showed that the solar climate in Birao is very favorable for an investment in CSP plants based on a good hourly solar radiation estimation tool.

2. STUDY AREA, METHODOLOGY AND STATISTICAL METHOD

Birao is a city located in the extreme north of CAR in the Sub-Saharan climate (Figure 1), with geographic coordinates of 10°17’ North, 22°47' East and altitude 464m. Thanks to this geographical position close to the equator, it benefits from a sunshine of about 6 kWh/m^2/day, the most important of all regions and cities of the Central African Republic (CAR) [16]. These selected models will be simulated under its climatic conditions and their performance will then be statistically evaluated in terms of estimating the values of global radiation on the ground on a horizontal surface in comparison with the data from the CAMS database, considered as the data measured in this work in the absence of measurements made by radiometric and meteorological stations [16]. The choice of CAMS is based on the results of works in the literature, which validate it as the best reliable solar radiation database [16, 24]. These data are taken over a period of 15 years (2005-2020) with a temporal resolution of one hour and for a clear sky. The different averages were then calculated. Note that these models used are for a clear sky. The model selected among the three is used to estimate the values of all components of solar radiation in the city of Birao. This model is coupled to the different sun tracking modes in order to make a comparative study on the optimization of the direct component of the solar radiation used by the moving solar collectors in order to maximize the direct incident flux and improve their efficiency. Then, a techno-economic analysis was then conducted based on the solar resource assessment to evaluate the feasibility of a parabolic trough CSP plant. The Figure 2 shows the flowchart of the methodology.

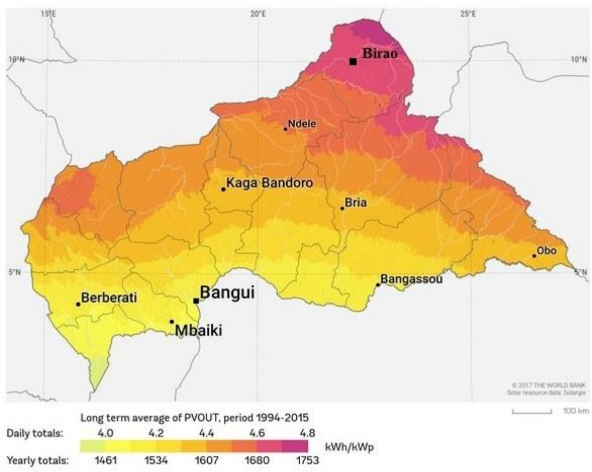

Figure 1. Solar map of the Central African Republic (Solargis, https://solargis.com)

The solar radiation estimation models of Perrin de Brichambaut, Capderou and Liu & Jordan are from the previous studies [40-42] respectively. The three models estimate global horizontal irradiance as a function of extraterrestrial irradiance and climatic parameters. Ground albedo was assumed as 0.2 based on land cover in the region. Azimuth-altitude, vertical-axis and tilted-axis tracking modes were simulated with surface azimuth angles of 180°, 90° and 0° respectively.

The statistical indicators of error calculation are used as criteria to evaluate the performance of the models. This makes it possible to compare them and to choose the one most adapted to the climatic characteristics of the study area. These indicators chosen are the mean bias deviation (MBD), the mean absolute deviation (MAD) and the root mean square deviation (RMSD). They are calculated from the following equations [24, 48]:

$$MBD = \frac{1}{n}\sum_{i=1}^{n}\frac{I_{e,i} - I_{m,i}}{I_{m,i}} \tag{1}$$

$$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{I_{e,i} - I_{m,i}}{I_{m,i}}\right| \tag{2}$$

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{I_{e,i} - I_{m,i}}{I_{m,i}}\right)^2} \tag{3}$$

where, n is the number of observations, e means estimated and m means measured.

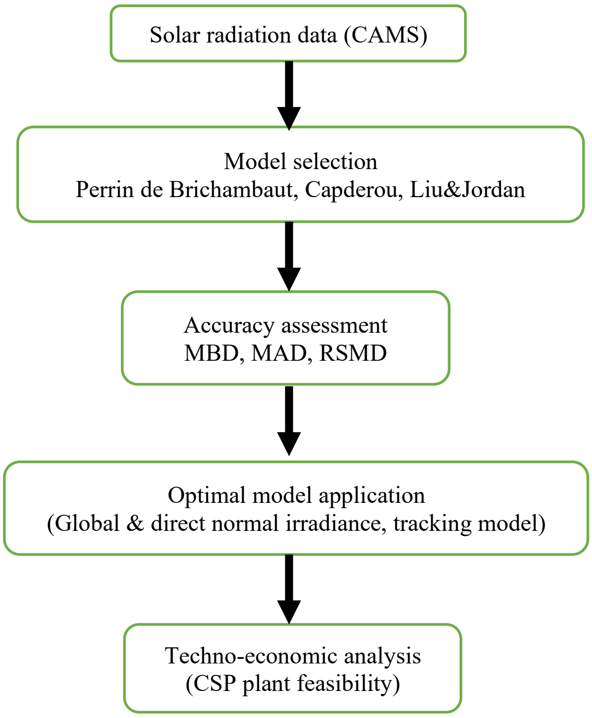

Figure 2. Flowchart of the methodology

3. MECHANISMS OF THE SUN-TRACKING SYSTEM: THE INCIDENCE ANGLES OF THE COLLECTORS

In order to optimize the solar energy received at the receiving surface of the solar collectors used, different mechanisms for tracking the sun in its path across the sky during the day have been developed. These mechanisms are based on the angle of incidence to collect the direct radiation of the sun to the maximum and used by solar collectors in motion. Solar concentrators are used by concentrating solar technologies (called thermodynamic solar technology) which have the principle of collecting and concentrating the direct solar radiation to the maximum by a reflecting surface on a solar receiver (linear or point). The tracking mechanisms of the sun are variable and differ from their modes of movement. This can be around a single axis or around two axes. For the first case, we distinguish three different ways and for the second case we talk about a complete sun tracking system. Tracking modes were analyzed to determine the optimal configuration for the Birao region based on solar geometry.

3.1 Single-axis tracking system

There are three modes of tracking around a single axis often used by concentrated solar technologies [23].

3.1.1 North-South polar axis with East-West tracking system

The collector axis is tilted at the polar axis. The tilt angle of the collector is equal to the local latitude. For this arrangement, the incident radiation is normal to the collector at the equinoxes (*d=0*) and the cosine effect is maximum at the winter and summer solstices. The equation is given by:

$$\cos(\theta) = \cos(d) \tag{4}$$

where, θ is angle of incidence.

3.1.2 North-South horizontal axis with East-West tracking system

The collector rotates around a horizontal North - South axis with a continuous adjustment to minimize the angle of incidence. The expression can be written as follows [23]:

$$\cos(\theta) = \cos(\phi)\cos(h) + \cos(d)\sin^2(h) \tag{5}$$

3.1.3 East-West horizontal axis with North-South tracking system

The collector rotates around a horizontal East-West axis with continuous adjustment to minimize the angle of incidence. The latter can be obtained from the following geometry [23]:

$$\cos(\theta) = \left[\sin^2(d) + \cos^2(d)\cos^2(h)\right]^{1/2} \tag{6}$$

3.2 Single-axis tracking system

This mode is typically used by Dish/Stirling systems to keep the reflective surface of the collector constantly perpendicular to the incident radiation by tracking the sun's path across the sky in two axes. This depends largely on the precision of the mechanism to ensure that the angle of incidence is equal to zero at all times of the day. The expression is given by [23]:

$$\cos(\theta) = 1 \tag{7}$$

4. TECHNO-ECONOMIC EVALUATION OF THE SOLAR POTENTIAL VALORIZATION BY CONCENTRATING SOLAR TECHNOLOGIES

According to existing data in the literature, solar photovoltaic (PV) power plants have on average a much lower discounted energy cost (0.038 US$/kWh) than solar thermal power plants (0.165 US$/kWh). This difference is due to the high initial investment cost of solar thermal plants. Solar thermal power plants are better than PV power plants from the efficiency point of view with other advantages such as cogeneration and long term thermal storage system. Nevertheless, they require for a normal operation a direct normal irradiation (DNI) of at least 5 kWh/m^2/day. In this study, the solar thermal technology is chosen to carry out the techno-economic analysis of the implementation project of solar power plant for energy generation. This study focuses on concentrated solar thermal technologies in relation to its aforementioned advantages and the energy contexts of the city of Birao.

This financial feasibility study of the project is based on the determination and analysis of the financial and energy parameters considered such as: annual energy produced, cost of electricity per unit, net present value, internal rate of return, benefit/cost ratio and discounted payback period. Inflation and exchange rates considered, simplified assumptions around operating and maintenance costs, and possible fluctuations in key costs like initial investment that can impact the feasibility outcomes.

The annual electricity generation**:** It is the annual electrical energy delivered by a CSP system from the solar irradiance received annually and can be calculated from the following relationship [49, 50]:

$$AEG = 365 * 24 * C_f * P_n \tag{8}$$

where, P_n, C_f are respectively the rated power of the CSP and its capacity factor.

The unit cost of electricity**:** This is the cost per unit of kWh delivered by a CSP system based on its annual electricity production. It can be estimated as follows [50]:

$$UCE = \frac{CRF * C_i + C_{omr}}{AEG} \tag{9}$$

With

$$CRF = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{10}$$

The terms CRF, C_i, r, C_{omr} and t refer to the payback factor, the initial investment cost, the discount rate, the operating cost of maintenance, operation and repair, and the life of the project, respectively.

Net present value**:** This is a financial indicator that designates a discounted cash-flow that represents the additional value created by an investment compared to what was required as the minimum to be realized by investors. It is calculated from the following relationship [50]:

$$NPV = -C_i + \sum_{t=1}^{T} \frac{B_i - C_{omr}}{(1+r)^t} \tag{11}$$

With

$$B_i = 8760 * C_f * P_n * P_e \tag{12}$$

The terms B_i, P_e represent the annual profit accruing to the investor from the sale of the electricity produced and the purchase price of the electricity respectively.

The discounted cost-benefit ratio**:** This is the rate of discounted profit that is realized from the initial investment throughout the period T [50].

$$\left(\frac{B}{C}\right) = \frac{1}{C_i} \sum_{t=1}^{T} \frac{B_i - C_i}{(1+r)^t} \tag{13}$$

The internal rate of return**:** This is a financial indicator that makes it possible to evaluate the relevance of an investment project. It designates the rate for which the NPV is zero. It is calculated from the following equation [50]:

$$-C_i + \sum_{t=1}^{T} \frac{B_i - C_{omr}}{(1+IRR)^t} = 0 \tag{14}$$

Discounted payback period**:** This shows the number of periods required to recover an investment, in months or years. The shorter the period, the more the investment is favored. The relation allowing its calculation is the following [50]:

$$DPP = \frac{\ln(B_i - C_i) - \ln\left[(B_i - C_i) - r * C_i\right]}{\ln(1+r)} \tag{15}$$

5. RESULTS AND DISCUSSIONS

5.1 Validation of the hourly global irradiance estimation model

Simulation of the estimation models used in this work allowed the global irradiance to be quantified monthly using the representative days recommended by Klein [41].

Figure 3 describes the evolution of the monthly daily average of the hourly global irradiance estimated by each of the models and in comparison with the data from CAMS (data). For each month of the year considered, the approximation of the estimates from each model by the measured data varies significantly. The Liu & Jordan model graphically tends to overestimate the global irradiance (with large maximum values) compared to the CAMS (data) data. It shows significant observable differences during the day and between months with MBD 17%; MAD 24% and RMSD 29%. Unlike the Capderou and Perrin models where on average the differences between their values and those of CAMS (data) are small. These two models are the best in predicting global irradiance in this region with MBD 5%, MAD 14%, and RMSD 17% for Capderou and MBD 4%, MAD 16% and RMD 20% for Perrin de Brichambaut (Table 1). These observed differences in predictions can be attributed to the mathematical expressions of the models and their different consideration of certain physical phenomena that solar radiation undergoes as it passes through the atmosphere (absorption and scattering by aerosols and certain constituents of the atmosphere). The Liu & Jordan model tends to overestimate the irradiance values. However, these two models differ in their estimates for the four seasons of the year. In autumn, Capderou's model (with MBD 5%, MAD 15% and RMSD 18%) predicts better compared to Perrin's (with MBD 4%, MAD 16% and RMSD 21%). This can be seen in Figure 3 for the months concerned. Table 2 calculating the average errors by season, shows that Capderou's model predicts global irradiance better in autumn, spring, and summer while Perrin's is preferred only in winter. This can be justified by the quality of the ground cover taken into account through the diffuse irradiance components in Perrin's model (backscattered radiation, from the ground, from the sky). Added to this are the observed variabilities of these seasons in different types of climate. The geographical and meteorological conditions in which the models were developed can also justify the models' levels of precision in estimation and their seasonal adaptability, as Katiyar and Pandey [18] and Marif et al. [39] have underlined.

Figure 4, in comparison with CAMS data, the trends clearly show the good predictions of the Capderou and Perrin models. Overall, the Capderou model can be used in the Birao city climate to estimate the global ground irradiance over a horizontal surface.

Figure 5 shows the evaluation of the diffuse, direct and global components of solar radiation for all months of the year from the Capderou model.

Table 1. Evaluation of the annual averages of the calculated monthly deviations of the models and their validation

Model	MBD (%)	MAD (%)	RMSD (%)
Liu Jordan	17	24	29
Capderou	5	14	17
Perrin	4	16	20

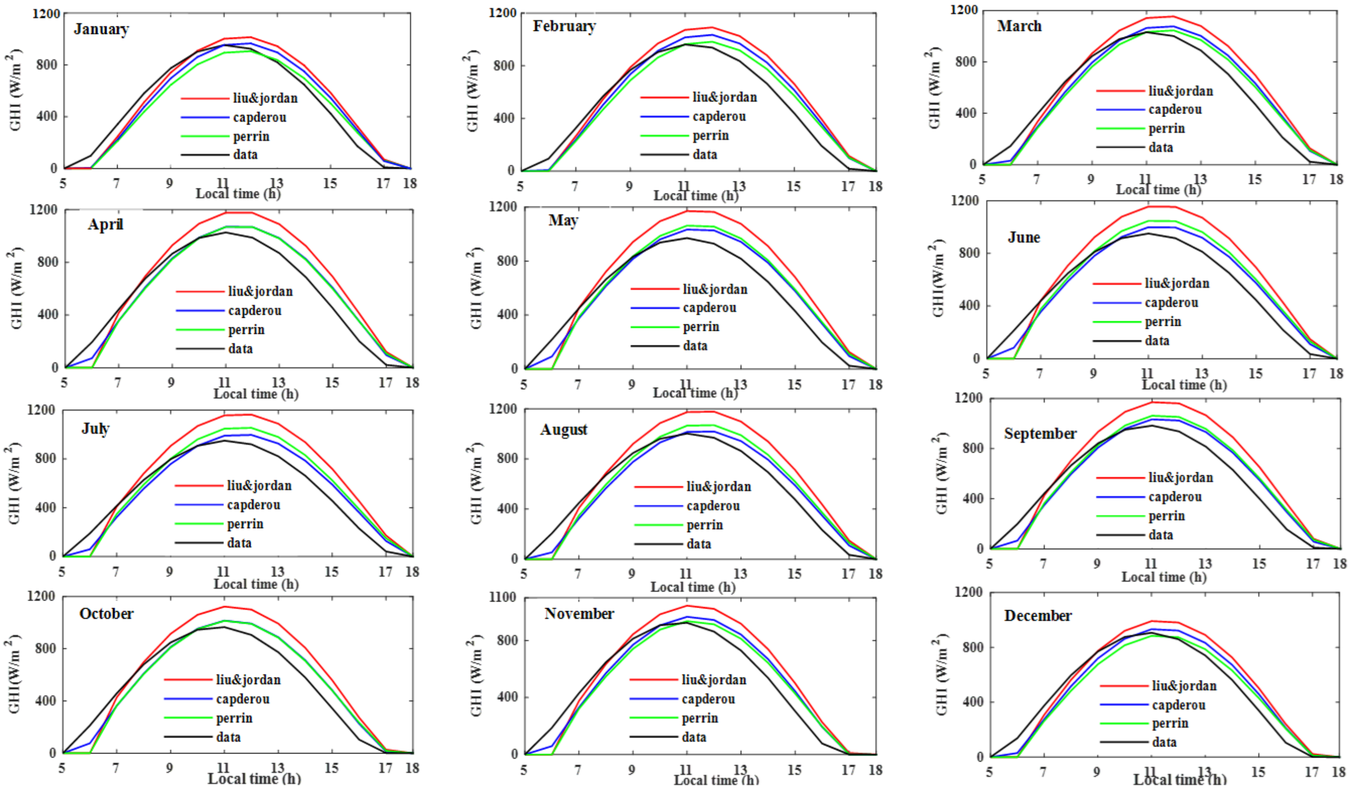

Figure 3. Diurnal variations of monthly daily averages of global irradiance values of the different models and the measured values

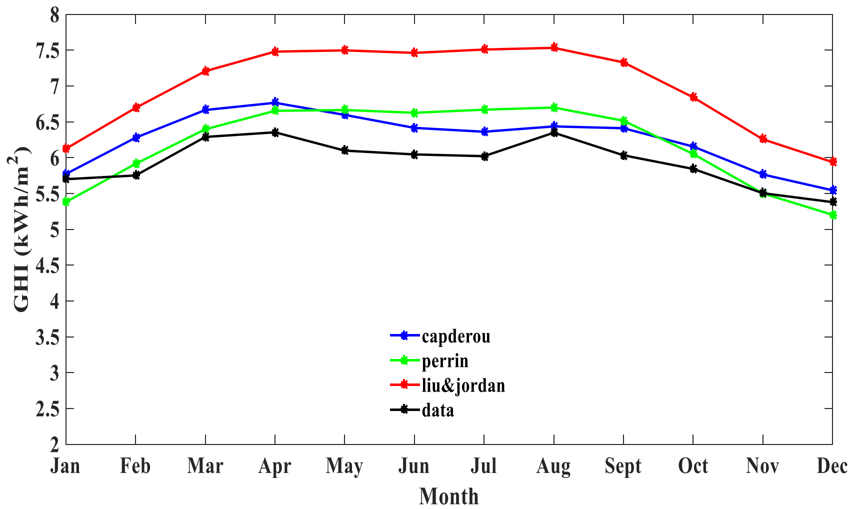

Figure 4. Monthly comparison of estimated daily global irradiance values from different models

Table 2. Assessment of model deviations by season

Model	MBD				MAD				RMSD			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Liu Jordan	0.11	0.18	0.22	0.17	0.19	0.25	0.28	0.24	0.23	0.30	0.34	0.30
Capderou	0.04	0.06	0.04	0.05	0.15	0.15	0.14	0.15	0.18	0.18	0.17	0.18
Perrin	-0.02	0.05	0.09	0.04	0.15	0.16	0.18	0.16	0.18	0.20	0.22	0.21

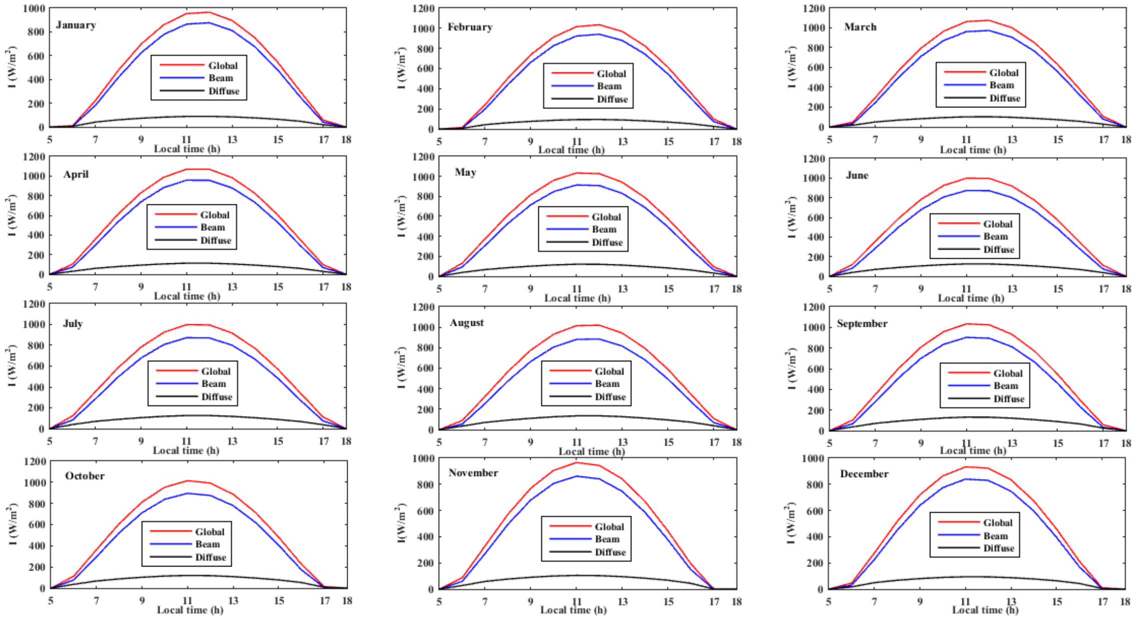

Figure 5. Variation of the monthly daily average of global, diffuse and beam hourly irradiance under clear skies on a horizontal plane by the Capderou model

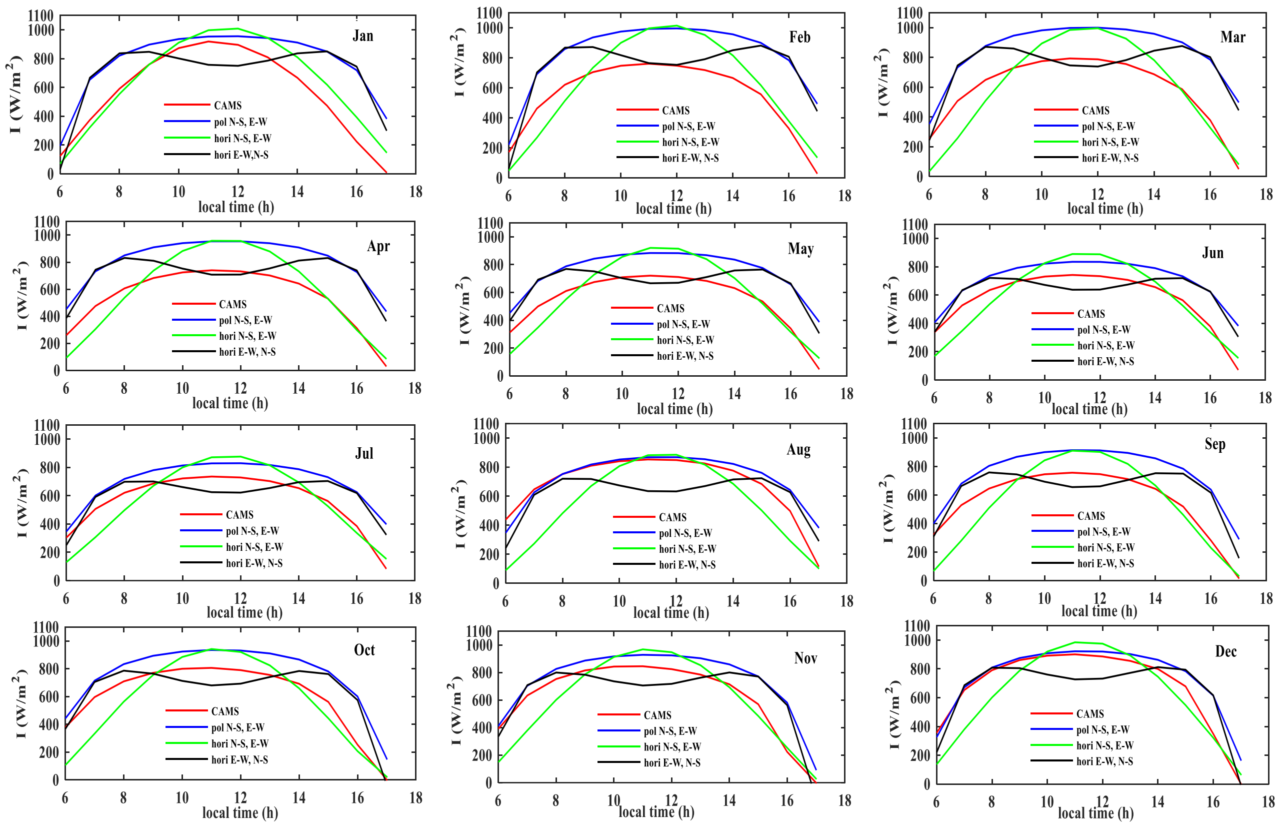

Figure 6. Comparison of the different sun-tracking modes used by the moving collectors

5.2 Monthly comparison of the different tracking systems

The Capderou model after validation is coupled to the different mechanisms for tracking the sun's path. In Figure 6, the different mechanisms have been used to evaluate the direct irradiance in each case and compare them to the two-axis tracking system taken as the ideal. Its data are also from CAMS under the same conditions as the global irradiance used in this study. Table 3 gives a quantitative appreciation of the different mechanisms used.

For the North-South polar tracking mode of East-West horizontal axis, the most unfavorable month is February with an RMSD of 50% and the most favorable month is August with an RMSD of 6.3%. For the North-South tracking mode of East-West horizontal axis, the most favorable month is July with RMSD of 0.2% and the most unfavorable month is August with RSMD of 19.8%. For the East-West tracking mode with a North-South horizontal axis, the greatest difference is observed during the month of February with RSMD 32% and the lowest during the month of November with RSMD of 2.3%. On an annual average, the North-South tracking mode of East-West horizontal axis with RSMD of 7% compared to the two other modes (with RSMD 30% and 15%) is the best adapted and closer to the complete tracking mode (with two axes). Nevertheless, choices of tracking mode can be made according to their monthly performance (Table 3) in order to maximize the collection of the direct solar radiation and thus allowing to considerably improve the optical yields of the collectors by maximizing the direct incident solar flux. These differences observed monthly and during the day can be due to the periodic variation of the declination of the sun which changes the position of the sun in the sky, influences the variation of the maximum height of the sun. In winter as well as in summer we expected to have a maximum cosine effect for the N-S polar axis tracking mode in contrast to the other modes but this is not the case compared to the CAMS data. This may also be due to the aspects described in section IV.1, which are responsible for the overestimation of the estimated radiation values. However, these seasonal variations in the observed model accuracy could influence the optimization of the direct irradiance estimate, and then impact on the energy and financial parameters of the project feasibility. It would be necessary to have the measured data of some parameters like the haze factor and then make a comparative study with the simulated data to appreciate the mathematical approach used as Marif et al. [39] did in their study in Algeria.

Figure 7 compares the estimates of direct solar radiation with the North-South East-West horizontal axis tracking mode and without the tracking mode. For each month, the amount of energy gained or lost when the North-South East-West horizontal axis tracking mode is used or not is shown. The direct solar irradiance with the North-South East-West horizontal axis tracking mode is estimated to be 2913 kWh/m^2/year and without tracking mode to be 2319 kWh/m^2/year.

Table 3. Calculation of the errors of the different monoaxial tracking systems compared to the data from CAMS for a complete tracking system as a reference

	RMSD												
System	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Mean**
Polar N-S axis with E-W tracking	0.372	0.503	0.441	0.499	0.379	0.240	0.237	0.063	0.350	0.263	0.191	0.092	**0.302**
Horizontal E-W axis with N-S tracking	0.122	0.132	0.021	0.086	0.078	0.017	0.002	0.198	0.030	0.064	0.046	0.083	**0.073**
Horizontal N-S axis with E-W tracking	0.222	0.323	0.259	0.311	0.213	0.090	0.068	0.103	0.127	0.059	0.023	0.037	**0.153**

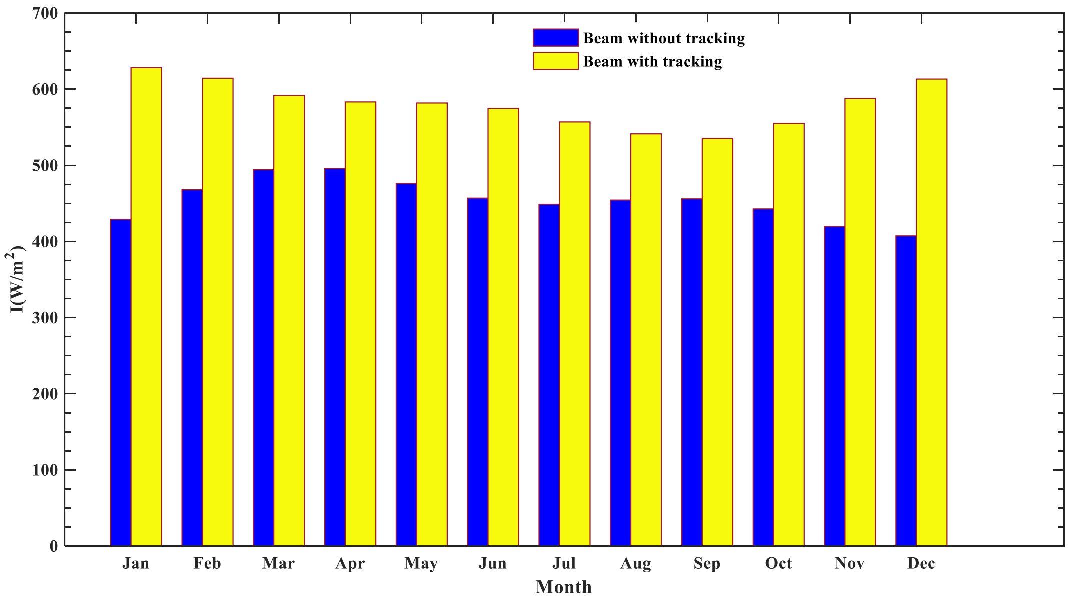

Figure 7. Comparison between the daily monthly averages of the hourly solar radiation received with the North-South tracking system of East-West axis and without tracking system

5.3 Techno-economic analysis of the CSP system implementation project

The techno-economic analysis aims at identifying the economic interest of the solar climate development in Birao via the CSP project. Since there is no existing CSP plant in CAR, the data and model for the CSP plant are taken from [49, 50]. Tables 4 and 5 shows the characteristics of the plant and its investment costs are assumed to be the same in this study.

The meteorological operating conditions are assumed to be similar for the case of this study and only the solar irradiance is the variable climatic parameter depending on the study site (Birao city) whose values were estimated by the Capderou model with the North-South tracking mode of East-West horizontal axis. The other assumptions necessary to carry out this study are:

- The annual operating cost of operation, maintenance and repair is estimated at 5% of the initial investment cost since these technologies are not developed in CAR;
- The discount rate is set at 10% given the investment climate in CAR;
- The payback cost (or residual value) of the CSP system that will be built is estimated at 3% of the initial investment cost;
- The useful life of the system is estimated at 30 years.
- The unit price of electricity on the market sold to individuals varies between 150 and XAF 182 according to the Central African energy company (ENERCA) [3]. Following recent improvements to the network, the market price has increased and varies according to the type of connection. Thus, in this study the price is set at 150 XAF/kWh or 0.23 Euro/kWh.

In all the financial aspects of this study, the FCFA and the Euro are the two currencies used (1 Euro=XAF 655).

Table 4. Technical characteristics of ANDASOL-1 thermal power systems [49]

Design Features	ANDASOL-1
DNI	1750 kWh/m^2/year
Nominal electrical power	49900 kW
Tower height	-
Receiver technology	Parabolic trough Solar field 510,120 m^2
Heliostats	-
Thermal storage capacity	7.5 h reserve
Steam cycle	-
Ground area	200 ha
Annual electricity production	179 GWh

Table 5. Financial parameters used for the techno-economic analysis of the CSP system [50]

Parameter	Symbol	Unit	Values
Capital cost	C_i	Million Euro	311
Discount rate	r	-	0.10
Purchase price of electricity	P_e	Euro/kWh	0.23
Useful lifetime of CSP	T	Years	30

In Table 6, for a direct solar irradiance value of 2913 kWh/m^2/year, the annual energy production is 297 GWh, with a capacity factor of 68%. With a positive NPV, the project is profitable, can generate added value. The unit cost per kilowatt is 0.16 Euro/kWh, which is far below the unit prices set by ENERCA [3]. The IRR is 45% for a return on investment of 9 years 3 months and 29 days. Thus the analysis shows that the project is viable and profitable. From the right choice of tool for the hourly estimation of solar radiation, the solar climate in Birao appears to be very favorable for an investment in CSP systems. The results of the annual production of the plant shows the importance of having a better modeling tool, optimizing the solar radiation coupled to the CSP collectors in order to further improve the profitability and viability of the investment.

Table 6. Estimated values of the financial and energy parameters used in the decision making process of the CSP implementation project in the city of Birao

Financial and Energetic Parameters	Values
Annual Electricity Generation (GWh)	297
Capacity factor (%)	68
Unit cost of electricity (Euro/kWh)	0.16
Net Value present (Million Euro)	196
Internal Rate of Return (%)	45
Discount Payback period (Year)	9.33
Benefit/Cost ratio	1.63

Sensitivity analysis of investment NPV to changes in other financial parameters

It is a technique to observe how an increase or decrease in the value of a financial input parameter affects the final result of a financial analysis. In this section, NPV is chosen as the most appropriate financial indicator in the decision making process of an investment project compared to IRR as the dependent variable.

The results of sensitivity analysis on the project by choosing the important input parameters are presented in Figures 8 and 9. In the case of the cost of capital, ceteris paribus, the 10% increase causes the NPV of investment to change from 196 to 151 Million Euro or a decrease of 22.95% while a 10% decrease causes the NPV to change from 196 to 240 Million Euro or an increase of 22.44%. As the positive change in the cost of capital increases, there is less and less cash flow generation and as the negative change in the cost of capital decreases, there is more and more cash flow generation. In the case of the cost of operation, maintenance and recovery, a similar trend is observed as in the case of the cost of capital, but with quantitatively very important fluctuations. Ceteris paribus, a 10% decrease in this cost leads to an increase in the NPV from 196 to 216 Million Euro, i.e. an increase of 10.20%. On the other hand, an increase of only 10% causes the NPV to vary from 196 to -167 Million Euro, i.e. a decrease of 185%. The NPV of this project is very sensitive to variations in this cost.

6. DISCUSSIONS

Of course, reducing the cost of capital can have a direct effect on the cost of operation, maintenance and repair, on plant dimensioning, on the quality of equipment purchased, and consequently on energy production. However, this reduction positively improves cash flow generation, as the higher the investment, the longer the payback period. This was noted in the first part of this techno-economic analysis of the two projects. It is therefore necessary to look for ways of optimizing the plant, in order to analyze the extent to which the initial investment can be varied without having a significant negative impact on the plant's other costs and compartments. This would promote the creation of financial flows and then value creation. Operating, maintenance and repair costs play a very significant role in value creation, given the sensitivity of NPV to either downward or upward variations. Decreasing costs are very favorable to increasing cash flows. So it's important to think about the mechanisms that can help reduce it. It turns out that this solar technology is not yet developed in Africa, and even less so in the sub-region, which would require a substantial input of outside expertise (technicians, engineers), and this would entail a hefty bill at the start of the project. However, efforts in research and development, followed by the training of national personnel (technicians, engineers and others) in CSP, could reduce the bill paid from a given point in the project life cycle, in order to offset the need for external expertise. To increase value creation while minimizing possible other effects on other inputs, the variation in the initial investment cost should vary between 0% and 10% in order to maintain a positive NPV. The positive variation in the price of electricity increases with the NPV. However, the implementation of various energy access projects by the Central African government, such as the PURACEL project financed by its partners, could reduce the unit cost per kilowatt hour in the country over the coming years. But this would also have an impact on investors, especially in solar thermal technologies (a technology with a high LCOE). Given the purchasing power of CAR households, increasing the price of electricity would further reduce the rate of access to electricity in the country. On the other hand, by reducing the cost, households will see their electricity bills revised downwards, and the rate of access to electricity will increase, but the creation of value will decrease. As a result, the variation in electricity prices is likely to remain between 0% and 5%, benefiting both households and investors.

Given the multi-faceted efforts to reach, achieve and make effective the Sustainable Development Goals (SDGs), in particular SDGs 7 and 13, only the initial investment cost and the cost of operation, maintenance and repair are likely to be revised downwards to make these projects more acceptable.

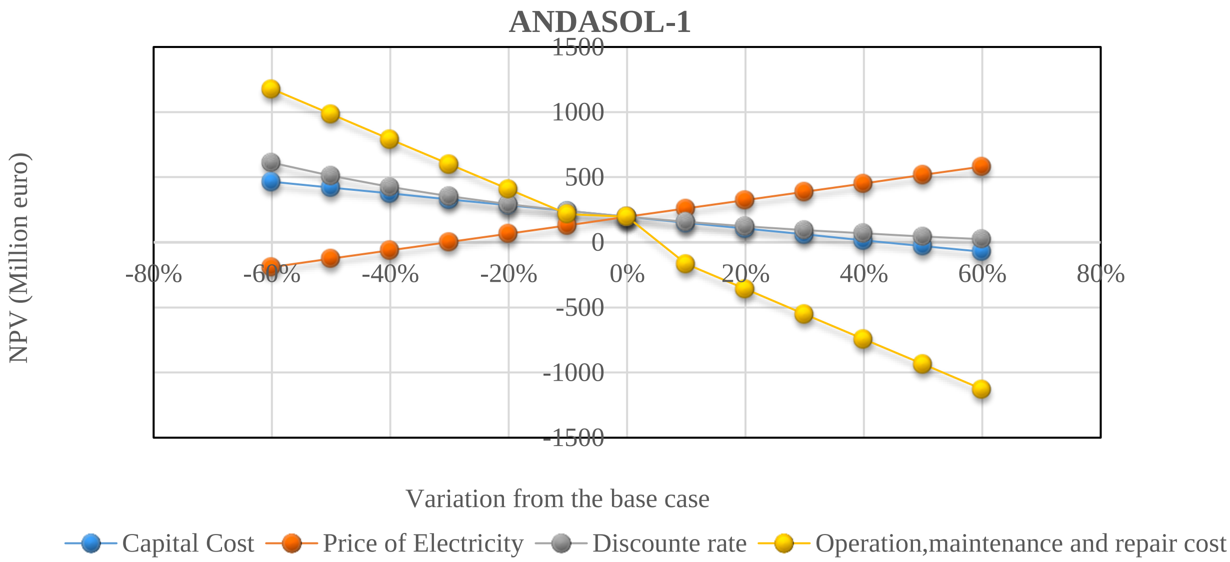

Figure 8. Sensitivity analysis of the investment NPV to variations in the cost of capital, electricity price, discount rate and operation, maintenance and repair

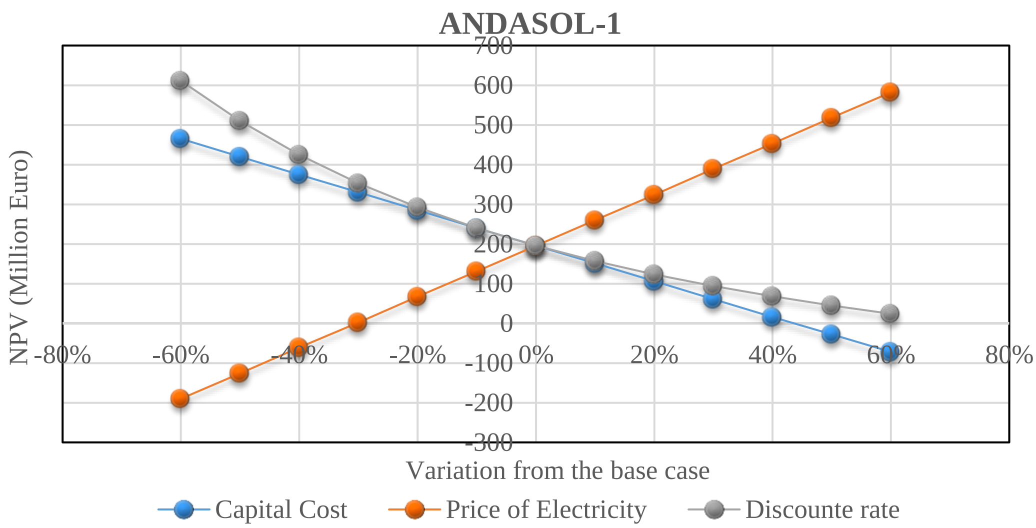

Figure 9. Sensitivity analysis of the investment NPV to variations in the cost of capital, electricity price and discount rate

7. CONCLUSIONS

This work has led to several results that have been analyzed and discussed. The main conclusions drawn from these results are on the one hand from the point of view of the modeling to the hourly quantification of solar radiation and on the other hand from the point of view of the techno-economic analysis of the project of implementation of solar power plant with CSP system in the city of Birao. Thus:

- The Capderou model from the results of MBD 5%, MAD 14%, RMSD 17% is the most suitable to estimate the solar irradiance in the city of Birao. Statistical analyses show that these models need adjustments to better take into account the climatic peculiarities of the city of Birao;
- The comparative study carried out on the various modes of follow-up showed that the mode of follow-up North-South of horizontal axis East-West with RSMD of 7% is the best adapted to optimize the direct solar radiation on all the year;
- This model being developed in the Saharan climate is well applicable in the sub-Saharan climate as in the city of Birao. However, it would be necessary to have measured data or to carry out measurements of certain parameters such as the haze factor and then to make a comparative study with the simulated data to appreciate the mathematical approach used as Marif et al. [39] did in their study in Algeria in order to refine the results.
- The simplified financial analysis showed that the solar climate in Birao is very favorable for investment in CSP plants based on a good solar radiation estimation tool. The project has a positive NPV of 196 Million Euro and an IRR of 45%.

The initial investment cost and the cost of operation, maintenance and repair are the key input parameters that can be modified to increase cash flows and promote value creation through structural mechanisms.

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NOMENCLATURE

AEG	Annual Electricity Generation, kWh/m^2 year
CAMS	Copernicus Atmosphere Monitoring Service
DDP	Discount Payback Period
GHI	Global Horizontal Irradiance, W/m^2
MAD	Mean Absolute Deviation
MBD	Mean Bias Deviation
NPV	Net Value Present
UCE	Unit Cost of Electricity

Greek symbols

ϕ	Latitude of location, degree
Θ	Angle of incidence, degree
CAR	Central African Republic
CSP	Concentrating Solar Power
GHI	Global Horizontal Irradiance, W/m^2
MAD	Mean Absolute Deviation
RMSD	Root Mean Square Deviation
n	Number of observations
h	the height of the sun
d	solar declination, degree
C_f	Capacity factor, percent
I	Average daily monthly solar radiation hourly, W/m^2