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CSP Parabolic Trough and Power Tower Performance Analysis through the Southern African Universities Radiometric Network (SAURAN) Data

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Abstract. The objective of this paper is to analyse the performance of parabolic trough and power tower technologies by selecting two radiometric stations in different geographic locations, with approximately equal annual direct normal irradiance (DNI) values, but with different monthly DNI distributions. The two stations chosen for this study are situated at the University of Free State, Bloemfontein, Free State Province and in Vanrhynsdorp, Western Cape Province. The annual measured DNI values for both these locations in South Africa are in the range of 2500-2700 kWh/m^2. The comparison between the different monthly DNI distributions of these selected sites includes an assessment of annual hourly data in order to study the performance analysis of the most mature concentrating solar power (CSP) technologies, namely parabolic trough and power tower plants. The weather data has been obtained from the Southern African Universities Radiometric Network (SAURAN). A comparison between the different monthly DNI distributions of these selected sites includes the assessment of hourly data.Selection of these radiometric stations has also been done on the basis that they have been operational for at least one year. The first year that most SAURAN stations have been online for at least one year is 2014, thus data from this year has been considered. The annual performance analysis shows that parabolic trough plants have a higher energy yield in Vanrhynsdorp while power tower plants seem to be more suitable for Bloemfontein. Power tower plants in both the locations have a higher annual energy yield when compared with parabolic trough plants. A parabolic trough power plant in Vanrhynsdorp in the Western Cape Province has very low monthly electricity generation in the winter months of May, June, July and August. This is partly due to the higher cosine losses in the parabolic trough 'one–axis' tracking systems and lower DNI values in the winter months. However, a power tower plant in Vanrhynsdorp performs better in these months. CSP plants are often regarded to have a potential to supply base load power in South Africa which has a morning and a more pronounced evening peak in both summers and winters. In such a situation, a parabolic trough plant in Vanrhynsdorp, with very low electricity generation in the winter months is not a suitable technology. A power tower must be considered instead in such a location. This gives us an indication that monthly DNI distribution might play an important role in CSP technology selection. Satellite derived data for these stations must be considered in the future in order to derive more accurate conclusions and recommendations for technology selection.

Keywords: concentrating solar power (CSP), parabolic trough, power tower, direct normal irradiance (DNI), System Advisor Model (SAM).

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INTRODUCTION

A concentrating solar power plant concentrates the beam irradiance, also known as DNI, from the sun. This is then converted into thermal energy and utilized to produce steam and consequently generate electricity. The power produced by a given CSP plant is directly proportional to the amount of DNI available at that particular site. Solar radiation varies not only with geographic location, but also fluctuates during the day and throughout the year. It is therefore essential for CSP developers to have a knowledgeable understanding of the available DNI at a particular site of interest; especially in terms of the monthly DNI distribution, as this is expected to affect the selection of appropriate CSP technology or its configuration. The thermal inertia of CSP plants during transient cloudy conditions is an example of the criteria that should be considered while selecting the appropriate CSP technology for that particular site.

NOMENCLATURE

CRSES: Center for Renewable and Sustainable Energy Studies
CSP: Concentrating solar power
DHI: Diffused horizontal irradiance
DNI: Direct normal irradiance
GHI: Global horizontal irradiance
GSET: Group for Solar Energy Thermodynamics
GW: Gigawatt
HTF: Heat transfer fluid
IPP: Independent Power Producer
kWh: kilowatt hour
LCOE: Levelized cost of electricity
MW: Megawatt
NREL: National Renewable Energy Laboratory
PPA: Power Purchase Agreement
REIPPPP: Renewable Energy Independent Power Producer Procurement Programme
SAM: System Advisor Model
SAURAN: Southern African Universities Radiometric Network
SM: Solar multiple
TESS: Thermal energy storage systems
TOD: Time of day
USD: United States Dollar
ZAR: South African Rand

The Southern African Universities Radiometric Network, (SAURAN), is an initiative of the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University and the Group for Solar Energy Thermodynamics (GSET) at the University of KwaZulu-Natal in Durban, South Africa [1]. The SAURAN initiative intends to improve the availability and quality of radiometric data in Southern Africa, currently including South Africa, Namibia, Botswana and Reunion Island. As of 2012, there were 30 DNI measuring stations across Southern Africa [2]. The majority of SAURAN's stations provide DNI, global horizontal irradiance (GHI) and diffused horizontal irradiance (DHI) data, time-averaged in daily, hourly and sub-hourly intervals. The weather data also includes air temperature, barometric pressure, relative humidity, total rainfall, wind speed, wind direction and standard deviation of wind direction. This data is freely available to the public and may be downloaded from SAURAN's website. The majority of SAURAN's ground stations are equipped with Kipp & Zonen CMP11 pyranometers for GHI and DHI measurements, SOLYS trackers and CHP1 pyrheliometers for DNI measurements. Some of these stations from SAURAN were used along with other stations in order to enhance the accuracy of the previous DNI map of South Africa. The weather station in Bloemfontein is located on the roof of the University of Free State while the station in Vanrhynsdorp is inside a rural farm. Both stations were installed in 2013 and experience very good solar exposure.

Figure 1 shows the updated DNI map as of the year 2014, with both Vanrhynsdorp and Bloemfontein clearly marked along with their respective annual DNI resource.

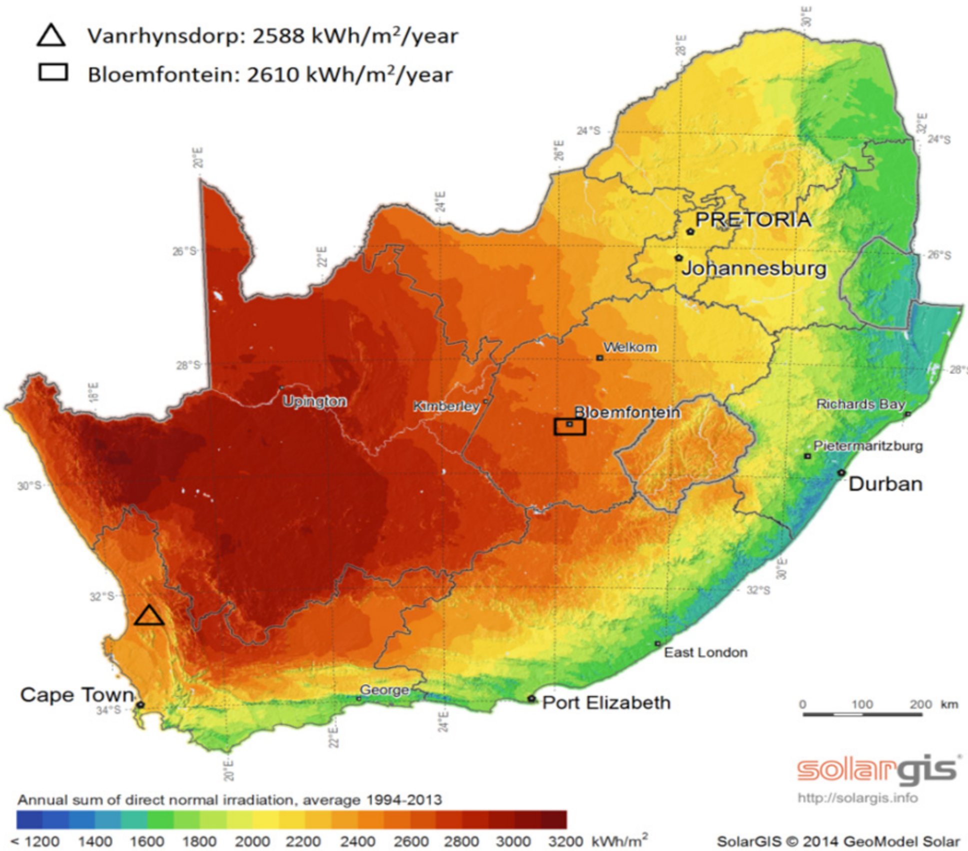


FIGURE 1. DNI map of South Africa, Lesotho and Swaziland showing the locations of the two investigated stations: Bloemfontein and Vanrhynsdorp [3]

Some areas in South Africa have annual DNI values as high as 3000 kWh/m^2, which is amongst the highest values in the world and is considered ideal for operating CSP plants [2]. Currently, most of the CSP plants being built in South Africa are located in the Northern Cape Province, which is far from transmission lines and load centres. The two sites chosen for this study are situated in the Free State Province and the Western Cape Province, have good solar resource, are closer to transmission lines and load centres, and have been potentially identified to accommodate CSP plants with a combined nominal capacity of 23.5 GW and 10.5 GW respectively [4]. The criteria used for identifying suitable sites for CSP plant sites are summarized in the following table below [5]:

TABLE 1. Ideal CSP site topography

Criteria	Approximate value
Solar irradiation	DNI > 2500 kWh/m^2 per year
Flat topography	Slope < 3%
Transmission line proximity	Site distance < 50 km
Surface area availability	Size > 2km^2
Water requirement	2-3 m^3/MWh [6]

Bloemfontein and Vanrhynsdorp have approximately equal annual DNI resources. However, as a result of dissimilar weather patterns the monthly distribution of the DNI at these sites are different as can be seen in Fig. 2.

The Western Cape experiences rainfall and lower solar resource in the winter months [7], whereas during this time the Free State has clearer days which lead to better solar resource and DNI values.

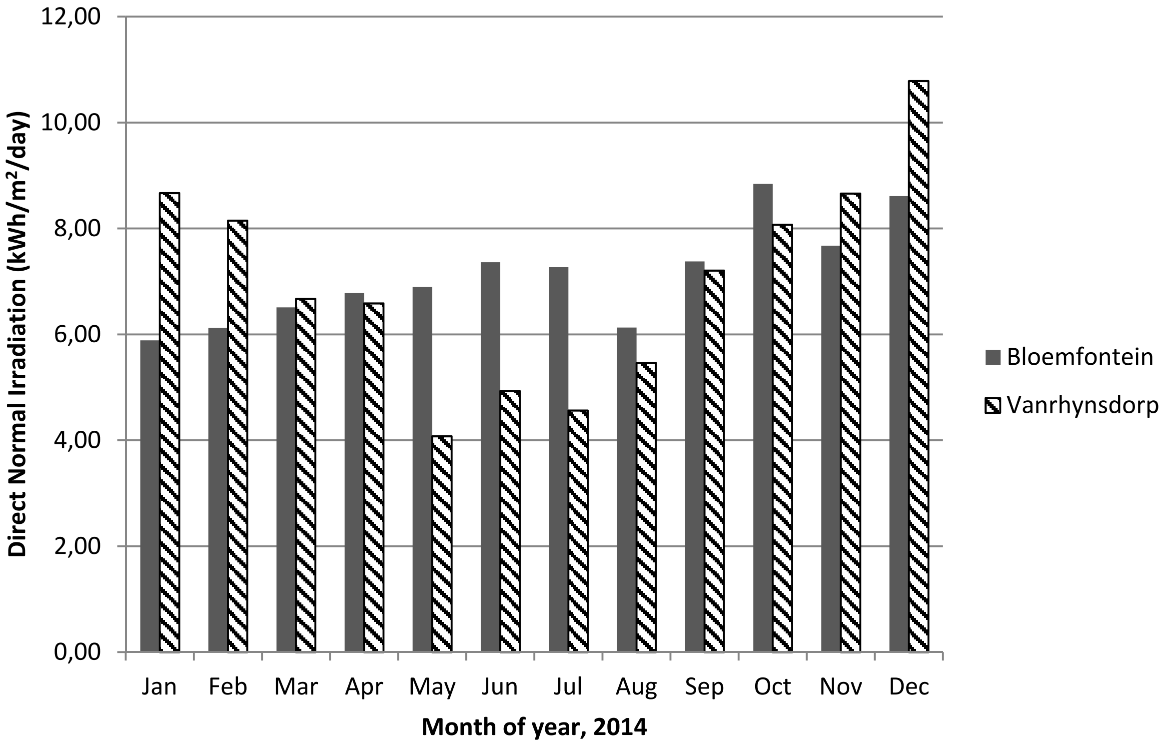


FIGURE 2. Average DNI per month of the two stations in 2014: Bloemfontein and Vanrhynsdorp

The weather data that has been considered is the data measured from the SAURAN weather stations during the year 2014, as this is the only full twelve-month period measured for these chosen locations up until the time of this investigation. Below follows a tabulated summary containing some of the weather data and topographical information for the sites in question.

TABLE 2. Topography and climate conditions of the selected sites

Topographical feature	Vanrhynsdorp	Bloemfontein
Latitude	-31.61748° (E)	-29.11074° (E)
Longitude	18.7384° (S)	26.18503° (S)
Altitude	130 m	1491 m
Annual DNI	2588 kWh/m^2	2610 kWh/m^2
Average temperature	19.81℃	17.54℃
Average wind speed	4.33 m/s	2.61 m/s

SIMULATION STUDY

The simulation study has been carried out using System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL), USA. SAM is a performance and financial model which has been designed to help people working in the field of renewable energy to make decisions based on the performance predictions and cost of energy based on some design inputs from the user. CSP technologies including parabolic trough and power tower systems can be modelled and simulated on SAM [8]. It has been used to predict the performance and cost estimates of the hypothetical investigated CSP plants. Parabolic trough and power tower plants of 100MW_e capacity have been simulated in both locations using Hitec Solar salt as the heat transfer fluid (HTF) as well as the medium of storage. Molten salt as a HTF in parabolic trough plants is not yet a maturely used configuration; however there is research being done in order to investigate the possible benefits thereof [9]. The round 3 tariff structure introduced by the South African Department of Energy by means of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) [10] has been implemented into the SAM model. It has been taken into account while optimizing the plant configurations for the respective locations to obtain the lowest possible levelized cost of electricity (LCOE) range. The weather data from SAURAN was imported into the SAM library as Bloemfontein and Vanrhynsdorp are not included in the package library. The input parameters are summarised in table 3.

TABLE 3. SAM simulation input parameter values

Parameter	Parabolic trough	Power tower
Net output at design	100 MW_e	100 MW_e
Design HTF inlet temperature	550 °C	550 °C
Rated cycle conversion efficiency	0.3731	0.3731
Condenser type	Air cooled	Air cooled
Storage type	Two tank system	Two tank system
PPA price	0.13 USD/kWh	0.13 USD/kWh
Analysis period	25 years	25 years

The two-tier tariff structure of round 3 has been incorporated into the simulation model. The round 3 scheme (introduced in May 2013) has a specified base tariff for the standard time, but during peak hours, it is multiplied by a factor of 2.7 as an incentive to the CSP developer for producing electricity during peak times. At other times, no payment is made for supplying electricity. Table 1 below shows the tariff structure for the time of day (TOD).

TABLE 4. Tariff structure for TOD in round 3 [11].

Period of day	Time of day	Tariff structure
Standard time	05:00 – 16:30 21:30 – 22:00	100 % of base price
Peak time	16:30 – 21:30	270 % of base price
Night time	22:00 – 05:00	0 (No payment)

The dispatch control for the thermal energy storage has been modelled to follow this schedule. Since there is no incentive to generate electricity at night, the power block has been modelled to generate electricity at the highest possible load (115%) at peak time. This is done until the receiver and the thermal energy storage system (TESS) cannot provide sufficient thermal energy for the power block's minimum load any more. During standard times, the turbine is operated at 100% of its capacity and during the night time the turbine operates at 25% of its capacity. The base tariff for round 3 was fixed at 1.46 ZAR/kWh or (approximately 0.12 USD).

Parametric Study

The 'thermo-economic' performance of both parabolic trough and power tower plants depends on the optimal sizing of its components. The thermal energy storage system and the solar field for both these technologies are two of the most cost intensive subsystems and should, therefore, be sized carefully. Increasing the number of hours of TESS and having a larger solar field increases the electricity generation but also increases overall capital costs of a CSP plant. The effect of these two variables on the LCOE on the full load hours of TESS and the solar multiple (SM) parameters have therefore been independently varied. For all the four cases the lowest range of the LCOE has been investigated.

The graph in Fig. 3 below shows an example of the results of the parametric study done for the 100 MW_e parabolic trough plant in Vanrhynsdorp. The results from the graph show that the lowest LCOE is obtained when the solar multiple is approximately at a value of 2.6 on the curve for 12 hours of thermal energy storage.

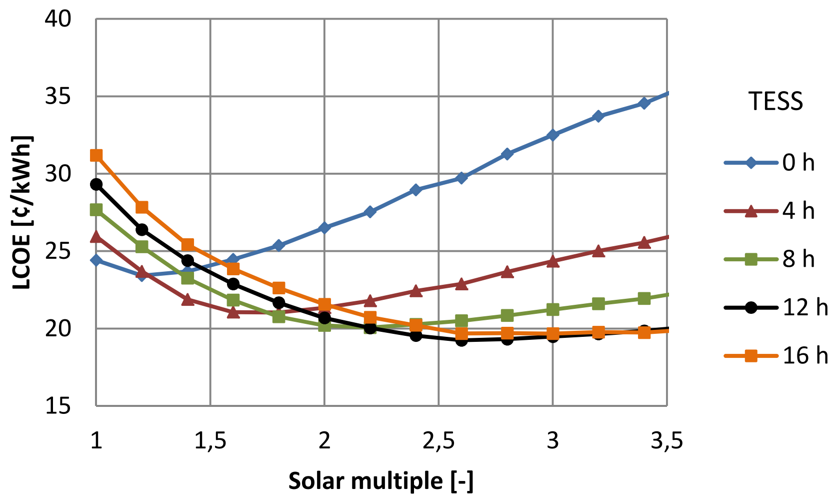


FIGURE 3. Parametric study for 100 MW_e parabolic trough in Vanrhynsdorp

RESULTS

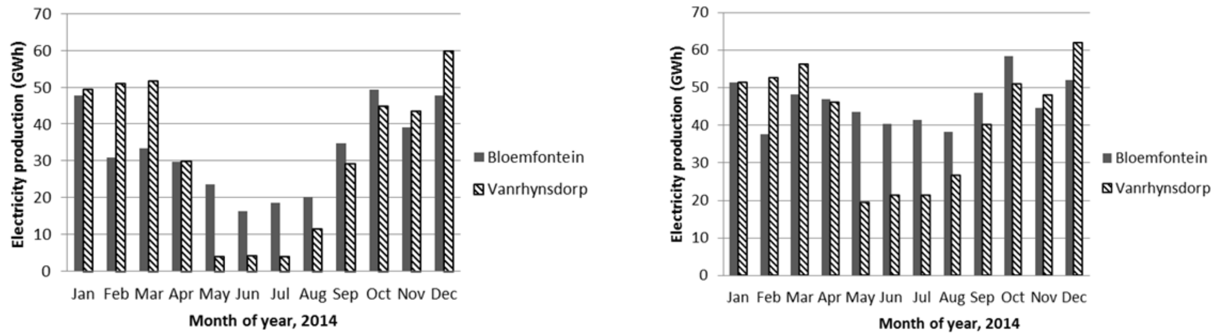
The results of the parametric study are summarised in table 5. It is important to note that the optimum configuration for each CSP plant has been obtained within a range of the lowest LCOE values. Figure 3 clearly shows that the LCOE does not vary significantly between a solar multiple of 2.6 and 3.5 for more than 12 hours of thermal energy storage. The respective parabolic trough and power tower configurations have been selected in such a manner that they are comparable to one another with respect to the two different chosen locations.

TABLE 5. Parabolic trough and power tower plant configuration results

Scenario	Solar multiple	TESS (h)	LCOE (USD/kWh)
Bloemfontein 100 MW_e parabolic trough	2.8	12	0.1940
Vanrhynsdorp 100 MW_e parabolic trough	2.8	12	0.1924
Bloemfontein 100 MW_e power tower	2.6	12	0.1605
Vanrhynsdorp 100 MW_e power tower	2.6	12	0.1640

Comparing the monthly electricity generation at Bloemfontein and Vanrhynsdorp it is clearly seen in Fig. 4, how the amount of electricity generated is directly influenced by seasonal resource change. The monthly electricity generation in Vanrhynsdorp is very low in the months of May, June, July and August when it experiences winter rainfall. This is also partly due to the higher cosine losses in the parabolic trough 'one –axis' tracking systems and lower DNI values in the winter months. Bloemfontein in the Free State has clear winter months hence the monthly electricity generation is not affected.

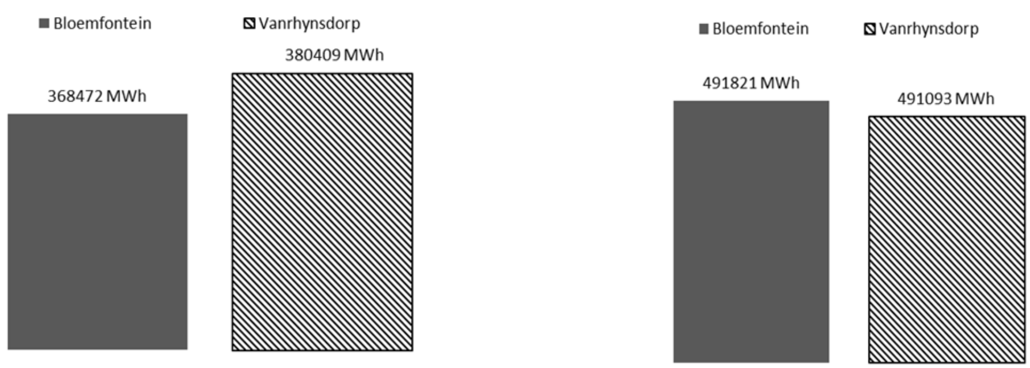
It is noted in Fig. 4 that there is a significantly greater difference between the electricity generation of the parabolic trough plants in (a) than between the power tower plants in (b) especially when looking at the winter months.



(a) (b)

FIGURE 4. Comparison of the monthly electricity production at Bloemfontein and Vanrhynsdorp for the respective technologies; (a) parabolic trough plants and (b) power tower plants

Comparing the annual electricity produced for each respective technology, it is noted from Fig. 5 that a parabolic trough plant in Vanrhynsdorp outperforms a similar plant in Bloemfontein. This result is not intuitive as Bloemfontein has a slightly higher annual DNI value. A power tower plant in Bloemfontein performs slightly better than a similar plant in Vanrhynsdorp, but the performance difference is almost negligible. The SAM results indicate that both locations favour power tower plants and that they have a significantly higher annual energy yield than parabolic trough plants. Bloemfontein's nearly linear trend in increasing DNI over the year 2014 from Fig. 2 is not apparent in Fig 4. Although the power produced is a function of the DNI solar resource, other parameters such as cosine losses and freeze protection has a significant effect on the energy yield throughout the year as well. In parabolic trough plants the aforementioned parameters have a prominent influence on the performance, especially in the winter months. This difference is clearly seen in Fig. 4 above.



(a) (b)

FIGURE 5. Comparison of the annual electricity production at Bloemfontein and Vanrhynsdorp for the respective technologies; (a) parabolic trough plants and (b) power tower plants

Conclusion and Recommendations

Although Bloemfontein has slightly higher annual DNI resource than Vanrhynsdorp, it seems that the SAM calculations show that Vanrhynsdorp would be the better choice for a parabolic trough plant. Both locations seem equally suitable when considering power tower plant technologies. Within the scope of this study, it seems that when considering parabolic trough plants, the choice of location becomes more significant. This work indicates that for parabolic trough plants using molten salt as the HTF, the optimum location might not be determined by the highest annual DNI. Freeze protection requirements are site specific and dependent on the weather patterns of the considered location. Factors such as cosine losses (higher losses in winter) also play a major role in this outcome since parabolic trough fields have only one axis tracking systems. It must be taken into account that the analysed data is from a single year. Further analyses combined with satellite derived data would be necessary in order to gain more accurate insight into the effects that solar resource distribution could have on the performance of parabolic trough and power tower plants. Adjusting future tariff structures in such a way that Independent Power Producers (IPP) receive a greater than zero tariff for the night time is very essential. This could ensure that CSP plant designs in South Africa are more cost effective in the future with respect to LCOE values. This recommendation is only necessary in the short term. However increasing the number of CSP plants in South Africa will lead to greater cost reductions and therefore become more cost competitive. It is also important to keep in mind that these results are from simulations done in 2015. Further cost reductions in plant components, especially in the solar field and storage systems, are necessary and would help in further reducing the LCOE.

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