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A Review of Andasol 3 and Perspective for Parabolic Trough CSP Plants in South Africa

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Abstract. Andasol 3 is a 50 MW parabolic trough concentrating solar power plant with thermal energy storage in Andalusia, southern Spain. Having started operating in 2011 as one of the first plants of its kind in Spain it has been followed by more than 50 in the country since.

For the reason that CSP plants with storage have the potential to compete against fossil fuel fired plants much better than any other renewable energy source a long-term review of such a plant operating on a commercial scale is needed. With data at hand documenting Andasol 3's operation over the course of one year between July 2013 and June 2014 we intend to provide such a review.

We calculated the plants overall efficiency, its capacity factor, the gross energy generation as well as auxiliary powers on a monthly basis to reflect upon its overall performance. It was also looked at the benefits caused by the thermal energy storage and especially how steadily and reliably the plant was able to operate.

With basic background information about physical, geographical and meteorological aspects influencing the solar resource, its variation and a CSP plant's performance a qualitative estimation for a parabolic trough plant located in South Africa was made.

INTRODUCTION

Reducing green house gas emissions is one of humanity's greatest challenges in the 21st century. At the same time the global demand for a reliable and steady energy supply increases constantly. The only long-term solution is to cover the need with renewable energy sources. Though, most renewables face problems supplying energy on demand. It is still a big issue to store energy generated from wind and photovoltaic. Thus, it may be dumped when not needed or cannot fulfill the demand at other times due to weather conditions.

In concentrating solar power (CSP) plants, however, the sun's irradiation is first converted into thermal energy, before being turned into kinetic and finally electrical energy. Thermal energy is relatively easy and cost-efficient to store in thermal energy storage (TES). This results into the major advantage of being able to buffer energy for times when the demand does not match with the solar irradiation (IEA, 2010). Therefore, CSP plants can serve for programmable electricity profiles much better than most other renewable energy sources.

The technology can contribute to grid stability which is an important step towards replacing fossil fuel energy supply. (Forrester 2014).

Today most commercial CSP plants concentrate the solar radiation onto a heat transfer fluid (HTF) circulating through a receiver in a solar field. The thermal energy is then used to generate and overheat steam through a heat exchanger in order to run a turbine.

On a commercial level two main focusing strategies are implemented.

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A central receiver solar field consists of a number of flat mirrors, which are referred to as heliostats focusing the sunrays onto one central receiver that is installed on top of a tower. Each heliostat needs to be tracked separately and two-axially.

In a line focusing solar field the sunlight is focused onto transmission pipes carrying the HTF. The pipes are aligned from north to south, which limits the system to a one-axial tracking from east to west (Müller-Steinhagen, 2004). The latter technology has been commercially used since the 1980's and is the most implemented CSP technology at the moment (Xavier et al. 2013).

The largest part of all CSP capacity worldwide has been installed in Spain and the US (Usaola, 2012). It is said that a normal direct irradiation (DNI) exceeding 2000 kWh/m^2 annually is needed for a CSP plant to operate successfully (Trieb, 2009). However, for a constant performance not only the total amount of energy received per area and year is of importance but also does the DNI variation throughout the year and the sun's incidence angle matter.

South Africa, as it receives a very high annual DNI, which is usable more efficiently than in southern Spain as will be explained later on offers great conditions for CSP (Fluri, 2009).

For this study data of a one-year operation period between July 2013 and June 2014 from the line focusing CSP plant Andasol 3 in southern Spain was analyzed. It aims to reflect upon its overall performance and seeks to draw a conclusion about the potential for such a plant in South Africa.

THE PLANT

Andasol 3 in southern Spain is a parabolic trough plant. Its solar field consists of almost 90 km of parabolic shaped trough mirrors concentrating sunlight onto transmission pipes in the focal point. The mirrors track the sun from east to west so that the aperture area of 497,000 m^2 is always perpendicular to this component of the solar irradiation. The hot HTF then goes through either of two heat exchangers. On one side steam is heated up to 393°C to feed a 50 MW turbine, which was forecasted to generate 200 GWh annually. On the other side the remaining thermal energy the field provides is used to charge the thermal storage. For this to take place the so-called solar salt, which consists of 60% sodium nitrate and 40% potassium nitrate is pumped from a cold tank through the heat exchanger into the hot tank. Starting at a temperature of 286°C, which is far enough above the salt's melting point, it gets heated up to 386°C. Although the solar salt would be capable of higher temperatures, the plant's operation temperature is limited to less than 400°C because above this point the HTF becomes chemically instable.

With a mass of 28,500t of solar salt the total storage capacity is 1010 MWh$_{th}$, which is equal to 7.5h of full load time.

Andasol 3 is located at one of the best sunspots in Andalusia, southern Spain providing a normal direct solar irradiation (DNI) of 2136 kWh/m^{2}a.

PHYSICAL ASPECTS INFLUENCING THE PERFORMANCE

Several physical aspects limit the performance of a CSP plant.

The power that can be generated is obviously limited by the available resource, the DNI, which measures the energy received per area by a surface that is always held perpendicular to the irradiation. Among its influence factors are the earth sun distance, the atmospheric transmittance, aerosol scattering and absorption, water vapor and gas absorption and the solar time (Bird et al, 1986).

Due to the variation of the irradiations incidence angles the solar field only has a certain optical efficiency. This will be explained further in the next paragraph.

The Carnot Efficiency then limits the fraction of the energy delivered by the solar field to the Rankin cycle that can be converted into kinetic energy. For Andasol 3 operating at a steam Temperature of 393°C and a cooling Temperature of 30°C the best possible efficiency results to be:

$$\eta_{max} = 1 - \frac{303K}{666K} = 54{,}5\% \qquad (1)$$

However, the thermal engines real efficiency is known to be much smaller.

A last aspect that needs to be mentioned are heat losses occur throughout the whole system. Especially the transmission pipes are sensitive to heat losses (Kalogirou 2012).

INCIDENCE ANGLES AND COSINE-LOSSES

Since the parabolic troughs of a line focusing system are installed horizontally in North-South direction, the aperture area can not always be perpendicular to the sun rays. Therefore, DNI itself is not the only determining factor for the performance of a parabolic trough plant. It is highly affected by the suns incidence angles (Lorente García, 2011).

Any surface that is not orientated at a right angle towards the sunrays can not receive the maximum energy the irradiation delivers. It only receives the energy equivalent to the projection of that area onto the plane perpendicular to the sunrays (FIGURE 1a). In a solar field this compression of the aperture area is referred to as cosine-losses because the plant receives less energy which obviously affects its efficiency.

For the seasonal shift in performance the worlds angle towards the ecliptic (δ =23.44°) plays an important role.

Because the earth rotates around the sun in this position the angle between the surface of the earth and the sunrays (α) in a certain place varies depending on the season and causes a compression in the y-direction. Whereas at the equator it is the most steady the further towards the poles one gets the higher the variation between seasons becomes (Iqbal, 1983).

The sun's daily east-west shift and, therefore, the compression in x-direction can be compensated by the troughs tracking the sun in this direction (FIGURE 1b). As a result the aperture area only experiences a compression in y-direction. With E_s as the sunray's energy, φ as the azimuth and $\vartheta = 90° - \vartheta^*$ as the zenith angle the cosine-loss is found to be:

$$E_{loss} = \sin\vartheta \cos\varphi \, E_s \tag{2}$$

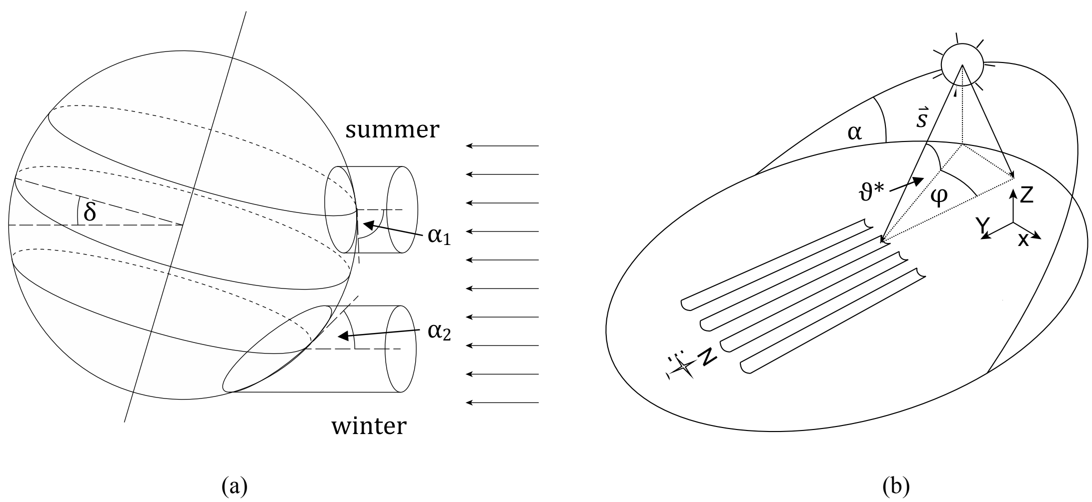

FIGURE 1: energy received per ground area in winter and summer at a certain latitude (a) and relevant irradiation incidence angles for a parabolic trough CSP plant (b)

The smaller ϑ and the larger φ get the smaller the cosine-losses become. During summer when α is closer to 90°, ϑ reaches smaller values and the losses are therefore smaller than in winter.

In order to get an idea of the scale of cosine-losses at a certain latitude (β) on earth we are going to adapt the formula for noon time. φ is then equal to zero and ϑ^* becomes α, which leaves us with the following equation for cosine-losses:

$$E_{loss} = E_s \cos\alpha \tag{3}$$

Now the maximum and minimum values for α over the course of a year can be found through the angle towards the ecliptic δ and the latitude β:

$$\alpha_{max,min} = 90° - (\delta \pm \beta) \tag{4}$$

Applying these angles for α gives us the turning points of cosine-losses at noon at a certain latitude.

STORAGE CAPACITY AND SOLAR FIELD SIZE

The DNI is obviously not constant throughout the day but reaches its maximum around noon. The turbine, however, is aimed to run at constant maximum capacity. For this to be possible the solar field needs to deliver the equivalent capacity long before noon and must therefore be oversized by a certain factor. As a result, the solar field provides more capacity than the turbine is capable of when exceeding a certain time in the morning. In a CSP plant without storage this energy needs to be dumped. In case storage is available, though, it can be kept for when the DNI is low (Montes, 2009). The characterizing factor by how much a solar field is oversized is called the solar multiple (SM). In a plant without storage it is typically about 1.4. A plant with storage needs an SM of about 2.4.

The ability to store energy increases the capacity factor and the value of the additionally available capacity since it can be shifted flexibly according to the demand (Kuravi, 2013).

The following graph (FIGURE 2) shows a typical scenario for a 24h operation period of a CSP plant with storage. The black line refers to the electrical capacity output of the generator in MW, blue represents the storage level in percent, yellow indicates the DNI in W/m^2. The area enclosed by the yellow and black line corresponds to the energy used to charge the storage. In practice the capacity available to the storage at a time is proportional to the TES level graph's slope.

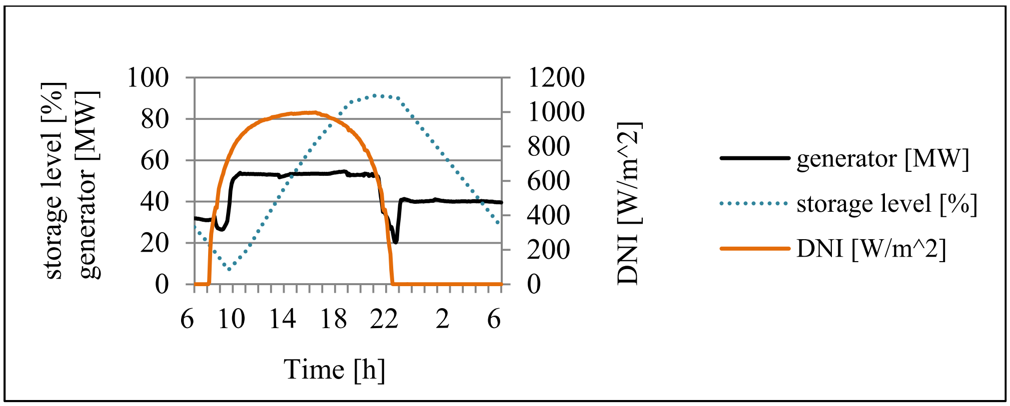

FIGURE 2: typical 24h operation period for Andasol 3

In this case the turbine capacity gets throttled down to about 40 MW_e after sunset in order for the plant to generate electricity throughout the whole night. During summer months, when the storage can be fully charged in a day, this is a typical operation mode for Andasol 3.

Of course the storage capacity could as well be used in various other ways. The turbine could be run at maximum capacity for another 7.5h into the night, it could serve for peak loads after sunset and again before sunrise the next morning, or it could buffer an overcast day and keep the turbine's capacity relatively constant.

No other renewable energy source can offer such benefits.

MONTHLY PERFORMANCE

The factors explained are the main influences affecting the overall performance of the plant. In FIGURE 3 the monthly DNI sum per square meter in kWh/m^2 and the total energy generated in GWh are shown. It is very obvious that the relation between the two is non linear as the generated energy decreases by a larger amount than the DNI does during winter months. This is mainly due to two reasons: Solar time in winter is shorter but the plant needs the same time or even slightly longer to start up in the morning and cosine-losses are higher in winter due to flatter incidence angles α.

A non-linear correlation between DNI and energy generated also results in an efficiency that is not constant. Dividing the total energy generated per square meter by the DNI multiplied by the aperture area gives us the overall gross monthly efficiency:

$$\eta_{gross} = \frac{electricity\ generated \left[\frac{Wh}{t_{month}}\right]}{DNI \left[\frac{Wh}{m^2 t_{month}}\right] * aperture\ area\ [m^2]} \quad (5)$$

This gross efficiency varies between 20.0% in July and 7.9% in December. The average efficiency for the whole year was found to be 13.8%. All values can be found in TABLE 1.

In order to get an idea of how well the installed capacity of 50 ME_e was used we calculated the capacity factor (γ) as:

$$\gamma = \frac{full\ load\ equivalent\ [h]}{t_{month}[h]} = \frac{electricity\ generated\ [Wh]}{50MW} \frac{1}{t_{month}[h]} \quad (6)$$

In July 2013 Andasol 3 was able to operate for the equivalent of 559 full load hours, which results into a capacity factor of 75.6%. This factor decreased to a minimum of 13.2% in January. The annual average was 34.8%. However, having operated for a total equivalent of 3601.0 full load hours within the whole eleven and a half months data was available for and having produced 180.1 GWh of electricity in that time the plant meets its expectations.

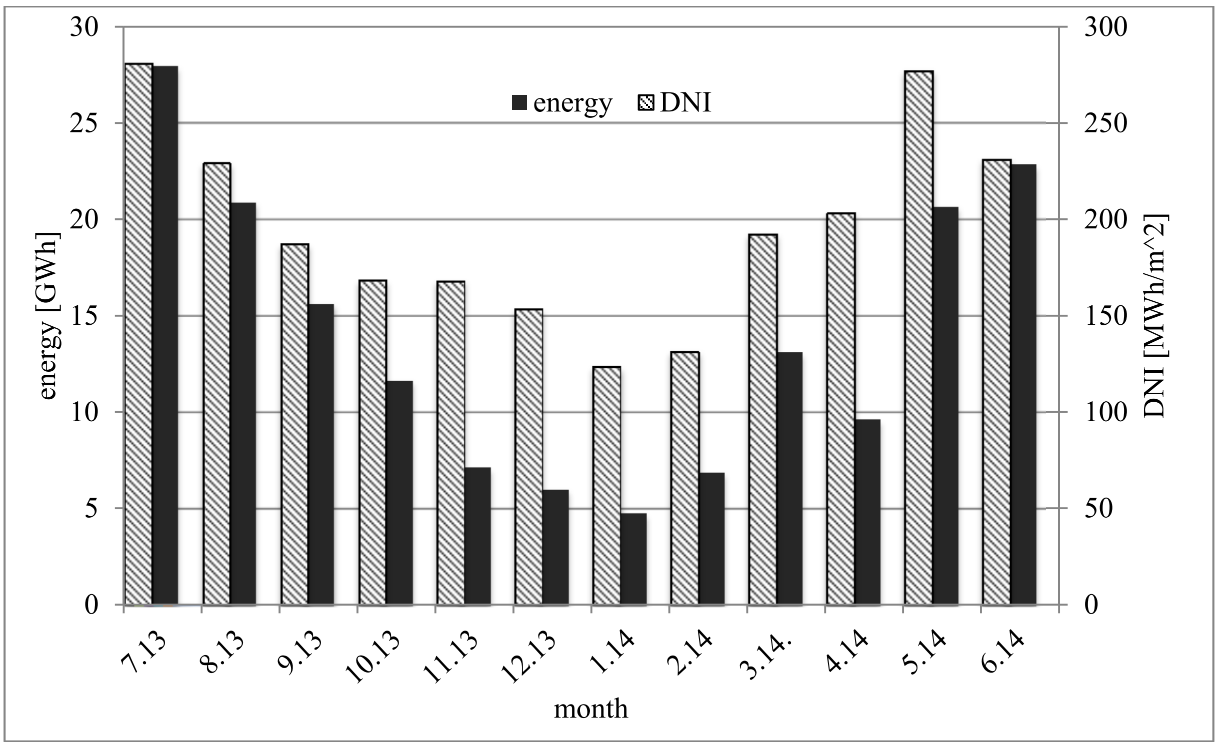

FIGURE 3: monthly DNI and gross energy generation of Andasol 3

TABLE 1: monthly data for Andasol 3: DNI, gross energy generation, full load operation time equivalent, capacity factor and gross efficiency

month	DNI [kWh/m^2]	gross energy generated [GWh]	full load equal [h]	capacity factor [%]	η_{gross}[%]
July '13	281,1	28,0	559,0	75,1	20,0
August '13	229,3	20,9	417,7	56,1	18,3
September '13	187,4	15,7	302,7	42,0	16,2
October '13	168,4	11,7	237,8	32,0	14,2
November'13	168,1	7,2	143,0	19,9	8,6
December '13	153,6	6,0	119,4	16,1	7,9
January '14	123,7	4,8	97,6	13,1	8,0
February '14	131,6	6,9	137,9	20,5	10,6
March '14	192,5	13,1	270,7	36,4	14,2
April '14	203,4	9,6	191,9	26,7	9,6
May '14	277,2	20,7	413,4	55,6	15,0
June '14	231,3	22,9	457,2	63,5	19,7

BENEFITS OF THE STORAGE

This performance could not have been achieved without thermal energy storage.
67.2 GWh out of the total 180.1 GWh were generated in a time of 2064.4 hours from the energy stored in the TES. This means 37.3% of the energy was allocated when no solar resource was available whatsoever, which is good proof for the flexibility of CSP plants with storage.

When running off the solar field the generator's monthly average capacity fluctuated between 48.7 MW_e in July and 35.1 MW_e in January averaging 42.8 MW_e for the whole year. At times when energy was consumed from the storage during nighttime the turbine was run at capacities between 35.8 MW_e in July and 24.0 MW_e in December. The annual overall average for storage operation was 30.9 MW_e.
Because these data were collected during warranty phase of the EPC contractor the owner expect some further optimization potential in the future.

LONG OPERATION PERIODS

The TES made it possible to run operation periods longer than 24 hours for 22 times within the year the longest one being 9 days and 18 hours. In total the plant could be run for longer than 24 hours for a total number of 62 days, meaning in one sixth of the year Andasol 3 generated power for 24 hours per day from the sun, which is great proof for CSP reliability.

FIGURE 4 shows the operation of Andasol 3 between 4.7.2013 and 9.7.2013. Days start at 6am. As can be seen the turbine ran constantly for about 142 hours. The high DNI enabled the TES to be charged entirely every day so that the turbine could operate at about 40 MW_e during the night. This is the scenario that was explained earlier in paragraph 2.3. The last day was then too overcast to be able to charge the TES to maximum and the electricity production at night could not be completed.

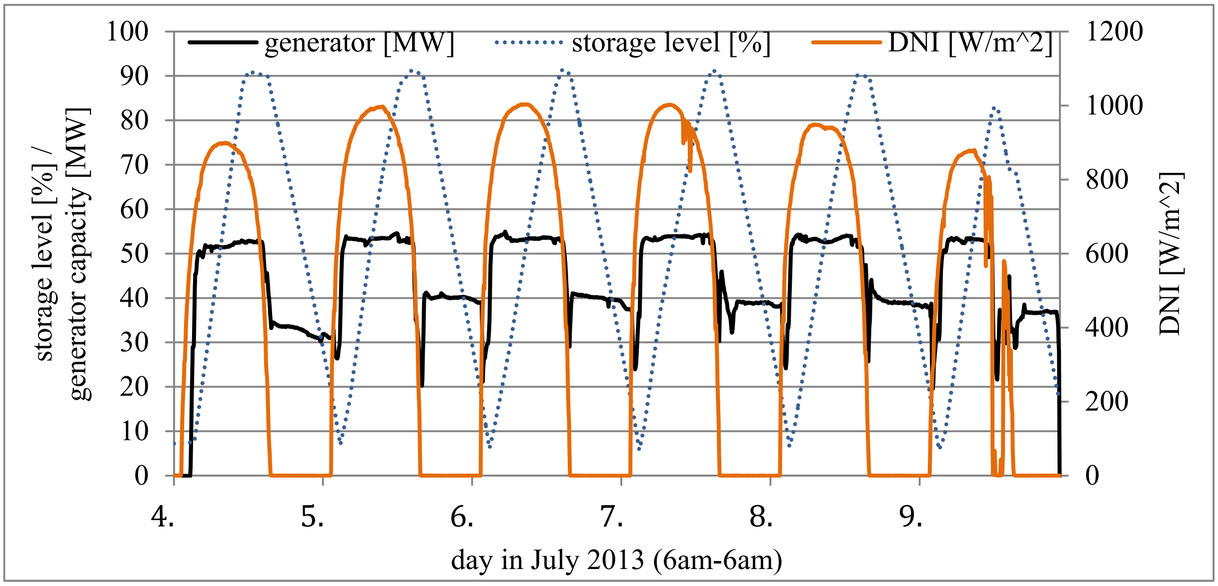

FIGURE 4: operation of Andasol 3, 4.10.-10.7.2013

Note: The capacity drop occurring each time when switching between field and TES operation is very likely to be due to cold oil sitting in the pipes coming from the TES or the solar field respectively when in stand-by. In order for this drop not to occur the cold oil would need to be preheated or removed from these pipes before switching operation mode so that it does not lower temperatures inside the exchange train.

AUXILIARY POWER

Up to this point all calculations were done neglecting any auxiliary power consumed by the plant itself. The auxiliary load is made up of oil and water pumps and the drives for the collectors. It generally increases for summer months with a higher solar resource because solar time extends and more energy is collected by the mirrors, which needs to be transported.

The total energy consumed by the plant throughout the year was found to be 27.2 GWh.

The absolute auxiliary load decreases in winter months. This is due to the fact that the solar field receives less energy, which needs to be transported, pumps, therefore run more slowly and the solar time is also shorter. However, the relative figure of auxiliary power over total power generated is opposite. It varies between a minimum of 12.3% in July and a maximum of 32.5% in January. This significant increase is caused by both the low production and higher effort to prevent the plant from freezing. All values are to be found in TABLE 2.

The relative increase in auxiliary power for winter months has major influence on the efficiency of the plant. Subtraction from the gross energy generated and division by the available resource gives us the real overall efficiency:

$$\eta_{real} = \frac{(electricity\ generated - auxiliary\ power)\left[\frac{Wh}{t_{month}}\right]}{DNI\left[\frac{Wh}{m^2 t_{month}}\right] * aperture\ area\ [m^2]} \tag{7}$$

The resulting real monthly efficiencies reach from 5.2% in January to 17.6% in July. The average real efficiency over the course of the whole year turs out to be 11.1%. All values are to be found in TABLE 2.

TABLE 2: auxiliary power and real efficiencies

month	auxiliary power [GWh]	fraction of gross power [%]	η_{real} [%]
July '13	3,41	12,20	17.57
August '13	2,90	13,86	15.80
September '13	2,27	14,46	14.38
October '13	2,07	17,74	11.47
November'13	1,69	23,55	6.55
December '13	1,64	27,16	5.75
January '14	1,55	32,48	5.24
February '14	1,60	23,06	8.14
March '14	2,29	17,44	11.34
April '14	1,85	19,15	7.70
May '14	2,89	13,99	12.92
June '14	3,06	13,38	17.25

SITUATION IN SOUTH AFRICA

For two main reasons a parabolic trough plant like Andasol 3, in case it was located in South Africa instead of Spain would perform better.

The region that is looked at to install CSP capacity in South Africa is in between approximately 25°-30°S whereas Andasol 3 is located at 37.13°N. For Andasol 3 this results into α-values between 29.43° and 103.69° and, therefore, maximum cosine-losses of 0.87 of the available DNI at noon according to equation (4).

For South Africa, however, the variation of α between seasons is less because it is closer to the equator. In Upington for example, which is a city in the northwest of the country at about 27°S, where CSP plants are under construction α only varies between 38° and 94°. Therefore, the highest value for cosine-losses of DNI at noon only accounts 0.78 which is 10% less than in Spain.

As explained earlier the generally smaller value for cosine-losses results in a higher efficiency. A larger amount of the DNI becomes usable for the plant and the efficiency drop in winter will be not as high.

Secondly, Upington offers a better solar resource than Granada. In FIGURE 5 the monthly DNI values of the two locations are compared. Observation time for Upington was July 2008 until May 2009. We did not have data for June, so the value for this month is the average of the two neighboring ones. It is very obvious that the DNI in Upington is higher almost all the time. For the whole year it sums up to 2665 kWh/m^2, whereas Granada reaches 2348 kWh/m^2. This is an increase in solar resource of 14%. However, the difference might be significantly higher. Comparing the 10-years average DNI value of 2136 kWh/m^2 annually at Andasol 3 to latest measurements by “GeoSun Africa” promise almost 40% higher DNI values around Upington.

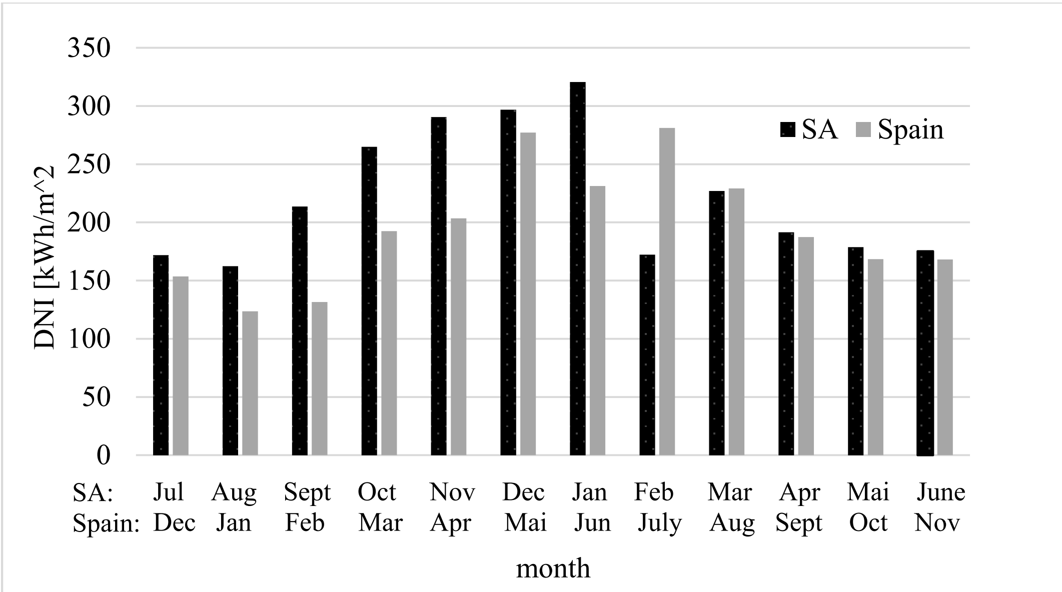

FIGURE 5: DNI in comparison: Granada vs. Upington

These circumstances conclude to the fact that a CSP trough plant like Andasol 3 will be performing much better in two aspects, if it was located in South Africa. Power generation will be higher due to a better solar resource and it will be more steady throughout the year so that the drop in efficiency during winter will be smaller because of generally steeper incidence angles.

CONCLUSION AND DISCUSSION

Having reflected upon the parabolic trough plants Andasol 3's performance based on data for a period between July 2013 and June 2014 we come to the conclusion that the plant almost met its expectations but. Within the time analyzed the it was able to operate for an equivalent of about 3600 full load hours, which is equal to a total amount of 180 GWh of electricity that was generated. This comes close to the estimations of 200 GWh annually made for Andasol 3 when constructed. In summer top capacity factors of 75% and real efficiencies of almost 18% were reached. Performance does decreases significantly in winter, though, which is a heavy load on the average performance.

The plant consumed a fraction of 15% of the gross energy itself to satisfy auxiliary loads. The overall real efficiency for the whole operation year results to be 11%, which is certainly not as high as expected. An increase of two or three percentage points would be desirable.

Two kinds of reasons are responsible for these findings. On the external side that cannot be influenced we have to consider the geographical location which is the reason for unfavorable incidence angles in winter and, therefore, a decline in efficiency. Outside temperatures can be around the freezing point in winter which explains the high auxiliary loads. It also has to be mentioned that the DNI value is certainly among the highest in Europe but in international comparison far better locations can be found.

On the other hand there are influenceable parameters that offer potential for optimization. It has to be looked at maintenance hours and their effect on the performance. Also an improved startup procedure has large potential to increase efficiencies. Furthermore, a solution to the capacity drop occurring when switching between field and storage operation should be considered (see figure 4). A bypass or a preheater could potentially be solutions.

Andsol 3 still proves the advantages of CSP with storage. The fact that 37% of the total energy generated was allocated when the sun was not shining and a total number of 62 days of 24-hour-operation is good evidence for the value of a TES. Among all renewable energy sources this is a quality only CSP plants can offer. It emphasizes these plant's flexibility and ability to serve for programmable electricity supply.

The fact that performance highly depends on the season shifts the focus to other regions in the world where conditions are more favorable in terms of these factors and a parabolic trough CSP plant could perform even better. South Africa offers one of the highest DNI values around the globe, which is also usable more efficiently than in southern Spain. Parabolic trough plants in this country would be able to operate more steadily and achieve higher efficiencies during winter months than in most places.

Therefore, South Africa has great potential to cover a large amount of its needed electrical capacity by CSP power plants with thermal storage.

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