

# MODELING DISPATCHABILITY POTENTIAL OF CSP IN SOUTH AFRICA

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## Abstract

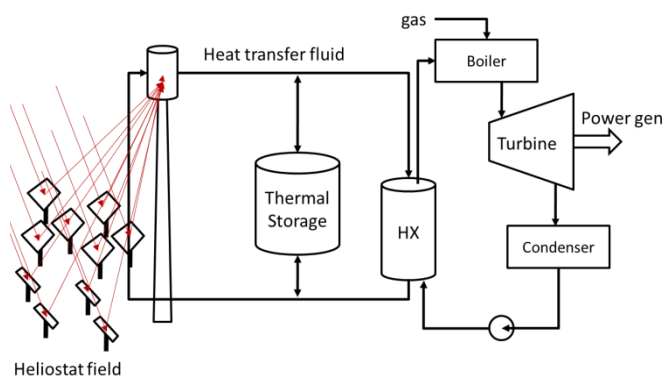
We present a new method to quantify the dispatchability potential of CSP as part of a broader project to determine the value of CSP in the future South African energy mix. The method uses a fast solving plant model that includes all key parameters of a CSP plant including thermal inertia and thermal storage. A spatial grid of solar and weather is used as inputs and the result is hourly power potential on the same spatial grid. For 1 year of data, 28 million inputs are required and 9 million outputs generated with solve times of approximately 30 minutes per run.

Results show that CSP plants with significant storage can deliver dispatchable power throughout the year regardless of weather when highly distributed. This new method will be enhanced with further refinement, features and validation in order to optimize CSP plant locations in a renewable system.

*Keywords: Concentrating solar power (CSP); potential; dispatchability; modelling.*

## 1. Introduction

Concentrating solar power (CSP) is power generation through the conversion of focused sunlight to thermal energy and then to electricity. The conversion to thermal energy presents an advantage over other renewable technologies: the ability to store large amounts of thermal energy at the plant that can be used to generate electricity later. The Gemasolar Thermosolar plant (Gemasolar in short) commissioned in Spain in 2011 demonstrated full load electricity production for 24 continuous hours during its first summer [1]. Figure 1 shows a basic illustration of the thermodynamic process and a photo of the Gemasolar plant in operation.



**Fig. 1. (Left) Basic Gemasolar plant configuration (Right) Gemasolar plant in Spain commissioned in 2011 (photo by author)**

CSP plants with large storage capacities and the ability to synchronise power to the grid quickly seem to

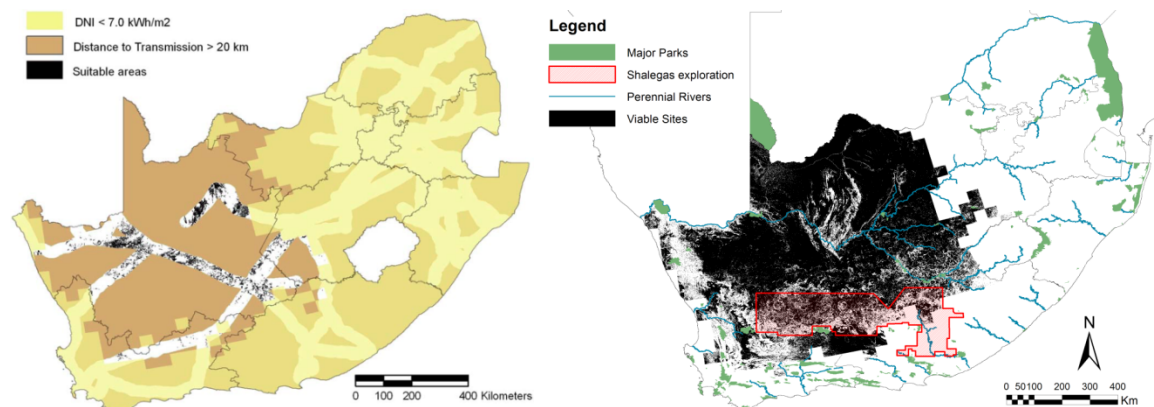
provide the potential for dispatch power. Dispatch power is power required at relatively short notice to bridge the gap between demand and supply.

We present a new method to model dispatchability potential of concentrating solar power (CSP). A primary goal is to provide some evidence of the value proposition of CSP, particularly in the South African context. The model is aimed at decision makers, particularly at the national level, to make informed decisions about the future energy mix, the location of plants and the structure of the transmission system.

The method combines an appropriately detailed technical plant model with real weather and solar data over a period of time. As the first model of this type, we made no attempt to optimize sites for CSP plants based on resource constraints, boundaries or any other factors. The introduction of this method will focus only on the potential of CSP dispatchability. The entire South African land surface was considered without prejudice. We did this in part to test the method in isolation but also because of the need to test the entire country on an hourly basis where sites that may be rejected based on annual output could be considered important as dispatch locations at certain times. Prior studies that have looked at the potential for CSP have done so on simple annualised energetic values and usually set lower annual direct normal irradiation (DNI) threshold values to determine suitable areas.

## 2. Background

The first significant study of CSP potential in South Africa was performed by Fluri [2]. This publication uses geographic information system methods to look for sites with good potential for CSP. Fluri determines the power potential using  $28 \text{ km}^2/\text{GW}$  and he only considers areas exceeding a daily average of  $7.0 \text{ kWh/m}^2$ . When considering the solar resource, suitable land and proximity to the existing transmission system, Fluri reports a potential of 547.6 GW for the whole country.



**Fig. 2. (Left) CSP potential short term by Fluri [2] and (Right) CSP potential area in the long term by Meyer [4]**

Meyer and van Niekerk [3] consider the potential of CSP in the short term by reviewing the capacity of the transmission system (with other factors) and in the long term by taking a less constrained view. This study does not comment on the power potential of the total viable land.

The methodology to model the dispatchability potential of CSP is summarised as follows. Firstly, a good system model for a CSP plant that includes thermal storage was required. The model was determined from first principles and needed to be flexible enough so that no particular configuration or technology was required. The reasons for a first principle model were speed and flexibility. Existing software tools for CSP modelling would be overly cumbersome for the number of solutions required. The optical to thermal model was validated using published data for existing plants and has been reported previously [4].

The second significant component of this study was the compilation of a complete set of solar and weather

data for South Africa for a full year. The data obtained required interpolation in order to get the various sources of inputs to 1 hour intervals, thus providing 8,760 sets of weather and solar data per location per year. Fortunately, the primary solar and weather parameters that impact the system model reduce to just 4 parameters: solar DNI, ambient temperature, humidity and wind speed. In the case of dry cooled plants, this reduces further to just 3, as humidity is not needed. This set accounts for cloud cover and any other weather effects. The Southern African region model contained 2,000 grid points, out of which a total of 823 points within the borders of South Africa were selected. Thus the total number of inputs was about 21.6 million. The output of the model is a single value for each point resulting in outputs that were only a third of the inputs at 7.2 million.

To introduce the method, we assume a constant demand implying that the plant simply produces power to its rating. For this paper, no thermal energy storage is withheld for later use except to keep running at full load at all locations studied until the storage is depleted. Some degree of dispatchability can be explored in this ideal model by scaling the turbine. The inclusion of real demand patterns and multi-criteria site selection will be added as a next step.

### 3. Method

#### 3.1. CSP Plant Model

CSP plants work on the principle of converting concentrated sunlight to high temperature thermal energy which then drives a heat engine and finally a generator. We focused on the central receiver plant type for this work but the model would be applicable to other types such as the parabolic trough or linear Fresnel type with minor adjustments.

Specifically, the Gemasolar plant shown in Figure 1 provided the framework for this study. We retrieved the key parameters of importance for this plant from the NREL/SolarPACES database of CSP plants [5]. The thermodynamic process in Figure 1 forms the basis for the model.

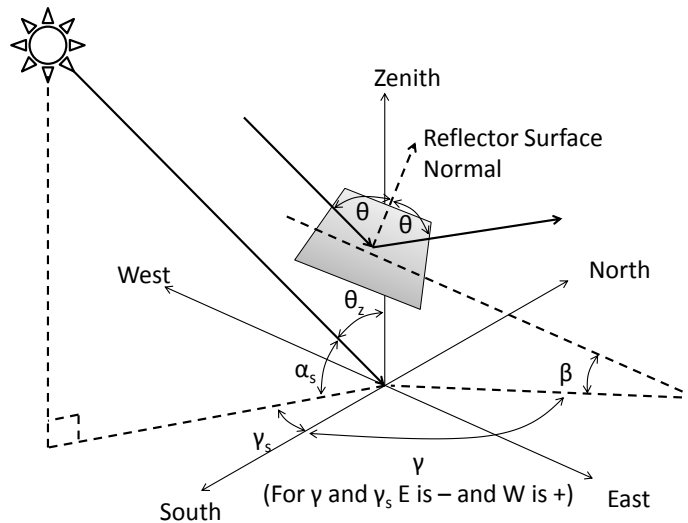
Item	Value
Country, Region	Spain, Seville Andalucía
Location	37°33' 44.95" North, 5°19' 49.39" West
Land area	195 Ha
Solar resource	2,172 kWh/m <sup>2</sup> /yr
Electricity Generation	110 GWh/yr (planned)
Cost	230,000,000 Euro
O&M jobs	45
Heliostat aperture area	304,750 m <sup>2</sup>
Number of heliostats	2,650
Heliostat size	120 m <sup>2</sup>
Tower height	140 m
Heat transfer fluid	Molten salt
Receiver outlet / inlet temperature	565 °C / 290 °C
Turbine capacity (gross)	19.9 MWe
Cooling	Wet
Storage	2 tank, 15 hours

**Table 1. Key Gemasolar plant parameters**

The plant model is quasi-dynamic because it uses average hourly data and basic quasi-static thermodynamic relations in addition to the dynamic (transient) response of thermal inertia and storage components of the plant. This approach appears to deliver good daily and hourly results based on validation [4]. This is confirmed by the findings of Wagner [6] who is responsible for the central receiver model in NRELs System Advisor Model software.

### 3.1.1. Solar parameters

The plant model requires a reasonably accurate sun position at any particular time. Solar time must be supplied or derived and contains standard time, longitudinal adjustment and the equation of time. We used the commonly used equation of time derived by Spencer [7]. From solar time, we derive the zenith ( $\theta_z$ ) and solar azimuth ( $\alpha_s$ ) angles (see Figure 2). A heliostat model uses this as the incidence ray and the position of the tower receiver provides the reflected ray direction. Vector algebra enables a quick determination of the heliostat normal as described by Gauché [4].



**Fig. 3. Solar angles with reference to sun and heliostat**

The remaining solar parameter is the direct beam component of solar energy (or DNI) that corresponds with the incident angle. More will be mentioned about this in section 3.2.

### 3.1.2. Optical and thermal performance of plant

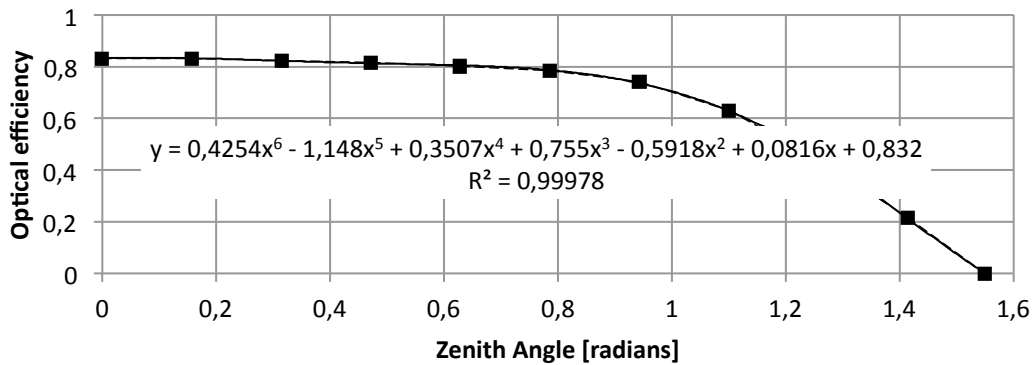
We modelled the optical performance using a method where the heliostat field is discretised into groups of heliostats in order to speed up the task. This method is outlined in detail by Gauché [4] and accounts for cosine, blocking and shading losses. For a plant with a circular type arrangement for the heliostats, such as found at the Gemasolar plant, the optical performance is dominated by the zenith angle and is relatively insensitive to solar azimuth angle. We point out that the heliostat layout for the Gemasolar plant is not available and is approximated using only the key plant parameters in table 1. For this study we sought a high degree of computational reduction, and the zenith angle domination was used to produce the curve fit with corresponding equation shown in Figure 4.

In addition, we account for efficiencies for heliostat reflectivity, availability, fouling and tolerance to produce the net optical performance of the plant.

An energy balance is performed on the receiver to determine energy collected ( $\dot{Q}_{out}$ ) and sent to the power block and storage.

$$(1 - \alpha)\dot{Q}_{in} = \sigma \epsilon_r \sum_{i=1}^n A_i F_i (T_{ri}^4 - T_a^4) + h A_r (\bar{T}_r - T_a) + \dot{Q}_{out}$$

The thermal radiation component requires that the receiver be discretized and solved for the temperature range between receiver inlet and outlet, hence the summation. Using the mean temperature ( $\bar{T}_r$ ) for the radiation component would lead to an under prediction for radiation by greater than 50 % at high receiver outlet temperature conditions. This receiver delivers thermal energy at 565 °C and is a set parameter in the model (it is also how real CSP plants are controlled), which makes it convenient for avoiding an iterative solution. The preceding rate equation also represents the hourly energy capture due to the quasi-dynamic nature yielding results in Whr.



**Fig. 4. Optical performance of the plant efficiency as a function of zenith angle only**

To keep the model generic enough, some plant parameters are determined by operation experience of CSP rather than fundamental models. Thermal inertia plays a significant role in the startup of these plants. The plant model assumes 60 min of full load thermal energy to charge the plant inertia. Depending on the day, this takes about 2 to 3 hours in the morning before the plant can generate power. This simplification works reasonably well against literature [8]. Twenty percent of the plant inertia can be used to run the plant when the thermal throughput drops too low; otherwise the thermal inertia is continuously replenished, and it also contains a loss term of 1 % per hour that continuously draws energy away from generating power.

### 3.1.3. Power block and thermal storage performance of plant

Thermal energy beyond the inertia component is delivered to the power block. In keeping with the requirements of this project, no specific heat engine is specified, meaning that a suitable generic formulation is required. A very simple model is the Chambadal-Novikov modification of the Carnot heat engine [9]

$$\eta_{th} = 1 - \sqrt{\frac{T_L}{T_H}} \quad \& \quad \dot{W} = \eta_{th} \dot{Q}_{pb}$$

This modification represents an endoreversible engine; that is, it contains irreversible external heat transfer and is ideal internally. Large optimised power plants closely match the result of this simplification as reported by Curson [10], and it is used here assuming that it will work on moderately sized CSP plants with any power block including combined cycle configurations. The low temperature reservoir is the hourly ambient temperature assuming dry cooling.

The power block will produce power to its rating while excess power will be diverted to the thermal storage system. The thermal storage system works in a similar manner to thermal inertia. For this project, the size of the storage was set to 15 hours of full load operation to emulate the Gemasolar plant. The thermal storage system has both a charge rate cap and a total charge cap. The round trip efficiency works out to about 97% by setting an hourly decay function of 0.998. As the real plant operates in Spanish conditions where the solar

resource is less than 2,200 kWh/m<sup>2</sup>/yr, a decision was made to permit a rate of 200 MW for the charge rate where the real plant is apparently limited to 120 MW<sup>1</sup>. This decision is due to the much higher solar resource in South Africa that in parts exceeds 3,000 kWh/m<sup>2</sup>/yr. This exposes the possibility that the reference plant is probably far from optimal for this study, but it does not impact the validity of the method.

Once the power block runs out of direct thermal power and reaches the 20% thermal inertia limit, thermal storage kicks in. For this initial study, storage is not withheld for later dispatch, and it will discharge until it is empty or more direct solar power is produced the next day.

### 3.2. Climate and solar resource data and models

In order to assess the potential across the entire country, we built a dataset of grid points with a resolution of 0.375 degrees spanning from latitude -21.5625 to -34.6875 and from longitude 14.8125 to 35.4375 (this specific range was chosen to match DNI grid resolution with weather data grid resolution, see below). In total there are just over 2000 grid points. Because of storage and bandwidth considerations, the assessment was only performed with data for the year 2005.

The most important parameter is, of course, DNI. We procured DNI time series for each grid point from the Helioclim-3 database [11]. Helioclim-3 provides DNI data estimated from Meteosat images in high spatial and temporal resolution from 2004 on. From prior work with this data, we know that the Helioclim data overpredicts DNI on cloudy days and underpredicts DNI on sunny days. However, the overall shape of the DNI curve matches well with measured data in South Africa. This will skew overall power output results, but will nevertheless allow us to analyze hourly day-to-day effects and seasonal variations.

Temperature and wind is based on ERA-Interim reanalysis data [12]. This data is available with a 0.75 degrees resolution. Therefore, each ERA-Interim grid value is used at 4 grid points of the final 0.375-degrees grid without performing spatial interpolation. In order to arrive at a temporal resolution of 3 hours, we used 6-hourly reanalysis values in conjunction with intermediate forecast values. The temperature was interpolated to 1-hour time steps with an iterative stepwise cubic approximation over 72-hour blocks. Wind is given as 10-minute averages every 3 hours. We calculated wind speeds from the u and v wind vector components and assumed that the average wind speed remains constant over the entire 3-hour period. Point validation of temperature and wind data against measured data from 10 stations of the South African Weather Service showed that generally temperature values showed a good match with ERA-Interim data, whereas wind is generally not well captured by the ERA-Interim data (especially in coastal and mountainous regions). However, comparison between a model run with (static) reference wind and temperature values and a run with ERA-Interim values showed less than a 1% difference in cumulative yearly power output, so the influence of these two parameters on output is minimal in the current model configuration. Work on improving the weather data basis will be important for future applications of the model, for instance, if wind shutdown speeds are to be incorporated in the analysis.

We chose 823 grid points covering the entire country of South Africa with no regard to land use, slope, or proximity to current grid connections. At each of these points, we “constructed” a CSP plant with the parameters outlined above and ran the plant model for 2005 data. Apart from model runs to check the consistency of output, we performed five main runs:

- (1) Model run with default parameters as outlined in the method section above.
- (2) Power block size reduced to 10 MW but with the same solar field and storage size as in run (1).
- (3) Power block size reduced to 10 MW and storage size reduced by half but the solar field remaining the same size.
- (4) Power block size reduced to 5 MW but with the same solar field and storage size as in run (1).
- (5) Power block size reduced to 5 MW and storage size reduced by three quarters.

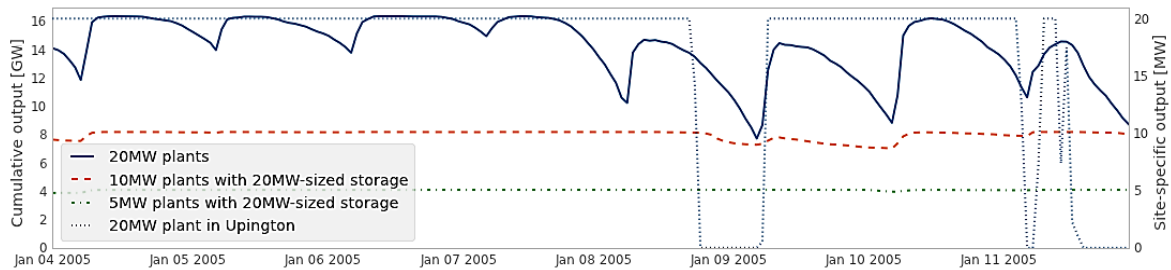
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<sup>1</sup> This is the only explicit positive deviation from the reference plant. In section 4, power block and storage size parameters are manipulated downwards to perform basic dispatch sensitivity tests.

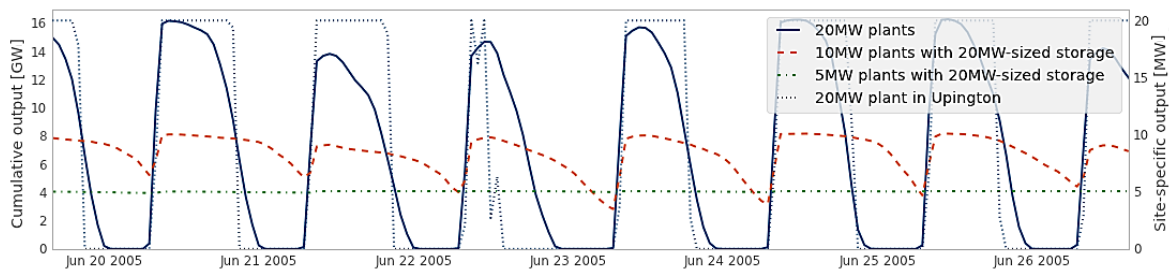


#### 4. Results and analysis

The model takes approximately 30 minutes to solve for 1 sweep of the country for a year of data. Figure 5 shows the results from these model runs for a representative period in summer, while Figure 6 shows the model runs for a representative winter period. Both figures show cumulative power production in the whole of South Africa from all 823 CSP grid points. They also include the output of an individual power plant (situated near Upington in the Northern Cape) for comparison.

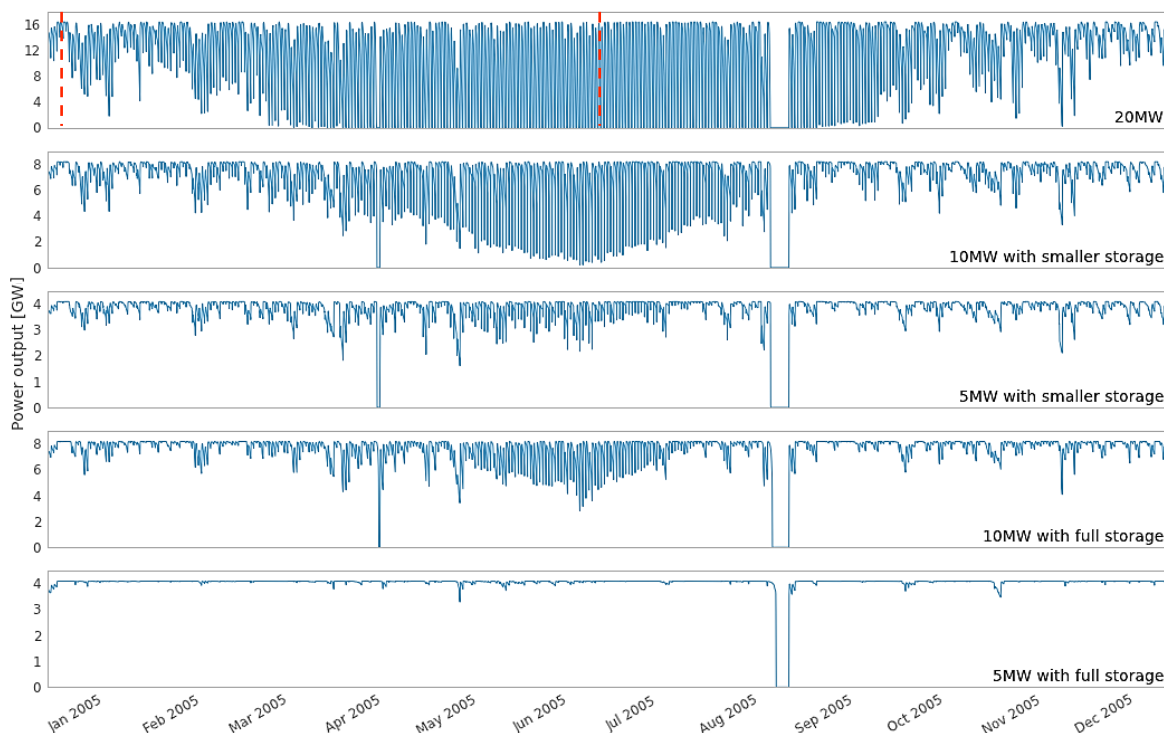


**Fig. 5. Model results in summer (only the three models with baseline storage capacity and Upington)**



**Fig. 6. Model results in winter (only the three models with baseline storage capacity and Upington)**

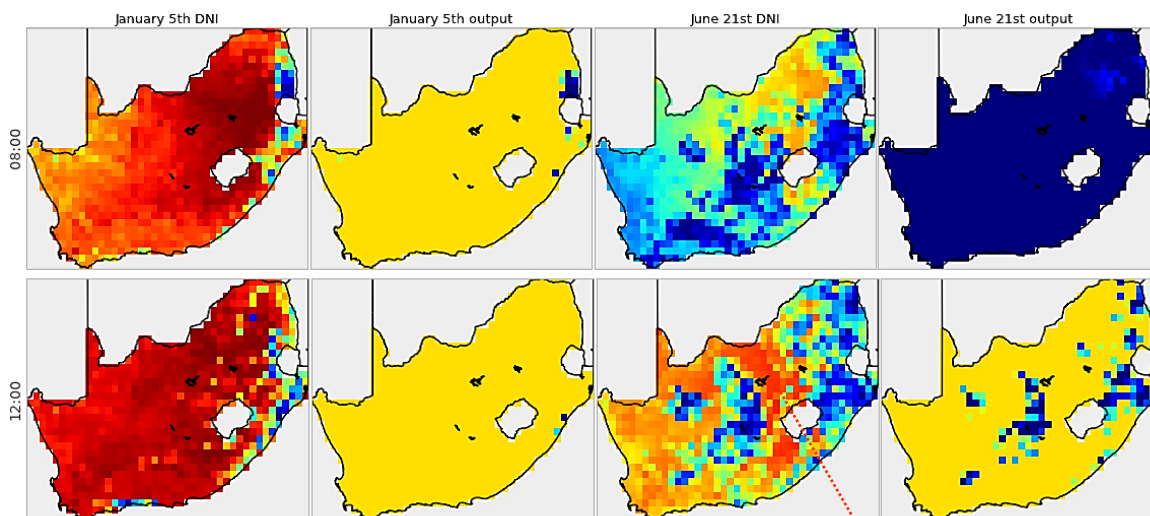
We clearly see in Figure 5 that the CSP fleet (823 plants) of 20 MW plants generally manages to reach the production ceiling of just over 16 GW for several hours a day but falls off overnight as storage at some sites becomes increasingly depleted. We also see a day of particularly bad weather across the country (Jan 9), where the Upington site is badly hit and output across the fleet drops significantly (but does not entirely stop!). The models with smaller powerblock capacities demonstrate increasing potential for dispatchability.



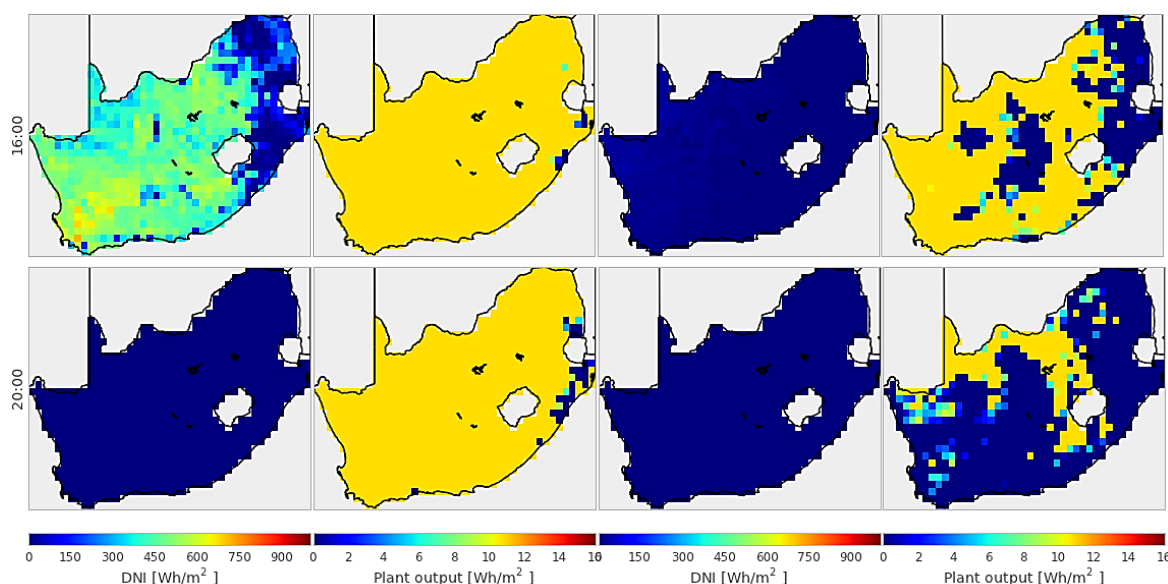
**Fig. 7. Whole-year power output**

In winter (Figure 6), the situation looks dramatically different. Power output from the fleet fluctuates in a daily rhythm from zero to the maximum output (which is only reached very briefly, if at all, on many days). Yet again, the flat power output curve from the 5 MW powerblock size model run demonstrates that even in winter full dispatch is demonstrated countrywide. All cumulative runs show impressive performance against a single site at Upington that struggles on some days.

Figure 7 shows the power output over the entire year for the five model runs. With decreasing power block size (and thus relatively increasing storage and solar field sizes) the ability of the CSP plant fleet to provide stable power increases. The period in September with no power output whatsoever in all five runs is an artefact due to 6 days of missing DNI data.







**Fig. 8. DNI and plant output per area on a summer day (January 5th) and a winter day (June 21st)**

Figure 8 shows the spatial results for the country for specific hours of two real days. January 5 is a good summer day (columns 1 and 2) and June 21 is a particularly poor winter day (columns 3 and 4). Both days are depicted in Figure 7 as vertical dashed red lines at the default plant.

The transition through the day shows the DNI and plant output both on a  $\text{Wh/m}^2$  basis. Despite the particularly poor winter day, power continues to be produced into the evening. We chose to demonstrate the spatial analysis using the full sized power block (20 MW) to illustrate the impact of weather more clearly. The reduced power block models become disinteresting in these plots as they simply show monochrome results (proving the dispatch potential), and it becomes better to refer to Figure 7.

The spatial representation gives a sense of the winter weather systems on June 21. The sunny strip NW of Lesotho translates into power production into the evening. The west coast shows what may still be sunrise at 8:00am. There appear to be multiple systems impacting the country that day, yet from a dispatch point of view just about the entire country could still dispatch at the quarter rating. This equates to the default plant being available for full dispatch for 6 hours in a 24 hour cycle.

It is difficult to validate the entire model, but since the plant model is validated against real and predicted plant performance, we accept that it works as it should. Furthermore, we can do spot checks on the data to ensure that it makes sense. The sum of all 823 plants deliver 16 GWh on excellent days when all power blocks are at capacity. We expect that at these times a good aperture based efficiency is in the region of 15% net. This plant yields 13.1% countrywide during the excellent days of summer.

## 5. Discussion, conclusion and further work

With the promising results from the previous section, it would be interesting to consider the cost of providing this dispatch capability. The default plant used in this paper was constructed for an estimated cost of 230,000,000 Euro<sup>2</sup> [5]. The levelized cost of electricity (LEC) is determined assuming a plant located in Upington has an interest rate of 8% for a full loan, a discount rate of 10%, a 30 year life and payback period and an initial annual operations and maintenance of \$ 65 per kW/year + \$ 3 /MWh escalating at inflation. Using typical mean year (TMY) data (not the 2005 year), one default plant produces 156,000 MWh per year. Using the standard definition, LEC works out to ZAR 1.48 per kWh. Stellenbosch has a similar annual solar

<sup>2</sup> 1 Euro = ZAR 10 & \$1 = ZAR 8

resource to the Spanish plant (per TMY data), and in Stellenbosch the plant produces 115,000 MWh per year. This translates to ZAR 2.01 per kWh, which gives a sense of the range for a single plant modelled in this work.

Stretching this cost exercise to the very limit of conservativeness, the cost of the entire country model that yields constant output to the lowest plot in Figure 7 is ZAR 5.28 per kWh. Optimizing the location of plants would lead to a lower cost between ZAR 1.50 and the value at present costs of CSP. As a matter of interest, the area required to meet a constant output that would deliver all of the 2030 electrical energy needs per IRP 2010 equates to about 0.4% of the land surface. This will also decrease in an optimization study and we should point out that the Gemasolar plant has a relatively sparse heliostat field which could facilitate dual land use.

To conclude, in this paper we presented a new methodology to understand the potential of dispatchable CSP in South Africa. The model combines an efficient but validated plant model with a grid of solar and weather data for the entire country without prejudice for a real year. A proxy for determining ideal dispatchability proves that it is possible to realise this capability year round. This method permits us to perform many interesting and valuable simulations moving forward including the ability to model the renewable energy system of South Africa using real retrospective data or forecasts.

Next steps include: Validating and refining the solar and weather inputs; Performing the simulation for multiple years of real data in order to understand annual fluctuations; including models of PV and wind; and ultimately optimizing scenarios of demand and supply to identify the ideal robust locations for CSP when part of a larger power generation system.

## Acknowledgements

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