DAILY AND SEASONAL DEPENDENCE OF THE EFFECTIVE COLLECTOR AREA OF SOUTH AFRICA'S OPERATING SOLAR POWER PLANTS

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Abstract

This paper overviews a project to catalogue the site specifications and collector configuration of operational solar power plants set up under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). The work aims to produce the first comprehensive compilation of the parameters defining the specifications of South African solar power plants. These parameters not only define the total collector area of the plant, but also the optical efficiency, which is in part determined by the degree of alignment of each collector with the solar beam. Their knowledge is thus crucial for solar resource assessment, including hourly and seasonal dependence, and ultimately the performance modelling of local solar power plants. The paper summarises the procedures employed for ascertaining the solar plant specifications, which include the analysis of Google Earth® images and site photographs.

Keywords: Solar power stations; solar irradiance; solar potential; South Africa.

1. Introduction

In the last eight years South Africa has established considerable medium-scale (5-100 MW) solar power generating capacity through its Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) [1]. These have already played a critical role in mitigating national electricity shortfalls experienced in recent months, and recent studies have established that the optimal energy mix requires an accelerated rollout for further renewable energy generating plants [2]. These findings have been recognised in recent electricity planning processes. The most recent draft Integrated Resource Plans for electricity (IRP) presents a preferred scenario in which solar energy would contribute 8.56 GW, or 11.4% of the national generating capacity in 2030, and as much as ~25 GW, or ~20% of the national total in 2050 [3].

In early 2019, 39 solar plants, totaling 1.98 GW set up under REIPPPP were already in operation (Table 1), while a further 18 plants selected under Round 4 bid and the Small Projects initiative (SP-IPPP) phases of REIPPPP were either getting ready for, or already under construction (Table 2).

The contracted plant capacities listed in Tables 1 & 2 only reflect the maximal supply to the national electricity grid, and does not represent the actual generating potential, which depends on a multitude of factors, often highly variable in time, relating to the solar position in the sky, sky transparency, instrumental configuration, energy conversion efficiency and storage capacity.

Despite the extensive public coverage of the renewable energy developments and the open process that led to the identification of preferred bidders, technical information on South African solar power plants is often difficult to secure. The patchy information and partial uncertainty of configurational details of South African solar power plants hampers the accurate modelling of their electricity generation. The initiative to systematically compile the collecting area specifications, summarised in this paper, seeks to address this shortcoming and to provide a better understanding of the performance of local solar plants.

Bird's eye images with Google Earth® constitute a unique, independent measurement and verification tool to determine the layout and configuration of South African solar plants. The paper shows how, combined with miscellaneous reports and photographs, these enable the definition of plant parameters such as collector tilt angle, row spacing, collector dimensions and site gradient. Knowledge of these then allows the calculation of the effective (i.e. loss corrected) collector area of the plant at any time of the day, on any day of the year. The complete plant specifications database for each South African solar plant, and resulting seasonal and time dependent effective collector area plots, are to be published elsewhere [4].

Type	Capacity (MW)	Name	Longitude(E), Latitude(S)
Parabolic trough	50	Bokpoort	21.995, 28.726
	100	Karoshoek	21.535, 28.487
	100	Kathu CSP	23.028, 27.613
	100	KaXu	19.593, 28.881
	100	XiNa	19.592, 28.892
Tower	50	Khi	21.078, 28.537
PV (fixed)	75	Adams 2	23.013, 27.366
	10	Aries	20.785, 29.496
	9	Aurora	18.503, 32.643
	10	De Aar (Mulilo)	24.005, 30.628
	46	De Aar Solar	24.034, 30.619
	75	De Aar 3	24.079, 30.580
	46	Droogfontein	24.752, 28.612
	75	Ilanga Lethemba	24.102, 30.595
	75	Jasper	23.382, 28.309
	73	Kalkbult	24.136, 30.160
	10	Konkoonsies	19.555, 28.889
	64	Lesedi	23.363, 28.313
	64	Letsatsi	25.922, 28.920
	75	Paleisheuwel	18.730, 32.420
	20	Prieska(Mulilo)	22.320, 29.967
	75	Prieska(Sonnedix)	22.362, 30.021
	75	Pulida	24.925, 29.043
	7	RustMo1	27.419, 25.739
	5	SlimSun	18.530, 33.350
	60	Tom Burke	27.985, 23.072
	9	Upington Airport	21.268, 28.418
	9	Vredendal	18.505, 31.635
PV (1-axis)	60	Boshof	25.195, 28.466
	70	Dreunberg	26.210, 30.837
	75	Kathu (PV)	22.920, 27.601
	37	Linde	24.652, 31.000
	75	Prieska	22.316, 30.036
	74	Sishen	22.932, 27.577
	28	Soutpan	29.252, 22.992
	30	Witkop	29.366, 24.042
PV (2-axis)	10	Greefspan	23.312, 29.391
	20	Herbert	23.802, 29.003
CPV	36	Touws River	19.929, 33.411

Table 1. South African solar power stations established under REIPPPP.

2. Parameterising solar power plant configurations

2.1. Effective collector area

Solar power plants are designed to maximise the conversion of incoming solar irradiance into electricity. In addition to the obvious plant size and photon-to-electricity conversion

Type	Capacity (MW)	Name	Longitude(E), Latitude(S)
Round 4	40	Aggeneys	18.891, 29.239
	68	Bokamoso	26.403, 27.165
	50	De Wildt	27.93, 25.64
	75	Droogfontein 2	24.701, 28.568
	75	Dyasonsklip 1	21.07, 28.58
	75	Dyasonsklip 2	21.06, 28.57
	55	Greefspan 2	23.31, 29.38
	75	Konkoonsies 2	19.564, 28.897
	75	Loeriesfontein	19.61, 30.51
	75	Sirius	21.10, 28.55
	75	Waterloo	24.79, 26.99
	75	Zeerust	26.07, 25.57
SP-IPPP	5	Adams 1	23.00, 27.39
	5	Bellatrix	23.18, 31.53
	5	Du Plessis 4	24.07, 30.63
	5	Heuningspruit 1	27.42, 27.45
	5	Steynsrus 1	27.54, 27.91
	5	Steynsrus 2	27.54, 27.91

Table 2. South African solar power stations to be established under REIPPPP bid window 4 and the first SP-IPPP allocation. In most instances the latest Google Earth images do not yet show evidence of construction activity – in these cases the location is based on other information, and is only given accurate to two decimal places.

efficiency, the performance of a plant also depends on the collector configuration, which should minimise cosine losses (reduced interception of sunlight due to an incident solar beam oblique to the collector) [5], shading losses and reflected light missing the receiver, e.g. end losses in parabolic trough collectors [6]. Calculating these losses, and the resulting plant performance in the course of a day and season, requires amongst other things knowledge of parameters such as collector row spacing and tilt angle (e.g. [7]).

The key parameter this study seeks to identify for each South African solar plant is referred to here as the effective collector area. The symbol employed here to signify this parameter is *Æ*. It represents the cross-sectional area normally incident to an incoming photon for which this photon will be intercepted by a collecting surface. Its size naturally depends not only on the direction of propagation of the incoming photon, but also on the alignment of the collectors at that point in time.

2.2. Direct and diffuse irradiance

Solar radiation processed into solar electricity reaches the collectors at ground level through several possible routes. The simplest and usually dominant path is that taken by what is referred to as direct irradiance, which refers to solar photons transmitted through the atmosphere without reflections. This component originates from the direction of the sun, and is commonly visualised as a solar beam.

In addition to this, there are also scattered photons reaching the collector from other directions in the sky. In addition to the solar position, the strength and angular distribution of this component strongly depends on atmospheric conditions, i.e. the concentration and nature of gases and aerosols.

Solar radiation reflected off the ground towards a tilted collector is sometimes considered as a yet an additional component, but may for the purpose of this study be treated together with the diffuse component, as effective collector area is only a meaningful concept in relation to the direct component. Henceforth any reference to the diffuse component also incorporates any photons reflected off the surface.

The first point to note is that the diffuse component plays no significant role in concentrated solar power technologies. The diffuse part only affects configurations using PV technologies. For the typical South African rural sites where most of the solar plants are located, which are generally in regions with low average aerosol loading and frequently at high altitudes, the diffuse component is usually much weaker than the direct beam. It is nonetheless still significant enough that it has to be incorporated in any realistic local solar plant electricity production model.

While the focus hereafter is on the cross-sectional total collector area encountered by the direct beam, the remainder of this subsection will briefly explore how collector area should be treated when dealing with diffuse radiation. In essence, it will then be necessary to define the effective collector area for each infinitesimal solid angle $d\Omega$ in the direction defined by elevation above the horizon angle ξ and an azimuth angle α.

$$Æ(\alpha,\xi,t)\ d\Omega = Naf(\alpha,\xi,t)\ d\Omega\ .$$

Note that $f(\alpha,\xi,t)$ is a very complex function where the time dependence not only highlights variations in the atmospheric composition, but also the changing position of the sun and the impact this has on the sky angular profile and even the degree of shading.

2.3. Significance of effective collector area for different solar power plant technologies

Six different configurational technologies have been employed in South African solar power plants to date. The peculiarities of the effective collector area formulation for each of these technologies are lined out in sections 2.3.1 to 2.3.5 below broadly in order of increasing complexity. While some of the technologies elaborated on have become less popular in recent times, and are therefore likely to only represent a small fraction of the future South African solar power station fleet, it is nevertheless useful to list all methodologies needed to quantify the generating capacity of the entire fleet.

2.3.1. Concentrated photovoltaic and Two-axis tracking photovoltaic

These two very different technologies share a geometric configuration, and the formula for the effective collector area is common to both. Note though that for total solar electricity generating calculations the diffuse component can be ignored for the CSP case but not for PV.

Plants employing the concentrated photovoltaic or multiple-axis tracking photovoltaic technology require each individual module's normal to be constantly aligned with the solar beam, meaning that there will be no cosine losses, only shading losses due to adjacent modules at large solar zenith angles. In its simplest form, the effective collector area is

$$Æ(t) = N[1-\sigma(t)]a$$

In reality this formula requires a small correction due to the fact that front row and row end modules experience less shading than those elsewhere in the field.

2.3.2. Solar tower

Solar tower plants consist of a field of heliostats, each of mirror area a, that reflect the incoming solar beam towards a hot spot situated at the top of a tower. Each heliostat is sited at a different spot, meaning that, to aim the reflected beam towards the hot spot, each individual heliostat i's alignment differs from the others. While care is normally taken to minimise shading of individual heliostats by adjacent ones, shading losses will invariably occur when ζ approaches 90°.

The effective collector area of a solar tower plant can therefore be approximated by the sum over all N heliostats

$$Æ(t) = a\ \Sigma[1-\sigma_i(t)]\cos\theta_i(t)$$

where θ_i is the angle that the normal vector of each individual heliostat makes with the incoming solar beam. The above formulation neglects minor losses due to deviation from the geometric optics law of reflection due to diffraction effects.

2.3.3. Parabolic trough

In all South African parabolic trough plants the individual troughs are aligned north-south. Here the effective collector area can be approximated to be

$$Æ(t) = Na[1-\sigma(t) -\varepsilon(t)]\cos\theta(t)$$

where θ depends on the solar declination δ, the solar plant latitude l and the plant site's north-south gradient (and of course on the time of day and the time of the year). As with other technologies, the collectors in the front row experience less shading, and a more accurate formulation for $Æ$ than above would need to incorporate that.

2.3.4. Single-axis tracking photovoltaic

This technology is in some respects analogous to the parabolic trough setup, with the collector able to rotate about a north-south aligned axis. But unlike its CSP counterpart, this technology also applies a technique referred to as backtracking, in which the positional adjustment of the individual modules is programmed to negate any shading, even though this means that the module alignment will no longer correspond to the maximum $\cos\theta$. So here

$$Æ(t) = Na\cos\theta(t) \ ,$$

where θ is now the smallest module normal-to-solar beam angle that can be achieved rotating the module around the north-south axis without adjacent module rows shading each other.

2.3.5. Fixed photovoltaic

For fixed photovoltaic solar modules the normal-to-solar beam angle θ is directly linked to the (time dependent) solar zenith and solar azimuth, as well as the fixed module tilt angle β and the solar module azimuth orientation angle α. All current fixed photovoltaic plants in South Africa have north-facing modules, i.e. $\alpha = 0$. The shading fraction σ is also a function of solar position, i.e. it varies in time, but its magnitude is also dependent on other parameters such as β.

For this technological class,

$$Æ(t) = Na[1-\sigma(t)]\cos\theta(t) \ .$$

3. Solar plant configurational parameters

3.1. Documented configurational parameters

Comprehensive compilations of all configurational parameters of a solar plant are rare. For South African solar plants, sources of information regarding site layout, collector specifications and operational mode include:

- Presentations made by the developers during the public consultation process organised by the National Electricity Regulator of South Africa (NERSA), which are all stored on that organisation's website.
- Environmental impact assessment reports and related documentation, sometimes available on the website of the company that coordinated these studies.
- Some solar power station operators maintain their websites, and these may list some plant configuration details.
- Miscellaneous reports sometimes provide details of solar farm technological specifics. One example might be a routine news report, often drawn up from a press release.

While usually reasonably accurate, these sources of information often provide incorrect details. This may be due to errors incurred during reporting, but could also be the result of real changes from the originally planned configuration due to practicalities and operational issues.

3.2 Google Earth inspections

Real bird's eye images of all South African operational solar plants and of some of the plants still under construction can be obtained through the Google Earth facility. These allow the verification of some of the configurational parameters mentioned in the previous sub-section. In addition, Google Earth provides basic measurement tools that can be applied to determine:

- Coordinates and altitude above sea level of any location within the solar plant perimeter. This also allows one to determine the site slope and the slope's orientation.
- The length of rows of collectors and the spacing between successive rows.
- Occasionally it is possible to zoom into the images enough to visually resolve individual modules (see Fig. 2). This then enables the independent determination of the arrangement of solar modules, including whether these are oriented in portrait or landscape mode, and the length and width of each row (in units of the number of modules).
- In conjunction with the measured row length, this can be used to estimate the dimensions of each module, which in turn can be used to verify the module specifications documented elsewhere.

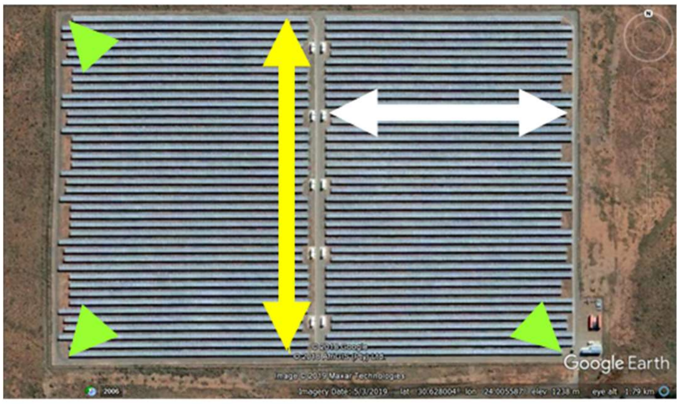

Fig. 1. Example of a Google Earth image of a South African solar power plant (Mulilo De Aar) [8]. Dimensions of the row lengths (white line), row spacing (yellow line divided by the gaps between the top and bottom row) and the plant altitude and slope (determined from the coordinates and altitudes of reference points indicated by green arrows) are easily determined.

Fig. 2. Close-up of the image shown in Fig. 1 [8]. The distance between the centres of adjacent modules is here determined by counting the 'ripples' in a particular row, and dividing this number into the row length.

3.3. Photographic analysis

Another very useful tool that may be employed in the determination of solar plant configurational parameters is the inspection of miscellaneous photographs that include some of the plant's solar collectors. Information that can be extracted from on-site photographs include the following:

- The layout of solar modules on a table, i.e. whether the module alignment is landscape or portray, and how many modules have been stacked vertically or horizontally per mosaic.
- It may be possible to set limits on the solar module dimensions, e.g. using the width-to-height ratio, or to narrow down the type of module. For example, is the pattern that defines the module, or its colour, consistent with the claimed solar module specifications?
- By identifying lines that are known to be parallel in reality, it is possible to determine the angles between parallel line systems. A good example of this is a collection of fixed photovoltaic solar modules, all at the same tilt angle, and aligned in the same direction. So the sides of the solar modules all constitute parallel lines in real life. In a photograph these will converge at a distant point in the photograph. The location of this point is mathematically dependent of the module tilt, and therefore this angle can be extracted from a suitable photograph.

Again great caution is called for when interpreting such photographs. Frequently online photographs claiming to display a specific solar plant were actually made at a different location. It is therefore imperative that the photograph should include evidence in it of being made at that location, such as the presence of a topographical feature or of signage clearly associated with a particular site.

4. Concluding Remarks

Each solar plant's configurational parameters are known to the plant's constructors and operators, but this information is not always made freely available to the public. Some details are occasionally listed in accessible documentation such as presentations to NERSA, environmental impact studies, press reports or operator and constructor webpages. Direct enquiries from the author to specific solar plant operators, requesting confirmation of configurational details reported by such sources, or seeking these details where nothing has been reported, have however not been replied to.

The systematic compilation of solar plant configurational parameters creates an important database of the factors required to calculate solar plant performance and intercomparison. The effective collector area is a key multiplier that enables quantisation of the conversion of the radiation incident on the plant's collectors (after traversing the atmosphere) electricity generation in the detector (which depends of material photovoltaic properties or mirror reflectance or heat storage efficiency).

This paper presents a compilation of medium-to-large South African solar power plants already in operation, or expected to achieve operation in the next few years. It defines the configurational technology of each plant and summarises the procedure required to determine the configurational parameters, and hence the effective collector area, of each plant as a function of season and time of day. The detailed analysis and presentation of each plant's effective collector area is ongoing, and is to be presented in a series of upcoming papers [4].

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