# Towards Optimizing Solar PV Collector Deployment in Inter-row Shaded Arrays

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**Abstract**

One way of reducing the Levelized Cost of Energy of large solar photovoltaic plants without adding any material costs is to optimize the collector row spacing and collector tilt, ceteris paribus. In this study a method of determining optimal geometric deployment parameters for Solar PV arrays where inter-row shading is a problem, is presented. The approach uses a techno-economic analysis which uses the Levelized Cost of Energy (LCOE) as the objective function to minimize. This approach is used to determine the optimum specifications for the row spacing (characterized by the ratio of row spacing to collector length – normalized row spacing S/L) and plane tilt angle, for different field-collector cost ratios, $C_f/C_c$. The optimum values of row spacing, and collector tilt are defined at the points of minimum LCOE for each of the $C_f/C_c$ values. A design chart that can be used to directly determine the optimum S/L and tilt angle values for a given $C_f/C_c$ was produced aided by the industry-standard PV computer simulation program, PVSyst. At a typical location in Zimbabwe (latitude 20.15$^o$ South) and at $C_f/C_c$ of 0.167, for instance, it was found that optimum values of minimum required land area; S/L and collector tilt are respectively, 0.84 ha/MW, 1.3 and 12$^o$. It was also established that the optimal tilt angle to be prescribed for multi-row PV arrays is very much smaller than that which would have been prescribed by the rule-of-thumb for unshaded arrays (e.g. latitude + 5$^o$), which has an effect on the loftiness and cost of the PV mechanical support structures required. Although demonstrated only for a particular location, the method of this study is replicable for any other location.

*Keywords: Inter-row shading, economical deployment, normalized row spacing, field-to-collector cost ratio, optimum tilt angle, Levelized Cost of Energy, PVSyst*

## 1. Introduction

For the economical deployment of solar collectors in multi-row arrays, inter-row shading is inevitable. This is due to contrasting effects, on cost of energy, of very large versus very small inter-row spacing. On one hand, very large spacing of collector rows, ostensibly to completely avoid shading, results in increased field costs (land area and longer electrical cables or interconnecting pipework), thus increasing the cost of energy. On the other hand, bringing the rows closer together tends to increase inter-row shading thereby reducing radiation collection on the collector surface and energy production, again increasing the unit cost of energy. Inter-row shading presents peculiarly complex problems in solar PV arrays since the energy output reduction is disproportionate to the amount of shading. It is therefore critical that the geometric deployment parameters of solar PV modules in multi-row arrays (i.e. row spacing and array plane tilt), are optimised, in order to maximise profitability of solar PV plant by minimising Levelized Cost of Energy.

The inter-row shading problem can be illustrated by Figure 1, which shows the cross section of a multi-row solar collector array with *k* rows. Depending on latitude of the location, the spacing between the collector rows (S), the tilt angle of the collector row plane from the horizontal (β) and the collector row length (L) and lateral width (W, to some extent), adjacent rows in the collector field tend to cast shadows on each other at certain times of the day when the sun is low in the horizon. In Figure 1, Normally, the Row 1 is unobstructed, but Row 2 may be partially shaded by Row 3, Row 3 by Row 2, and so on, under point C, Duffie and Beckman, 2013.

To completely avoid inter-row shading, the rows should be sufficiently spaced such that at no time during the day will adjacent rows cast shadows on each other. However, this creates other technical and economic issues, such as the need to use larger land area, longer and larger diameter sized cables to avoid excessive voltage drops, longer maintenance roads, longer security fences, etc.


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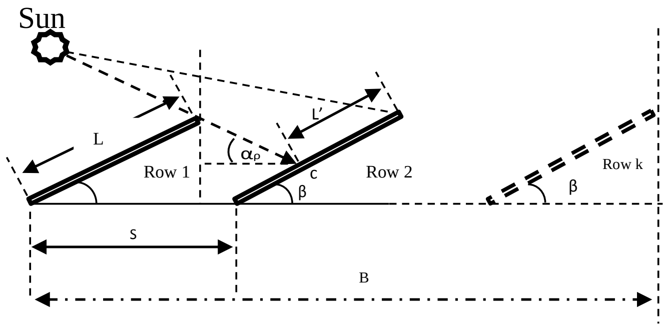


**Fig. 1: Illustration of inter-row shading in multi-row solar array**

Several methods and models, Kalogirou, 2014, have been developed by different researchers to analyse the effect of inter-row shading firstly on radiation incident on solar collectors and of late on the overall effect on the electrical output of Solar PV collectors. Hove, 2004a described two methods that could be used to estimate the effect of inter-row shading on radiation incident on the solar collector surface. The first method assumes a solar collector field whose row length is very large compared to other field dimensions such as row width such that the effect of end penetration of radiation can be neglected. This method is particularly unsuitable for solar PV collectors as mentioned in his works as it tends to overestimate the shading effects and will not give reliable results as solar PV is very sensitive to partial shading. The second method can be used to calculate the effects of inter-row shading on solar collector field of any system dimensions and more suitable for solar PV collector fields as it divides the module into finite rectangular elements that can be dealt with using the binary approach where each element at each defined moment of time is either shaded (0) or unshaded (1). This will be useful in this study as we try to model the output of each silicon solar cell I-V characteristic using the single diode model inbuilt in PVSyst software to predict the electrical output of solar PV array in partial shaded conditions as in inter-row shading.

This together with earlier work done in Jones and Burkhart, 1980, where the shading effects are also estimated but with the assumption where the row length is very long relative to other system dimensions, provide the basis for understanding the effects of inter-row shading on solar energy input on the collector surface.

Elsayed and Al-Turki ,1991 also developed a method of calculating the shading using the scale factor coefficient and two basic shading factors i.e. the special case when collectors are tilted with an angle equal to latitude angle and for a field using collectors with ratio of length to width equal to 2. A chart is then produced which can be used to predict the average row shading factor. The method takes care of both beam and diffuse radiation by also taking into consideration the collector view factor.

Appelbaum and Bany (1979) described a numerical shading model based on the shadow of an inclined pole. The method can account for the beam radiation shading both long and short row collectors. However, the treatment of diffuse radiation had some errors as observed by Jones and Burkhart (1980), who also neglected end penetration effects in their method.

Hove 2004b goes further to develop a model to do an economic optimisation of the deployment parameters through minimising average input solar energy cost into the collector field. Optimal spacing and tilt were determined by means of techno-economic analysis trade-off between maximizing energy yield performance, on one hand, and the corresponding collector and field cost on the other. This gives a good foundation to understand how radiation income is affected by the deployment parameters of row spacing, tilt and row width. The inputs into this model were costs of land, cabling, pipes etc. collectively referred therein as field costs. However, the analysis did not consider the impact of partial shading on PV energy output.

This approach will be developed further in this study with focus now on the solar PV collector array electrical energy yield rather than just the input solar energy. The levelized cost of array energy yield will then be used to optimise deployment parameters considering the sensitivity of electrical energy output of solar PV collectors to partial shading.

Topic et al (2017), presented a mathematical model to maximize lifetime profit by optimizing PV system configuration for a given installation area, the result is to have the optimal number of rows and module angle that can fit in a fixed given area for maximum lifetime profit. However, in this study the minimum installation area required is one of the key outputs.

The sensitivity on PV output to partial shading was demonstrated by Sari-Ali et al (2014), who used a two-diode silicon solar cell model to investigate experimentally the effect of shading on the losses on the output I-V characteristic curve of Si solar cell. The reference found out that the output power decrease due to shading was significantly disproportionate to the amount of shading.

Deline et al (2013) developed a simple model to approximate uniform shading in large PV arrays which uses I-V curve simulations at cell level using the single diode silicon solar cell model. This is then used to analyse the I-V characteristics of both shaded and unshaded sub-modules, and these are summed up to produce module, string and system level I-V curves for a given shade configuration. This justifies the fact that partially shaded sub-modules in a module with bypass diodes can be treated as fully shaded and the model was compared to field experiments and was found to be within 2-6% maximum error for Si-multi-crystalline modules. The same approach is used in the development of PVSyst software that will be used for simulation in this study.

Mermoud 2012, provides an analysis of the inter-row shading effects on losses due to different radiation components using PVSyst software simulation i.e. beam, diffuse, albedo and mismatch electrical effects over a full year and found out that the diffuse and albedo losses are more pronounced. The beam losses were found to be very small (at less than 9% of the total loss) because the inter-row shading occurs at low sun angles in the morning and late afternoon when beam radiation is also low. However, the effect in the differential illumination of the collector surface due to beam losses is amplified by the internal electrical connections of the silicon solar cells inside the module. It was also confirmed that when the bottom cells of a module string are shaded; it affected the whole string and the effect of by-pass diodes for energy recovery is minimal, further confirming the sensitivity of solar PV to partial shading.

Mermoud and Lejeune 2010, demostrated that in PVSyst, the electrical shading effect is depended on the length of the strings and the number of strings in parallel. The full shading electrical loss over a period is done through a simulation over this period. The simulation algorithm has a worst case scenario if shading orientation renders bypass diodes ineffective which is based on the assumption that if cells within a submodule are shaded the whole submodule output is disregarded. This however is not entirely accurate as some power is salvaged through the effect of bypass diodes, which are also taken into account through module layout in the same simulation. This puts to the fore the importance of electrical configuration of the array on the effect of partial shading on electrical output.

Denholm and Margolis, 2008, looked at impact of array deployment and array electrical configuration on the land-use requirements for Solar PV plants in USA. Major considerations looked at where the PV energy density or the energy per unit of land (or surface area). This is a function of the array power density (power per unit land area occupied) and the PV generation which is the energy generated per unit of power (kWh/kWp). The results showed that there is a strong dependence of energy density on system configuration, which is significantly greater than the dependence of energy density on the difference in solar resource between different states in the USA. This means that it is very important to optimise deployment parameters as well as the electrical configuration of a solar PV plant in order to maximise the use of available land.

Recently, Sánchez-Carbajal and Rodrigo, 2019, analysed the inter-row shading problem in greater detail. They correctly note that the optimization of collector deployment in a solar energy array depends on various factors, the efficiency of the module, the field aspect ratio, the cost of system components, among others. They went on to analyse the sensitivity of deployment optimization to each of the influencing factors. However, despite a very thorough model on recieved radiation analysis and the effect of shading on it, they did not come up with a clear-cut rule for optimal deployment. Their model is also not clear on how it differentiated between the loss in radiation received due shading and the PV electrical output after the effects of the modification of I/V characteristics of the module or string due to the shading effect.

This present study attempts to estimate more closely the optimal deployment parameters of the PV field; normalised row spacing and collector tilt angle, taking into consideration the relative costs of field and collector and taking Levelized Cost of Energy as the objective function. The industry-standard PV simulation software, PVSyst has been selected as the analysing tool, since it can calculate PV electrical output for any collector configuration and brand of PV module. In its “Module Layout” function, PVSyst is able to analyse the PV system per sub-module (part of separated by by-pass diodes) and approximate the power output and voltage contribution of the sub-module to module, and subsequently to the string I-V characteristics. This method of approximation of PV output is much closer to reality than just using the fraction of shaded collector area as basis for estimating the PV output. The presented method is easy to follow and adopt as it is more practical and uses an off-the-shelf commercially available industry standard Solar PV simulation software tool. The method of the study will be illustrated by a case study of a 1MW solar PV plant at Bulawayo, Zimbabwe, latitude 20.15ºS. This study method is unique, when compared to other methods in the literature, because it does not only use a PV simulation software which can accurately calculate the energy output for any PV module configuration considering shading, but also the method can explicitly show the effect of relative field to collector costs on choice of deployment parameters.

This paper is laid out as follows: 1. Introduction, 2. How PVSyst Models Inter-row shading, 3. The Study Method, 4. Results and Discussion, 5. Example of applying the study results 6. Conclusion, and 7. References

## 2. How PVSyst Models Inter-row shading

The industry-standard PV simulation program PVSyst (www.pvsyst.com/features/ , 2019) was used in this study as it was considered to handle the shading problem as needed by the authors. PVSyst uses hourly meteorological data obtained from either of two databases, namely Meteonorm 7.1 or NASSA. Meteonorm for instance, generates accurate and representative typical meteorological years (TMY) from any place on earth and the data is obtained from more than 8000 weather stations and satellite data. Data periods are from 1960 -1991, 1991-2010 and 1996-2015 for irradiation data and 2000-2009 for other parameters. The data can be obtained using 36 output formats including CSV, TMY1, TMY2, TMY3, PVSol, PVSyst, Polysun, SAM etc.

The meteorological data generated by Meteonorm are monthly, daily, hourly and minute values and it uses interpolation to calculate typical years for any location worldwide. In PVSyst only monthly values of Meteonorm are downloaded into the inbuilt database and the hourly values are then synthetically generated. The parameters obtained from Meteonorm data include Global Horizontal Irradiation (GHI), Diffuse Horizontal Irradiation (DHI), Ambient Temperature (TA) and Wind Velocity (WindVel).

In PVSyst, for the simulation of the effects of inter-row shading on electrical output, shading factors for beam radiation, on one hand, and for diffuse and albedo radiation, on the other hand, are treated differently. The beam radiation shading factors for each hour are produced by simulating the sun's height and azimuth. In the "Three D" shadings function each sub-module is represented by a finite rectangle and becomes electrically un-responsive to beam radiation, when a part of the rectangle is shaded. The shaded sub-module can still produce some current and voltage due to the diffuse and albedo radiation received by the sub-module. The beam radiation shading factors for each hour are then produced by simulation, Mermoud, 2012

The shading factors for diffuse and albedo radiation are constant with time of the day and season, but only depends on the module geometrical layout and surface azimuth. They can be calculated based on an isotropic diffuse sky model (e.g. Liu and Jordan, 1961).

The effect of partial shading on electrical energy output of the array depends on the electrical connections between the sub-modules or modules (series, parallel etc.) in the array. PVSyst uses the finite rectangle approach as in (Hove, 2004a) to compute the shading factors with each rectangle representing a module or string of modules depending with array size and configuration.

A close estimation of modelling of the finite rectangular approach to calculating the shading factor as used by Pvsyst can be illustrated by a method deveoped by Hove, 2004a to calculate the effects of inter-row shading on solar collector field of any system dimensions and this method is more suitable for solar PV collector arrays. In this method the collector module is divided into finite rectangular elements that can treated using the binary approach where each element at each defined moment of time is either shaded (0) or unshaded (1). This approach actually determines more accurately the points that are shaded on the collector and will give more accurate results in the analysis of shading effects on electrical output of a solar PV collector since PV modules are quite sensitive to partial shading due to internal interconnections between silicon solar cells inside the module. This aspect is added to the complexity of the position of bypass diodes and module electrical connection configurations.

When a PV module is partially shaded there are two kinds of losses to consider namely the irradiation losses on the surface of the module and the electrical mismatch losses due to differential illumination of the module surface. In this study we focus on one approach to treat the electrical losses due to shading, namely the “Module Layout”. This function gives a more accurate evaluation involving the exact position of each PV module in the “3D construction”, as well as in the electrical system. It identifies each electrical string in the array, and its attribution to a given string inverter input is used for shading loss calculation

An example of the shading loss calculation for strings under different shading conditions using the “Module Layout” function can be illustrated by the I/V characteristics at each inverter input as in Fig 2.

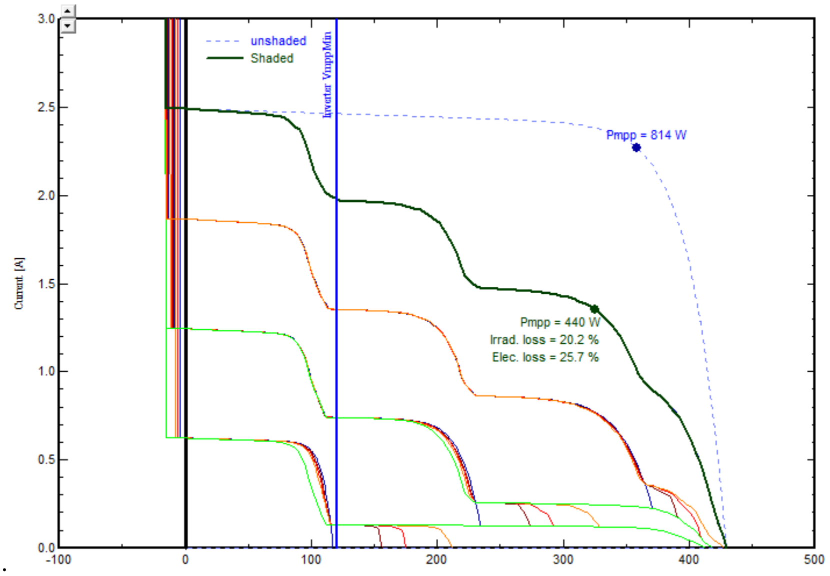


**Fig. 2: I/V characteristic curves of strings under partial shading conditions as calculated by Module layout model of PVSyst**

In figure, the strings #1 and #2 (with lower $P_{mpp}$ values) will operate at their residual current corresponding to the diffuse and albedo part. Their production due to beam is completely lost. One can have completely different figures where the MPP point is below the inverter's minimum voltage. In this case the voltage will clip on this value, and the shading loss may be very high. The shading losses are evaluated for this MPPT input, with respect to the unshaded $P_{mpp}$ value. This loss is the sum of the irradiance deficit ("linear" part), which is estimated using the number of sub-module shaded summits and the electrical mismatch losses. The total loss is the difference $P_{mpp}$ (unshaded) - $P_{loss}$(irradiance) - $P_{mpp}$ (shaded). The notches in the I-V characteristic are due to the effect of bypass diodes, Diaz-Dorado et al (2014).

## 3. The Study Method

A case of a 1MW solar PV plant in Bulawayo, Zimbabwe latitude 20.15$^0$ was considered to run simulations of different combinations of array tilt and array spacing-to-row width ratio (S/L). A plant size was defined and designed using PVSyst software with collectors oriented at 180° azimuth (0$^0$ in PVSyst) i.e. facing north. The most important output of the simulations for this study being the electrical energy delivered by the PV array and the electrical energy delivered by the overall system to the Grid.

Using PVSyst software the system was defined in terms of the PV plant size, choice of type and size of PV modules to be used, number of modules in series and the number of module strings. The choice of type, number and sizes of inverters to deploy was also considered.

Tab. 1 gives the basic system definition parameters for the 1MW PV plant for Bulawayo.

The “3D shading scene” method was used. It allows the designer to physically place the modules into an array with chosen dimensions in terms of number rows, length of rows and row width and it goes further to interact with the

"Module layout" function to really consider the geometric as well as the electrical placement of each module in the array and calculates how partial shading affects the output of each module based on the module layout.

**Tab 1: System Definition parameters for the Bulawayo Case study**

| Item No. | Description | Specification |
|---|---|---|
| 1 | PV Plant size | 1000kW$_p$ (1MW$_p$) |
| 2 | PV module type | Yingli Solar *(poly 72 cells, 3 bypass diodes)* |
| 3 | PV module rating | 300W$_p$, V$_{mpp}$ 36.27V, V$_{oc}$ = 45.27 (at STC) |
| 4 | Number of modules | 3333 |
| 5 | Modules in series | 15 |
| 6 | Number of strings | 222 |
| 7 | Inverter | Green Power, 20kW, MPP input voltage 450-800V DC, output |
| 9 | Number of inverters | 50 |

Several configurations of electrical layouts and attributions are possible but for this study a basic attribution in which at least modules in a string are at the same level along the row width such that when they are shaded only the inverter they are connected is affected and the rest of the system can continue to deliver power. It should also be noted that the orientation of modules, either in portrait or landscape influences how the shading affects electrical outputs depending on the arrangement of sub-modules and how they are interconnected through bypass diodes, Bayrak et al (2017), Marco et al (2013).

**Tab. 2: Typical extract output of the simulation for the Bulawayo (latitude 20.15°) PV plant**

| Tilt (degrees) | Azimuth (degrees) | GCR (%) | S/L | GlobInc (kWh/m²) | GlobEff (kWh/m²) | ShdLoss (kWh/m²/yr) | ShdElec (kWh/yr) | EArray (kWh/yr) |
|---|---|---|---|---|---|---|---|---|
| **0** | 0 | 78.57 | 1.27 | 2171 | 2096 | 0 | 0 | 1893762 |
| **1.58** | 0 | 78.57 | 1.27 | 2192 | 2117 | 0.7 | 0 | 1911496 |
| **3.16** | 0 | 78.57 | 1.27 | 2211 | 2136 | 2.2 | 0 | 1927589 |
| **4.7** | 0 | 78.57 | 1.27 | 2229 | 2153 | 4.9 | 0 | 1941622 |
| **6.32** | 0 | 78.57 | 1.27 | 2246 | 2167 | 8.8 | 2055 | 1951688 |
| **7.89** | 0 | 78.57 | 1.27 | 2261 | 2179 | 13.2 | 5399 | 1958080 |
| **9.47** | 0 | 78.57 | 1.27 | 2274 | 2188 | 18.7 | 7702 | 1963595 |
| **11.05** | 0 | 78.57 | 1.27 | 2287 | 2195 | 25.0 | 9400 | 1967760 |
| **12.63** | 0 | 78.57 | 1.27 | 2297 | 2200 | 32.1 | 22270 | 1958858 |
| **14.21** | 0 | 78.57 | 1.27 | 2307 | 2202 | 40.3 | 33303 | 1949552 |
| **15.79** | 0 | 78.57 | 1.27 | 2315 | 2202 | 49.1 | 40934 | 1941691 |
| **17.37** | 0 | 78.57 | 1.27 | 2321 | 2200 | 59.0 | 64795 | 1915662 |
| **18.95** | 0 | 78.57 | 1.27 | 2326 | 2195 | 69.3 | 78652 | 1897853 |
| **20.53** | 0 | 78.57 | 1.27 | 2330 | 2189 | 80.5 | 108981 | 1861770 |
| **22.11** | 0 | 78.57 | 1.27 | 2332 | 2179 | 92.4 | 148752 | 1814116 |
| **23.68** | 0 | 78.57 | 1.27 | 2333 | 2169 | 104.6 | 172940 | 1780731 |
| **25.26** | 0 | 78.57 | 1.27 | 2332 | 2156 | 116.9 | 188124 | 1754817 |
| **26.84** | 0 | 78.57 | 1.27 | 2330 | 2142 | 129.0 | 199518 | 1731870 |
| **28.42** | 0 | 78.57 | 1.27 | 2327 | 2127 | 140.9 | 209315 | 1709563 |
| **30.00** | 0 | 78.57 | 1.27 | 2322 | 2111 | 152.8 | 216625 | 1688554 |

For the optimisation of the collector deployment in the array, PVSyst's "Optimisation Tool" was employed. This tool helps to easily find the optimal values for the PV deployment parameters i.e. normalised row spacing, S/L, and array tilt, $\beta$. It performs automatically a set of simulations, where for example each parameter is varied, in turn, ceteris paribus, according to a specified range. The results of all simulations are stored, and can be accessed as a CSV file, for further analysis.

Tab. 2 shows the output of the PVSyst "Optimization Tool" simulation of array deployment parameters for a 1MW PV plant at Bulawayo, Zimbabwe at latitude $20.15^0$S.

From the complete version of Tab. 2, parametric curves (with S/L as the parameter) of actual array output energy normalised with array output energy for a horizontal collector against tilt angle were plotted. From this plot, the relationship between the optimal tilt angle and S/L was derived.

To enable calculation of Levelized Cost of Energy by PVSyst, cost data for land, cabling, collectors etc. are required. The land area required was calculated using the following formula:

$$A_L = \left[(k-1)\frac{S}{L} + cos\beta\right] WL \qquad \text{(eq. 1)}$$

In eq. 1, k is the number of rows of the array, S/L is the normalized row spacing as defined on Fig. 1, L is the collector length, $\beta$ is the array tilt angle and W is the width of the row in the east-west direction.

All the other inputs are entered in the normal way into PVSyst, but were separated into field-related costs (land owning and development, cables, maintenance roads, security fence, etc.), $C_f$, and collector-related costs (PV modules and PV mounting structure), $C_c$.

The ratio $C_f/C_c$ was used to characterize the cost structure of the PV plant, i.e. the relative value of the field-related elements to that of the collector related elements. A reasonable range of $C_f/C_c$ values were created and were used to calculate the LCOE, for different pairs of optimal tilt angle ($\beta$) and optimal normalized row spacing (S/L).

## 4. Results and Discussion

The complete version of Tab. 2 can be used to plot parametrically, the plant array normalized energy output against the tilt angle, $\beta$, for different values of tilt angle, S/L on Fig. 2.

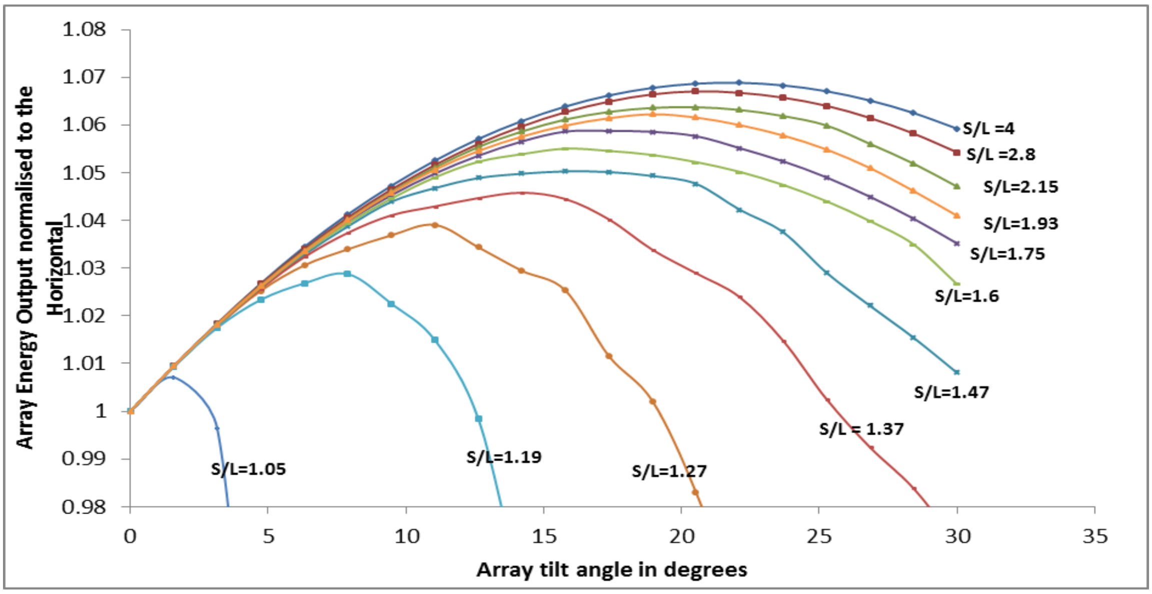


**Fig. 3: Normalized array energy output against collector tilt angle for different values of S/L.**

It is clear from Fig. 2 that the normalized array energy generally increases with increase in row spacing, but the marginal increase becomes smaller as the row spacing is increased, since the shading effect is approaching zero. On the other hand, the energy output first increases to a maximum, then decreases as the collector is increased. For each S/L there exists an optimal tilt angle, which maximizes the energy output.

Assuming that the upfront costs of the plant for each S/L is independent of collector tilt, we can use Fig. 2 to determine, once and for all, the locus of the curve that determines the only possible combination of S/L and β that gives optimal deployment. The equation for this optimal S/L-$\beta$ curve can be estimated by eq. 2 derived by curve-fitting the plot of $\beta_{opt}$ against $S/L_{opt}$, shown on Fig. 4.

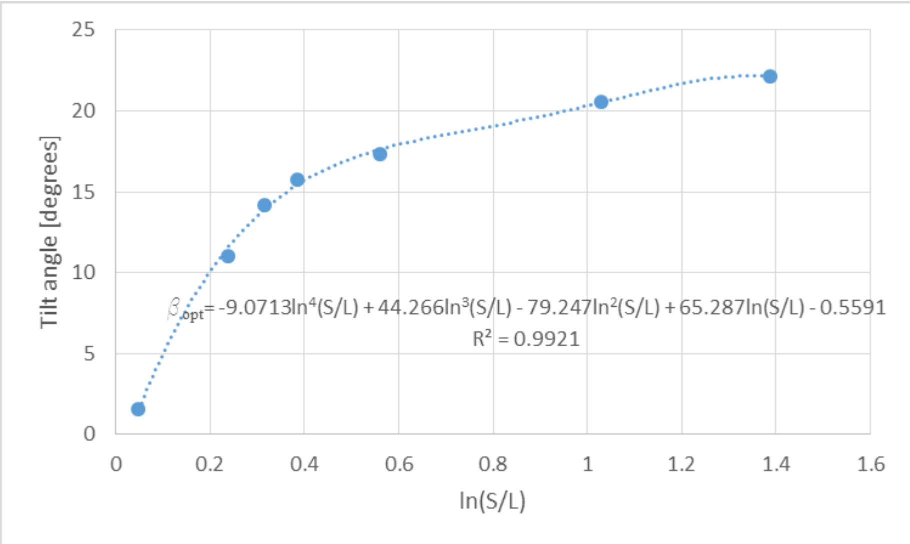


**Fig. 4: Relationship between optimal tilt angle and the normalised row spacing**

With a very good correlation ($R^2 = 0.9921$), the equation relating $\beta_{opt}$ with S/L is given below.

$$\beta_{opt} = -9.0713 ln^4\left(\frac{S}{L}\right) + 44.266 ln^3\left(\frac{S}{L}\right) - 79.247 ln^2\left(\frac{S}{L}\right) + 65.287 ln\left(\frac{S}{L}\right) - 0.5591 \quad \text{(eq. 2)}$$

Now eq. 2 gives the locus of combination coordinates of S/L and β for optimal array deployment. What it does not say is which of these optimum combinations should be deployed. The correct coordinates of S/L and β to choose should depend on the relative cost of field costs and solar collector costs, as observed by Hove et al, 2004. It should be expected that if field costs are low relative to collector costs, larger values of S/L (larger land) can be used to increase energy output and reduce LCOE. On the other end if the field costs are relatively large, it is more costly to increase S/L. This leads us to introduce the parameter $C_f/C_c$, representing the relative costs of field (land, cables, maintenance roads, security fencing etc) to solar collector costs (PV modules and mounting structure).

Fig. 5 shows how to optimize the normalized row spacing and tilt angle for different values of $C_f/C_c$. The Levelized Cost of Energy (LCOE) is used as the objective function. Although only the collector field deployment is being optimized, the LCOE of Fig. 5 has been calculated for components of the whole solar plant. The value of S/L which results in the minimum LCOE for each value of $C_f/C_c$ is the optimal value of normalized row spacing. The corresponding value of the tilt which goes with this spacing can be directly read on the "Locus of $\beta$ versus S/L" curve, on the secondary vertical axis.

The locus of optimum deployment in Fig. 5 shifts to the left as $C_f/C_c$ increases. However, there is a limiting S/L beyond which the rows cannot be brought any closer (e.g. in an effort to reduce field costs) together despite increases in $C_f/C_c$. This is because if the rows are brought any closer than this limiting S/L value (shown by the locus becoming vertical at the extreme left), inter-row shading effects on the specific energy yield of the plant (SE) will increase disproportionately with any small decrease in S/L. It can be observed from Fig. 5 that, for instance, for a $C_f/C_c$ value of 0.15, the LCOE at the optimal normalised spacing is \$0.119, compared with \$0.143 at "rule of thumb" tilt of 22° and normalised spacing of 4, which is 20% more cost. This underscores the importance of optimising deployment parameters.

Tab. 3 shows the optimum S/L and corresponding β for different $C_f/C_c$ extracted from Fig. 5. It also shows the difference between the specific energy output and Levelized Cost of Energy for the optimized case and for the case when the spacing is optimized but the rule of thumb tilt angle (tilt = latitude) is used. The specific energy output and Levelized Cost of Energy vary significantly from the optimized case to the case when the spacing is optimized but the tilt is not optimized correspondingly. This underscores the importance of optimizing simultaneously both the spacing and tilt angle to maximize the economic viability of the PV solar plant.

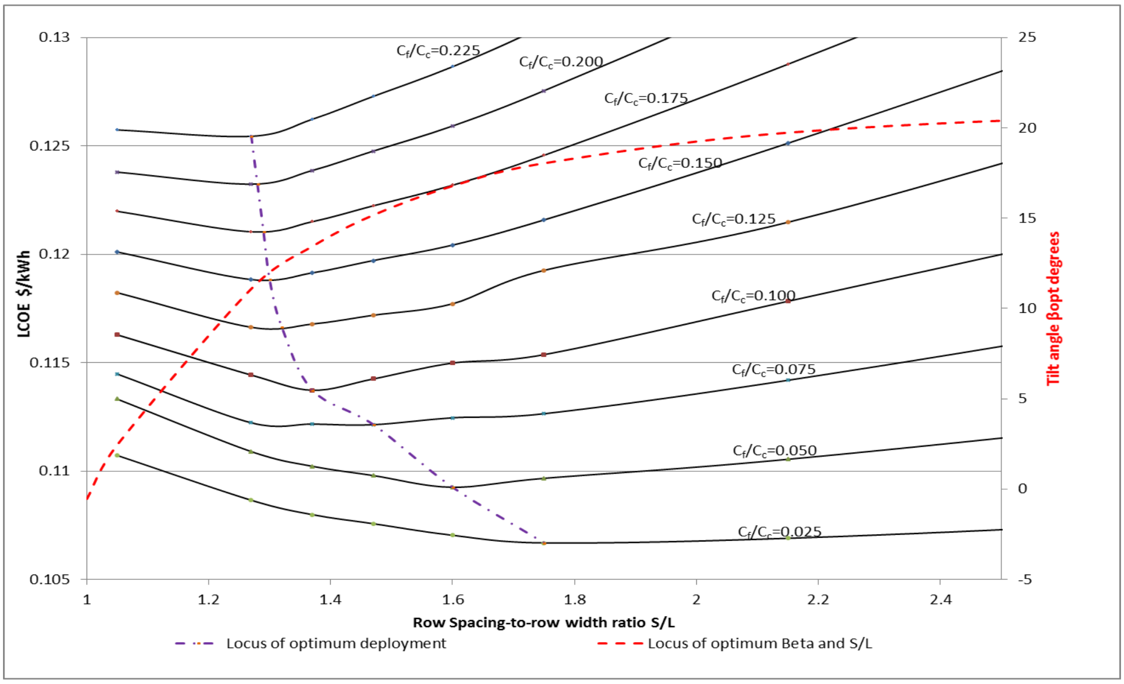


**Fig. 5: Determination of Optimum Deployment. The figure shows the plot of LCOE against S/L for different values of $C_f/C_c$. The value of S/L corresponding to the minimum of each curve determines the optimum normalized row spacing. The corresponding value of collector tilt can be read directly from the "Locus of optimum Beta and S/L" curve.**

**Tab. 3: Comparison of specific energy yield and LCOE for Tilt angles optimised for inter-row shading and the tilt angle with no shading considered**

| $C_f/C_c$ | $S/L_{opt}$ | $\beta_{opt}$ degrees | $SE_{optimised}$ $kWh/KW_p/yr$ | $SE_{tilt=latitude}$ $kWh/KW_p/yr$ | $LCOE_{optimised}$ \$/kWh | $LCOE_{tilt=latitude}$ \$/kWh |
|---|---|---|---|---|---|---|
| **0.225** | 1.27 | 11.09 | 1788 | 1584 | 0.1255 | 0.1402 |
| **0.200** | 1.28 | 11.36 | 1788 | 1584 | 0.1232 | 0.1377 |
| **0.175** | 1.29 | 11.62 | 1788 | 1584 | 0.1210 | 0.1352 |
| **0.150** | 1.30 | 11.87 | 1788 | 1584 | 0.1188 | 0.1327 |
| **0.125** | 1.32 | 12.35 | 1788 | 1584 | 0.1166 | 0.1303 |
| **0.100** | 1.37 | 13.43 | 1800 | 1721 | 0.1137 | 0.1182 |
| **0.075** | 1.47 | 15.16 | 1807 | 1765 | 0.1121 | 0.1135 |
| **0.050** | 1.6 | 16.77 | 1816 | 1792 | 0.1092 | 0.1095 |
| **0.025** | 1.75 | 18.03 | 1822 | 1802 | 0.1067 | 0.1065 |

From Tab. 3, the variation of optimum deployment parameters of the solar plant (S/L and β) against a reasonable range of $C_f/C_c$ can be plotted on Fig. 6. The land area required per MW is also shown on Fig. 6. The land area per MW is determined by the layout of the array and be characterized by the number of array rows, k (see eq. 1). This figure can be conveniently used as a design chart for optimizing the solar PV field deployment parameters, as demonstrated in Section 5.

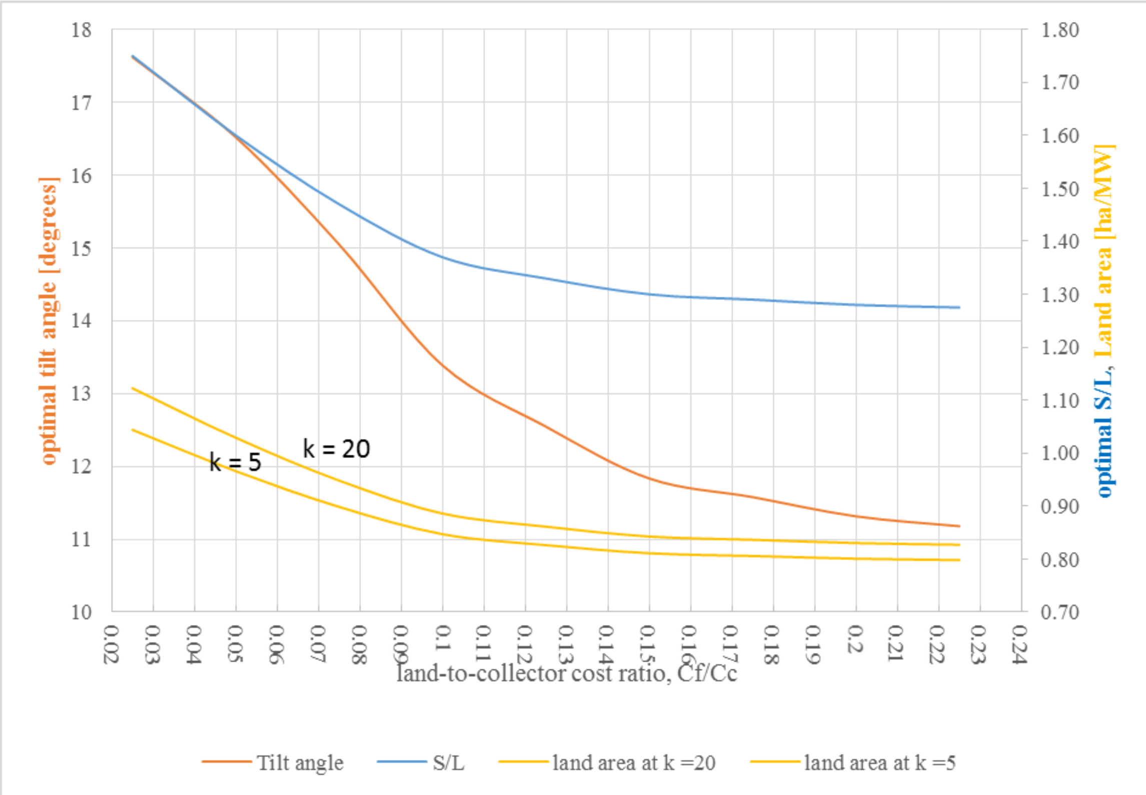


**Fig. 6: Optimal deployment of solar PV collectors in inter-row shaded arrays at Bulawayo (latitude 20.15 South, longitude 28.28 East)**

It is shown from the preceding that the main parameter that determine the economic deployment of collectors in an inter-row shaded array, at a given site, is the ratio of field (land, cables, maintenance roads, security fence, etc.) cost to collector (modules and mounting structure) cost, $C_f/C_c$. This parameter determines the optimal normalized row spacing; the optimal tilt angle that goes with it and then the minimum land required for the solar plant.

## 5. Example for applying the study results

In this section the way to use the results of this study in practice is demonstrated. Suppose one wants to develop a 1 $MW_p$ solar plant and is interested on how to lay it out for minimizing the plant LCOE. The question is what the row should be spacing and tilt angle of the solar collectors. Suppose, further, that the field width (east-west dimension) of the available land is 100 m.

The solar PV modules to be used, together with the size of mounting structure, are described on Tab. 5 below.

**Tab. 5: Module and mounting structure details**

| | | | |
|---|---|---|---|
| Module brand | Renesola JC250M-24/Bb | Short circuit current ($I_{sc}$) | 7.12 A |
| Maximum power ($P_{max}$) | 250 W | Mounting structure length | 100 m |
| Voltage at maximum power ($P_{max}$) | 28.52 V | Dimensions | 1641 mm x 993 mm x 41 mm |
| Current at maximum power | 6.57 A | Cell type | 156 x156 mm Polycrystalline, 60 (6 x 10) pcs in series |
| Open circuit voltage ($V_{oc}$) | 35 V | Number of modules per structure | 200 (100 horizontal x 2 vertical) |

**Tab. 6: Unit Costs of Infrastructure**

| Item | Cost | Item | Cost |
|---|---|---|---|
| PV module at $ 0.38/Watt | 380,000/MW | Cables | $1.5/m$^2$ |
| Mounting structure @ $ 0.12/Watt | 120,000/MW | Maintenance roads | 1.5/m$^2$ |
| Total collector costs | 500,000/MW | Security fence | 0.5/m$^2$ |
| Land owning and development | 6.5/m$^2$ | Total specific field costs | 10/m$^2$ |

To determine the value of $C_f/C_c$, we need the area of land, in order to determine field costs. Since this is also a function of $C_f/C_c$, we need to use an iterative procedure based on eq. 1 and Figure 6, to solve the problem. Using Table 6, the value of L is 2 x 1.641 = 3.282 m, and the field width is W = 100 m. That means 200 modules of 25 Watts fit on one structure, giving a power deployment of 50 kW/structure. The value for the number of rows can now be determined; k = 20 (1000 kW/50 kW). The value of S/L can be guessed (any number between 1 and 2 will do), and the corresponding value of β can be obtained from eq. 2. For example, S/L = 1.5 can be chosen and the corresponding tilt is β = 15.59, from eq. 2.

From eq. 1, the land area may be computed with inputs of S/L and β, together with the values of W and L mentioned before. The field costs are obtained by multiplying the land area with the specific field cost. The collector cost per MW can be computed from collector cost per Watt given on Tab. 6, and the total collector costs obtained by multiplying it with the plant power. The ratio $C_f/C_c$ can therefore be computed.

Using Fig. 6, a new value of S/L corresponding to can be read, and a corresponding β obtained again from eq. 1. The process can be repeated with the new values of S/L and β, until the S/L and β values obtained from successive iterations are almost equal. The values of S/L, β and land area obtained in the last line of iteration are the optimal deployment parameters for the solar plant. In the present case, the optimal deployment parameters are $S/L_{opt}$ = 1.295, $\beta_{opt}$ = 11.72 degrees and minimum land area = 8390 $m^2$/MW, as shown in Tab. 7.

**Tab. 7: Iterative procedure for obtaining optimal deployment parameters**

| S/L | β [deg.] (eq. 2) | k | Land Area [$m^2$] (eq. 1) | Field Cost, $C_f$ [$] | Plant Power [MW] | Specific Collector Cost [$/MW] | Collector Cost, $C_c$ [$] | $C_f/C_c$ | S/L (Fig. 6) | β [deg.] (eq. 2) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.5 | 15.59 | 20 | 9670 | 96698 | 1 | 500000 | 500000 | 0.193 | 1.285 | 11.49 |
| 1.285 | 11.49 | 20 | 8335 | 83346 | 1 | 500000 | 500000 | 0.167 | 1.294 | 11.72 |
| 1.294 | 11.72 | 20 | 8390 | 83905 | 1 | 500000 | 500000 | 0.168 | 1.294 | 11.72 |

It is important to check that the minimum gap required for maintenance, referred to as collector spacing in Sánchez-Carbajal and Rodrigo, 2019, is adequate after setting the row spacing. The gap between the collectors is given by $S - Lcos\beta$ , which is 1.03 m in the present case. This is considered to be adequate for maintenace people to manouvre between collectors.

## 6. Conclusion

This study proposes an approach that should be used to specify the optimal row deployment of collectors in a large solar PV array. Following the thinking in Hove, 2004b, it is realized that the optimal spacing and tilt of the collectors, at any location with given latitude and climatic data, is determined by the relative costs of the field components (land owning and development, electrical cables, maintenance roads, etc.) to the cost of solar collector components (PV modules and mounting structure). Reduced row spacing, which should go together with appropriate reduction in collector tilt angle, obviously increases the loss of radiation received by the collectors but determining the radiation loss alone is not enough to predict the electrical losses due to shading. The overall electrical losses due to shading depends in a complicated way with both the radiation loss and the resulting I/V-characteristic transformation of the PV module. On the other hand, increasing row spacing (ostensibly in order to reduce shading effects), increases the (cost of) land area used by the PV plant together with other field costs such as maintenance roads, electrical cables, etc. This realization led to the identification of the PV simulation program, PVSyst, as a tool that can be innovatively used to prescribe the optimum collector deployment in an inter-row shaded array.

The software PVSyst can estimate the electrical output of the shaded PV array depending on prescribed module layout, row spacing and collector tilt. It can also perform an economic analysis of the plant, yielding the Levelized Cost of Energy (LCOE), depending on the cost structure of the system components. In the study, the software is applied innovatively to calculate the LCOE for different combinations of field-to- collector costs ($C_f/C_c$), normalized row spacing (S/L) and collector tilt (β). The combination of S/L and β that results in the minimum LCOE for each value of field-to-collector cost ($C_f/C_c$) describes the optimal deployment of collectors in the array. The main result is the development of a chart, from which the optimal values of collector normalized spacing, tilt angle and required land can be prescribed for a known value of $C_f/C_c$. The results show clearly how the collector row spacing, collector tilt angle and used land area should be reduced with respect to the increased value of $C_f/C_c$, for any site with given latitude and climatic conditions. It also shows that non-optimized deployment parameters can result in up to 20% more LCOE when compared to optimized ones, showing the importance of this study. This method to a large extent is a big step towards the optimization of solar PV collector deployment in inter-row shaded arrays and is recommended for application by designers and project managers of large Solar PV plants for maximum economic benefits.

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