Rectangular Spiral Inspired Approach for Estimating Area of Solar Photovoltaic Plants in India

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Executive Summary

In pursuit of achieving its clean energy goals, India is moving aggressively towards establishing large solar plants. Land being a finite resource in a densely populated country like India, an approach for planning for these plants aiming towards better utilisation of available land resource is certainly of interest. There is merit in looking at a design approach which aides planning by offering high packing density leading to reduced land utilisation. The objective of this work is to propose a method which can provide the rational area estimate of a plant factoring sizing considerations from electrical, maintenance, and shading aspects. The idea for the plant design is inspired by the number pattern illustrated in the Ulam spiral. From the perspective of planning, the proposed approach aims to provide an area estimate which could set the boundary conditions in term of realistic potential estimation and minimum land area required. Further, this report provides insights with respect to land area requirements across the latitudinal spread for India. Also, it provides an estimate of the solar power potential for ground mounted utility scale plants in India.

The highlights of this work are as follows:

- Proposes a novel approach for estimating land area of a solar PV plant
- State wise benchmark area estimates per MWp of plant capacity are derived
- Better land utilisation could increase the solar power potential by 20%
- The revised solar energy potential for utility scale PV systems is estimated to be about 391 GWp

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1. Introduction

1.1 Motivation for the Studies

In a densely populated and agriculture dependent country like India, land is a critical resource. It is not short in availability per se but due to challenges in its acquisition, the effective land area available for setting up land-intensive Renewable Energy (RE) plants is relatively scarce (NITI Aayog, CII, SSEF, & RAP, 2015). In contrast, to keep up with its climate goals, India is pursuing an aggressive RE target of 175 GW by 2022[1] (NITI Aayog, 2016). This is a fraction of the true RE potential identified throughout the country. The total solar power potential across the country was identified to be around 748 GWp (NISE & MNRE, 2014) and the on shore wind power potential at 100 m hub height was estimated to be about 302 GW (NIWE, 2015).

In the effort towards realising this potential, one crucial aspect of discussion has been concerning the land required for meeting all energy needs from RE sources. Based on estimates, considering that land acquisition might be difficult, it was initially indicated that India cannot meet all of its energy requirements with RE sources alone, (Sukhatme, 2011). Contrasting insights were later presented with respect to land area requirement covering two important aspects namely –'Land Transformation' and 'Land Occupation'. The focus of this report is towards building solar plants (with no mechanical tracking systems). In this context, it was pointed that, a solar plant would occupy more land area to set up compared to a coal power plant; however, it transforms less area when compared to the same. Finally, it was concluded that land availability may not be a limiting constraint for tapping the requisite solar energy resources (Mitavachan, H; Srinivasan, 2012). This aspect was acknowledged and the original assessment was revised (Sukhatme, 2012). These discussions indicate that there is merit in developing a generic approach which quantifies the land area requirements factoring in the technical aspects of a solar power plant.

Currently, India has an installed solar power capacity of 25 GW (CEA, 2019). Considering its current official target and declared potential there is a need to assess and estimate the land area requirements towards meeting these goals. The approach covered in this report aims to provide useful insights in this context. The various estimates for land area required per unit MW for a solar Photovoltaic (PV) plant in the Indian context are listed in Table 1. These estimates serve as benchmarks for various sectoral analyses. But, they do not capture effects of increased power rating of the PV module for the same module area and the latitude of the site (and hence the tilt angle of the module) tailored to a plant for a specific site. In an effort to provide a comprehensive estimate, this report presents an approach for sizing a solar photovoltaic plant considering electrical, maintenance, and shading aspects.

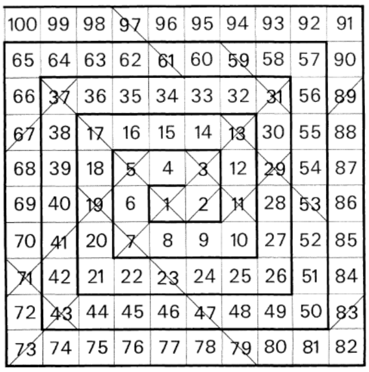
Table 1: Benchmark estimates of area requirement for solar PV plants in India

S.no	Remark	Area per MWp (acres)	Entity	Reference
1	Generic consideration for all India	5	CERC	(CERC, 2014)
2	Minimum area required for setting a solar plant	3.7	SECI	(Kumar & Thapar, 2017)
3	Generic area requirement	4 - 5	IREDA	(IREDA, n.d.)
	Mono-crystalline plant	3 - 4		
	Thin film plant	7.5 – 9		

[1] This constitutes 100 GW from solar (60 GW from utility scale, 40 GW from roof top photovoltaic systems), 60 GW from wind, 10 GW from biomass and 5 GW from small hydro power based capacity (MNRE, 2015; NITI Aayog, 2016).

1.2 Inspiration for the Approach

Nature has inspired some of the best engineering designs. One such case is inspired by the phyllo-taxis disc pattern which is the configuration of florets on the head of a sunflower (Vogel, 1979). This concept was used for providing a theoretical design for the heliostat field arrangement in concentrated solar power plants (Noone, Torrilhon, & Mitsos, 2011). The work covered in this report for PV plants draws inspiration from the prime spiral also known as the Ulam spiral (Stein, Ulam, & Wells, 1964). The Ulam spiral is a simple method of visualising prime numbers that reveals the apparent tendency of certain quadratic polynomials to generate unusually large number of primes. Ulam began to number intersections, starting near the centre, with 1, and moving out in a counter-clockwise spiral. He began circling all the prime numbers. The prime numbers seemed to have a tendency to crowd into diagonal lines as illustrated in Figure 1. Near the centre of the spiral the lining up of primes is to be expected because of great “density” of primes and the fact that all primes, except 2, are odd (Gardener, 1971). The pattern presented by the Ulam’s spiral has been used in applications ranging from identifying patterns in distribution of nucleotides in DNA (Cattani, 2011), to data record extraction for web technology applications (Anderson & Hong, 2013), and also to ‘object and pattern’ identification using raster models (Kitano, Katsuhiko, Kakimoto, Urakawa, & Araki, 2015).



Source: (Gardener, 1971)

Figure 1: Basic Ulam Spiral

In this report we don’t focus on the pattern of prime numbers, rather we focus on the placement of numbers which builds this rectangular/square spiral. We use this pattern to map the physical placement of PV arrays and Power Conditioning Unit (PCU) blocks towards building the plant. Before delving into the application of the spiral (described in detail in section 2.3.2), an understanding of the framework of proposed approach is necessary.

1.3 Structure of the Report

Post setting the context in sections 1.1 and 1.2, the proposed approach for area estimation is then explained in detail (section 2). A case illustrating the proposed approach is provided (section 2). To check the robustness of the approach, the area estimated for select existing plants is compared with that of the declared area in public records (summary in section 3.2, details in Appendix G). We derive and illustrate some India specific insights, (section 3.3). We estimate the solar power potential in India using the proposed method (section 4). Finally, we draw conclusions, identify scope for future work and identify applications of this work in related policy implications (section 5). The nomenclature for various parameters indicated in this report is provided in Appendix A.

2. Proposed Approach

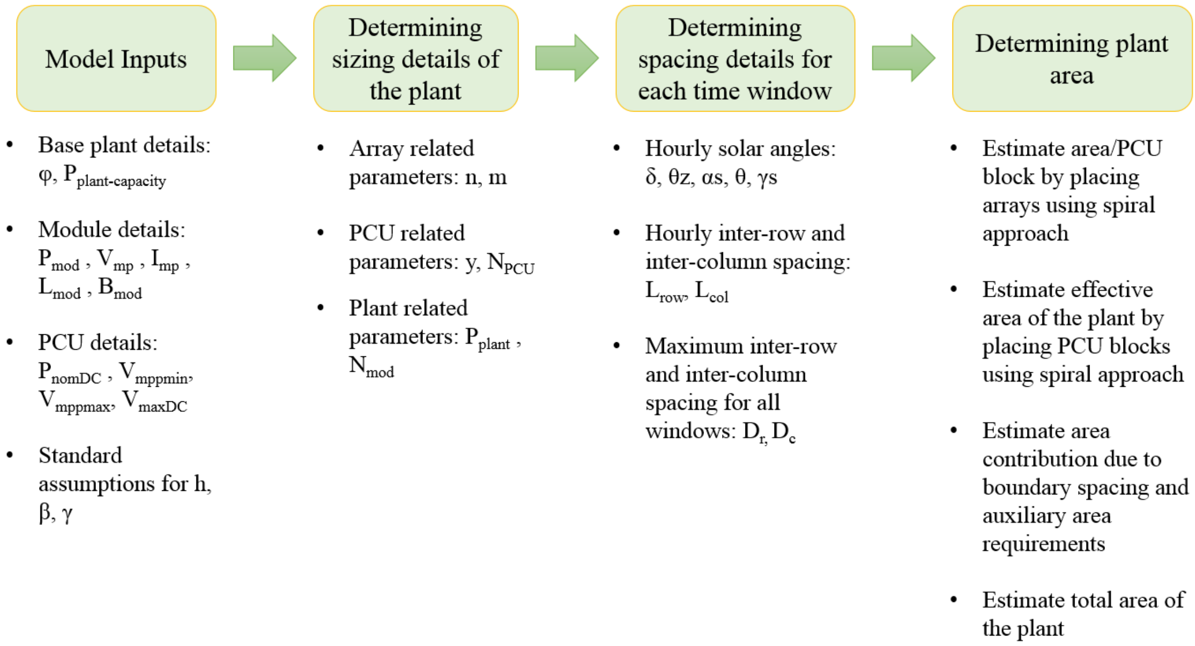


Figure 2: Illustrative process flow for area estimation

Figure 2 summarises the process flow for the proposed approach. The objective is to arrive at the best rectangular area for setting up the plant for a given time window of operation (considered in Local Apparent Solar Time referred as solar time in this report). A time window of operation is typically the hours during which the solar plant operates, such that the shadows of the surrounding structures like neighbouring PV arrays, do not affect the power output of any module. Here, we consider three time windows of operation: 7 am to 5 pm, 8 am to 4 pm and 9 am to 3 pm. It can be noticed that these windows are of decreasing duration. This consideration is due to the fact that in the early hours of sunrise, the sun's rays are too oblique and hence would cast longer shadows. This in turn would require greater distance between array structures to ensure shadow-free panels which leads to a higher land area requirement. The idea is to consider the decreasing length of shadows subtended by the tilted panels for the hours beyond sunrise for spacing between module structures, thus reducing the land requirements. This makes us choose the optimum time window, where the trade-off between the energy gains and additional land area needed is suitable. The list of assumptions considered in this approach are listed in Appendix B.

2.1 Estimation of Sizing of System Components and Capacity

The first step is to obtain the number of inverters/PCUs required for a plant of target capacity, $P_{plant\text{-}target}$ (in MWp, DC)

$$\text{No. of PCUs in plant} = N_{PCU} = \frac{P_{plant-target}}{P_{nomDC}}$$

The result for N_{PCU} obtained above is rounded down to the nearest integer in order to provide a conservative design and not oversize the system. By virtue of specification of voltages in the PCU datasheets, they bear the relation: $V_{mppmin} < V_{start} < V_{mppmax} < V_{maxDC}$. We consider the midpoint of the Maximum Power Point Tracking (MPPT) range of the PCU as the design point (as indicated in point 7, Appendix B). This reference point would give an appreciable margin for variation across both extreme limits of the MPPT range. The corresponding voltage and rated current at this midpoint can be calculated as follows:

$$V_{mid} = \frac{V_{mppmin} + V_{mppmax}}{2}$$

$$I_{mid} = \frac{P_{nomDC}}{V_{mid}}$$

It can be noted that during plant operation, the operating voltage is free to fluctuate within the MPP range. The design point of the module would be the MPP condition at Standard Testing Condition (STC) (V_{mp}, I_{mp}). Hence, using this, the number of modules in series for voltage addition (forming 1 module string) can be calculated as:

$$m = \frac{V_{mid}}{V_{mp}}$$

The value of 'm' can be rounded up (as applied here) or rounded down to the nearest integer.

The DC power seen by the PCU is a product of voltage and current. The module strings account for matching the appropriate reference PCU voltage. The current matching is done by sizing the required number of module strings in parallel ('n') to meet the power rating of the PCU. Ideally, a single array of 'm x n' panels should meet the power requirements of the PCU. However, the resultant array may not be feasible from maintenance stand point. Hence, the number of module strings in parallel is split into two components:

- 'n' module strings in parallel per array
- 'y' arrays in parallel per PCU.

The size of the array is limited by the height of the structure (as indicated in point 3, Appendix B). This consideration is agnostic to the dimensions of the module.

First we estimate 'n', considering the array to be tilted at an angle of β with respect to the horizontal (ground surface) facing due south (γ = 0°, for sites in Northern hemisphere) in line with point 2 from Appendix B. The height of the array structure not considering the ground clearance can be generically represented as 'h'. Considering point 3 from Appendix B, for this study h = 1.5 metres

$$n = (h/(L_{mod} \times \sin\beta))$$

'n' is rounded down to the nearest integer to adhere to the array height restriction. In similar fashion, the number of arrays in parallel 'y' could be estimated as:

$$y = {I_{mid}}/{(n \times I_{mp})}$$

'y' is rounded down to the nearest integer to limit the current addition at peak conditions to be close to design point. In summary, the number of modules at various levels is indicated as follows:

$$\text{No. of modules per string} = m$$

$$\text{No. of modules per array} = m \times n$$

$\text{No. of modules per PCU} = m \times n \times y$

$\text{No. of modules for the plant} = N_{mod} = m \times n \times y \times N_{PCU}$

$\text{Rated Capacity of the plant } (MW_p) = P_{plant} = N_{mod} \times P_{mod} / 1000000$

$\text{Pure module area of the plant} = N_{mod} \times L_{mod} \times B_{mod}$

2.2 Estimation of Inter-Row and Inter-Column Spacing for Various Time Windows

In order to calculate the inter-row and inter-column spacing, the appropriate solar angles are computed for no shading operation tailored to the location of interest. The various solar angles considered have been listed in Table A.1 of Appendix A and the relevant equations are listed in Appendix C (Duffie & Beckman, 2013). An illustration of these solar angles is presented in Figure 3.

The inter-row and inter-column spacing is dependent on the time window of observation; closer the time window is to the sunrise period, longer are the shadows subtended by the arrays and hence greater would be the inter-row and inter-column spacing. Theoretically, the benefit of a wider time window (one that is closer to sunrise and sunset) is that the solar radiation captured and hence converted to electrical energy is slightly higher. However, the relative contribution due to this extended time window is minimal, as during the hours closer to sunrise and sunset the intensity of the solar radiation is reduced. In this approach, we focus only on the aspects related to plant area. In this context, the length of shadow subtended by the tilted panel is first computed for every hour along the E–W (L_{col}) and N–S (L_{row}) directions using the following equations:

$L_{row} = n \times L_{mod} \times \sin\beta \times \cos\gamma_s / \tan\alpha_s$

$L_{col} = n \times L_{mod} \times \sin\beta \times \sin\gamma_s / \tan\alpha_s$

For the time windows: 7 am to 5 pm, 8 am to 4 pm, and 9 am to 3 pm, the maximum of L_{row} and L_{col} are identified as D_{row} and D_{col} respectively. A collection of these elements is represented as inter-row (D_r) and inter-column (D_c) spacing sets.

$D_{row} = \text{Max}\,(L_{row})$, here $D_{row} \,\varepsilon\, D_r$

$D_{col} = \text{Max}\,(L_{col})$, here $D_{col} \,\varepsilon\, D_c$

2.3 Estimation of Plant Area

Post determining D_r and D_c, we estimate area of the plant in stages as described in Figure 2. We first build a generic algorithm for applying the spiral pattern (described in section 2.3.1), next we apply this to build the algorithm for estimating the area of the plant (covered in section 2.3.2) and finally we cover the aspects related to boundary spacing and metrics assessing land utilisation (covered in section 2.3.3 and 2.3.4).

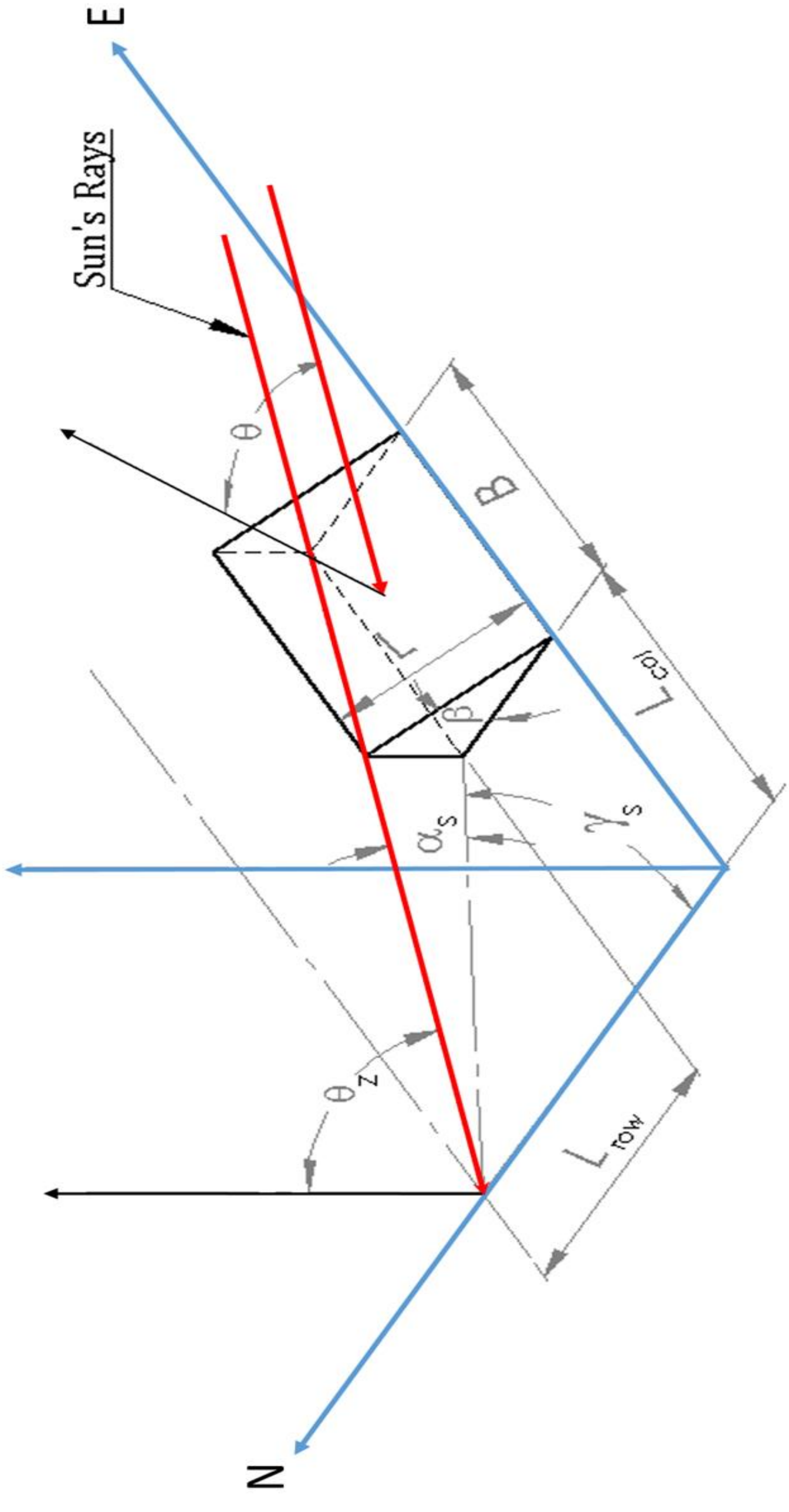


Figure 3: Illustration of solar angles for a panel at fixed tilt facing due south (γ = 0°)

2.3.1 Inferences From the Spiral Pattern and Designing a Generic Algorithm

Before we move to the specifics of area estimation, an understanding of the spiral pattern would be useful. To present a generic case, let us consider 'X' units each of length 'L' and breadth 'B', to be arranged along the spiral pattern. For a given time window, each unit would be spaced with the corresponding D_{row} and D_{col} with respect to the other units. These units would be further enclosed with a boundary spacing of 'a' along length and 'b' along breadth. Figure 4 illustrates above mentioned arrangement for X = 25 units along with the direction conventions for length and breadth. Note, the direction of the spiral considered here is clockwise whereas the direction indicated in Figure 1 was anticlockwise. This change in direction of spin does-not affect the properties exhibited by the spiral which holds true for both cases. For the purposes of this study we will consider a spiral with a clockwise spin.

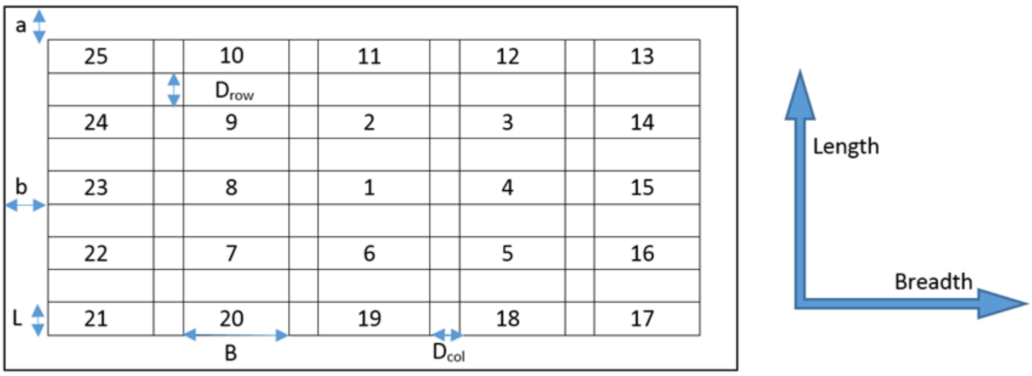


Figure 4: A schematic representation of units being placed in the clockwise spiral pattern

The spiral poses some very interesting symmetries, which could be tapped for designing an algorithm which mimics this pattern. If we neglect the quantum of spacing and look at the mere placement of numbered units in the spiral, it appears as shown in Figure 5.

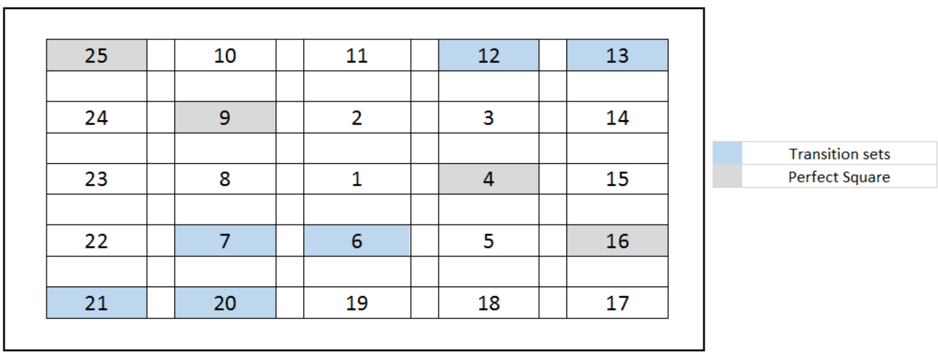


Figure 5: Illustration of transition sets, square, and rectangular matrices

We find that the numbers (say N) which are perfect squares form a square matrix with dimensions $\sqrt{N}$. If N forms a rectangular matrix, then post N+1 the direction of placement of units (or numbers in this case) is shifted by 90º in the clockwise direction unless it reaches a unit corresponding to a square matrix. This set (N, N+1) will henceforth be termed as the transition set. Once encountering a block which forms a square matrix, the direction of placement of blocks is again shifted by 90º in the clockwise direction. It can be noticed that due to the pattern of the spiral, a unit completing a rectangular matrix increases the dimension of the matrix along the length and a unit completing a square matrix increases the dimension of the matrix along breadth.

Further, the identification of the dimensions of the nearest square/rectangular blocks of the matrix for a given number of units X (neglecting the inter-row/column spacing) is as illustrated in Table 2. Here N_L and N_B are blocks along the length and breadth which in turn reflect the dimensions of the matrix formed by X units.

Table 2: Distribution of dimensions of matrix set for a given set of 'X' units

N_L*N_B = X units (for square/rectangular blocks)						
N_L↓/N_B→	**1**	**2**	**3**	**4**	**5**	**6**
1	1					
2	2,3	**4**,5				
3		**6**,7,8	**9**,10,11			
4			**12**,13,14,15	**16**,17,18,19		
5				**20**,21,22,23,24	**25**,26,27,28,29	
6					**30**,31,32,33,34,35	**36**.....

N - Square matrix **N** - Rectangular matrix

Now that we understand how the dimensions of the spiral matrix work, next we build a generic algorithm for incorporating D_r and D_c. Let us consider a generic unit with its corresponding space components as indicated in Figure 6. The unit considered is of dimensions L × B (length × breadth), with a generic inter-row spacing set of D_r and inter-column spacing set of D_c.

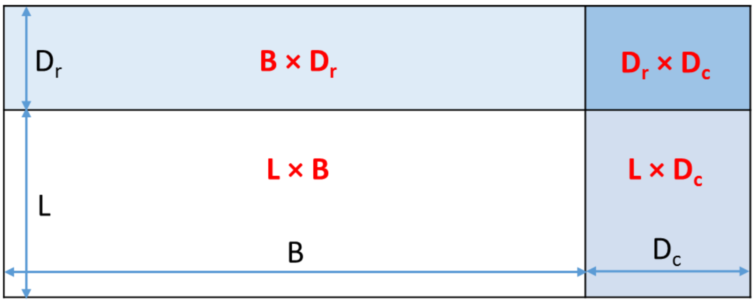


Figure 6: Representation of generic unit (dimensions in black and area in red)

The nomenclature for various parameters related to the application of the spiral algorithm is listed in Table A.2 of Appendix A. The area of the unit indicated in Figure 6 can be indicated as follows:

A_{unit} = Area of the unit

$= (L + D_r) \times (B + D_c) = L \times B + B \times D_r + L \times D_c + D_r \times D_c$

We can classify the unit area in terms of four components. Each component is obtained by the product of two parameters. They are namely,

$L \times B$ = Area of the unit of dimensions L, B

$L \times D_c$ = Area contributed by dimensions L and the inter-column spacing (D_c)

$B \times D_r$ = Area contributed by dimensions B and the inter-row spacing (D_r)

$D_r \times D_c$ = Area contributed by intersection of D_r and D_c.

With reference to Figure 4, when the units are arranged using the spiral, the blocks are further segregated into two categories:

- Enclosed set: The combination of units which form a square or rectangular matrix. Parameters related to this are denoted with subscript '*e*'
- Outlying set: The combination of units which do not conform to the square or rectangular matrix structure. Parameters related to this denoted with subscript '*o*'

Based on the structure of the spiral discussed earlier, one can estimate the area of both the sets using the following relation:

A_e = Area of enclosed set = $(N_{Le} \times L + N_{Re} \times D_r) * (N_{Be} \times B + N_{Ce} \times D_c)$

A_o = Area of outlying set = $(N_{Lo} \times L + N_{Ro} \times D_r) * (N_{Bo} \times B + N_{Co} \times D_c)$

Here,

$N_{Le/o}$ = Number of units along length contributing to the enclosed or outlying set

$N_{Re/o}$ = Number of inter-row spacing sections along length contributing to the enclosed or outlying set

$N_{Be/o}$ = Number of units along breadth contributing to the enclosed or outlying set

$N_{Ce/o}$ = Number of inter-column spacing sections along breadth contributing to enclosed or outlying set

Consider an example illustrated in Figure 7 for X = 24 units, units up to 20 make the enclosed set and units 21 to 24 make the outlying set. Here $N_{Le} = 5$, $N_{Lo} = 4$, $N_{Re} = 4$, $N_{Ro} = 3$, $N_{Be} = 4$, $N_{Bo} = 1$, $N_{Ce} = 3$, $N_{Co} = 1$

$A_{block} = A_e + A_o$

A generalised representation of the above expression in term of a single variable for each of the area components is indicated in Appendix D.

Figure 7: Illustration of enclosed and outlying set for X = 24 units

In summary, if we consider X units of dimensions L x B with inter-row spacing of D_r and inter column spacing of D_c, then the following steps illustrate the generic approach to estimate the various coefficients for arranging these units in a spiral pattern:

1. Obtain the number of units (X) to be arranged in the spiral pattern
    a. X = y, for estimating module area cover for one PCU block
    b. X = N_{PCU}, for estimating module area cover for the entire plant
2. Initialise, the two main counters are 'R' and 'S'.
    a. R traces the growth of the units along length and S traces the growth of the units along breadth.
    b. Further, due to the nature of the spiral and hence the matrix pattern created by it, R and S trace the formation of a rectangular and square matrix respectively
    c. R x S gives the dimension of the enclosed set
3. Estimating the dimensions of the enclosed set. The unit counter (U) is set to 1 and is looped to X in steps of 1:
    a. First we account for the area contributed by the unit itself
    b. If the U is a perfect square, we increment S by 1, acknowledging growth of matrix along the breadth
    c. We initiate the rectangular matrix count at U = 2 by incrementing R by 1. Also, we initiate the space area due to inter-row spacing by incrementing A_BDr by 1
    d. Beyond U = 3, the accounting for both inter-row and inter-column spacing must be done. An interesting feature of the spiral is that when U creates a rectangular matrix (marking the 1st element of a transition set), the number of inter-column spacing (A_LDc) is a perfect square. But, it has to be noted that the transition sets (such as U, U+ 1: 6, 7; 12, 13; 20, 21 ... etc.) share the inter-column spacing, with no addition of the inter-row spacing. This is accounted by tracing and applying appropriate correction using a set of '_temp' variables for A_BDr and A_LDc. Further, crossing a transition set typically marks the formation of a rectangular matrix and hence R is incremented by 1. The appropriate counters are reset once we cross the second element of the transition set.
4. Estimate the number of units in the outlying set (N_o).
5. Estimate N_{Le}, N_{Be}, N_{Lo}, N_{Bo}, N_{Re}, N_{Ro}, N_{Ce}, N_{Co} and the direction of adding outlying set (along breadth or length). This should account for aspect of the spiral that:
    a. If the enclosed set is a square matrix (R = S), the outlying set is added along the breadth (B_Flag = 1)
    b. If the enclosed set is a rectangular matrix (R > S), the outlying set is added along length (L_Flag = 1)

It has to be noted that when we combine the enclosed and the outlying sets to form a single matrix, if the outlying set is added along the breadth (B_Flag = 1), then length of the combined matrix would increase by a factor of ($L + D_r$). Similarly, if the outlying set is added along the length (L_flag = 1), then the breadth of the combined matrix ($B + D_c$).

The algorithm for implementation of the spiral algorithm is provided in Figure 8 and Figure 9. Here, the principal of counting follows, by first accounting for the block and then the spacing associated with it.

2.3.2 Applying the Generic Algorithm for Area Estimation of PV Plant

The inter-row and inter-column spacing of D_r and D_c respectively are applied consistently for spacing the arrays and PCU blocks. The area estimation at both levels would be done for all three time windows. The L and B will change appropriately based on level of the area estimation (for one PCU block or the plant).

For estimating the area of a PCU block, the generic unit is an array and there 'y' arrays that need to be arranged to build one PCU block each of dimensions:

L = Length of an array strip = $n \times L_{mod} \times \cos\beta$

B = Breadth of the array strip = $m \times B_{mod}$

The dimensions of the PCU block for each time window can be computed by applying the spiral algorithm as follows:

$L\_array_e = N_{Le} \times L + N_{Re} \times D_r$

$B\_array_e = N_{Be} \times B + N_{Ce} \times D_c$

$L\_array_o = N_{Lo} \times L + N_{Ro} \times D_r$

$B\_array_o = N_{Bo} \times B + N_{Co} \times D_c$

$Net\_Area\_PCU = L\_array_e \times B\_array_e + L\_array_o \times B\_array_o$

$L_{PCU} = L\_array_e + B\_flag \times (L + D_r)$

$B_{PCU} = B\_array_e + L\_flag \times (B + D_c)$

$Effective\_PCU\_Area = L_{PCU} \times B_{PCU}$

Here the coefficients, N_{Le}, N_{Be}, N_{Lo}, N_{Bo}, N_{Re}, N_{Ro}, N_{Ce}, N_{Co}, B_flag, and L_flag correspond to the arrangement of 'y' arrays in spiral.

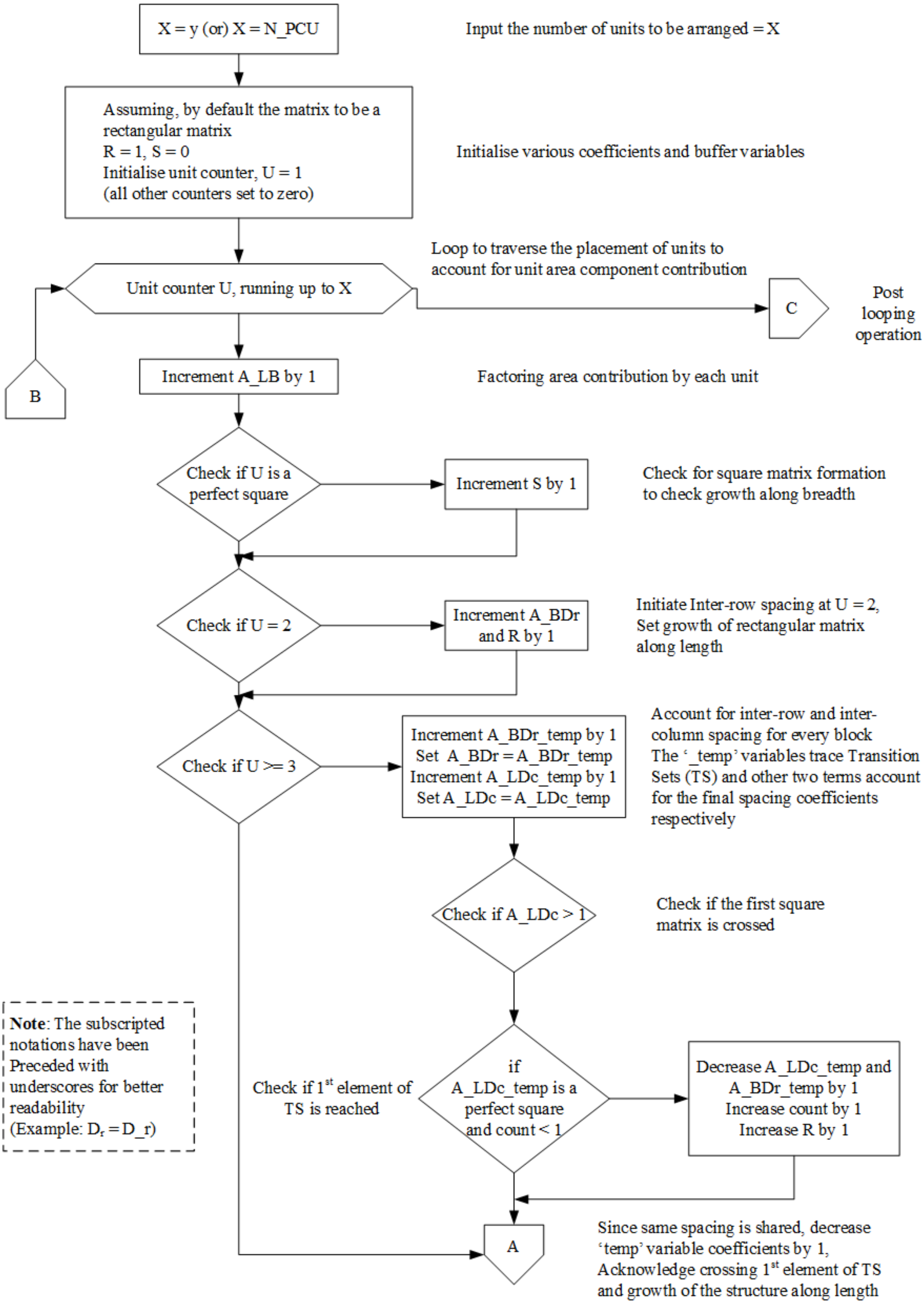


Figure 8: Generic algorithm for implementing the spiral pattern

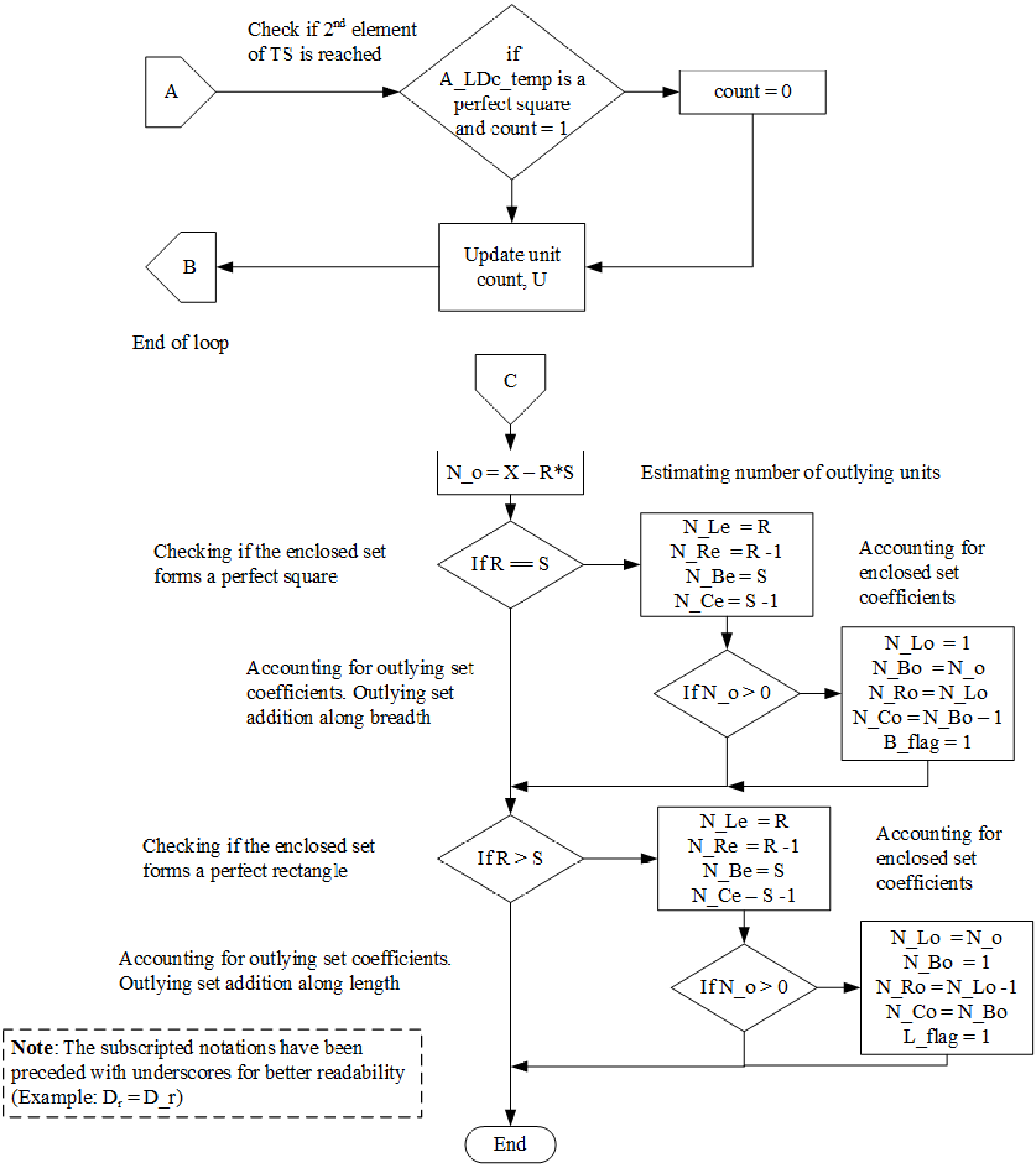


Figure 9: Generic algorithm for implementing the spiral pattern

When computing the area of a plant, the length (L) and breadth (B) of the generic block, for the spiral, becomes the length of the PCU block (L_{PCU}) and breadth of the PCU block (B_{PCU}). The dimensions of the plant for each time window by applying the spiral algorithm for 'N_{PCU}' could be computed as follows:

$L = L_{PCU}$

$B = B_{PCU}$

$L\_PCU_e = N_{Le} \times L + N_{Re} \times D_r$

$B\_PCU_e = N_{Be} \times B + N_{Ce} \times D_c$

$L\_PCU_o = N_{Lo} \times L + N_{Ro} \times D_r$

$B\_PCU_o = N_{Bo} \times B + N_{Co} \times D_c$

$Net\_Area\_Plant = L\_PCU_e \times B\_PCU_e + L\_PCU_o \times B\_PCU_o$

$L_{Plant} = L\_PCU_e + B\_flag \times (L + D_r)$

$B_{Plant} = B\_PCU_e + L\_flag \times (B + D_c)$

$Effective\_Plant\_Area = L_{Plant} \times B_{Plant}$

Here the coefficients, N_{Le}, N_{Be}, N_{Lo}, N_{Bo}, N_{Re}, N_{Ro}, N_{Ce}, N_{Co}, B_flag, and L_flag correspond to the arrangement of 'N_{PCU}' PCUs in spiral. An illustration of the growth of the plant to various levels is indicated in Figure 10.

2.3.3 Applying Boundary Spacing

The next step would involve the addition of the area contributed by the boundary spacing components 'a' and 'b', using the pattern illustrated in Figure 6 as reference. Using the following formulae, this could be accounted and total area of the plant can be calculated:

$Area\_BS\_along\_length = 2 \times b \times (L_{Plant} + 2 \times a)$

$Area\_BS\_along\_breadth = 2 \times a \times B_{Plant}$

$Total\_Plant\_Area = Effective\_Plant\_Area + Area\_BS\_along\_length + Area\_BS\_along\_breadth$

Figure 11, Figure 12 and Figure 13 provide a visual illustration of estimation of plant area, for an asymmetric number of PCUs ($N_{PCU} = 17$). The auxiliary area requirement for administrative buildings, PCU housings, and extended pathways is further added to the 'Total plant area' of the setup. The auxiliary area considerations are elaborated in Appendix E. The core idea of the proposed method focusses on generating the closest rectangular or square area formation for N_{PCU} blocks for a PV plant. In cases where N_{PCU} doesn't exactly form a square or rectangular matrix there is a possibility, that there is no need for auxiliary area requirement. This is due to the fact that the area left over due to the asymmetry of the layout (shaded area indicated in Figure 12 and Figure 13) could more than compensate for this requirement. The correction in auxiliary area requirement due to asymmetry of sizing parameters is indicated in Appendix E.

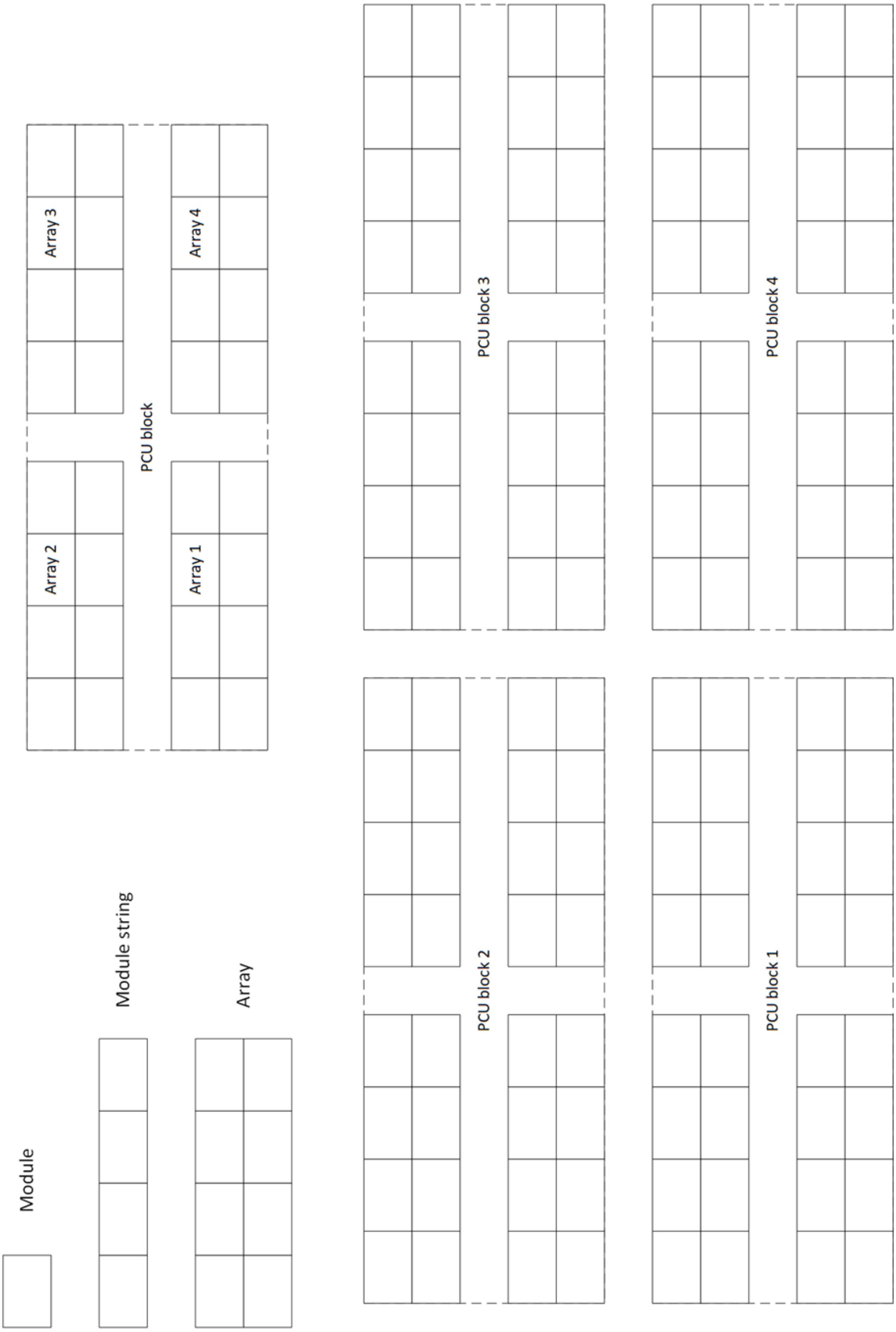


Figure 10: An example case of plant design for n = 2, m = 4, y = 4, and N_{PCU} = 4

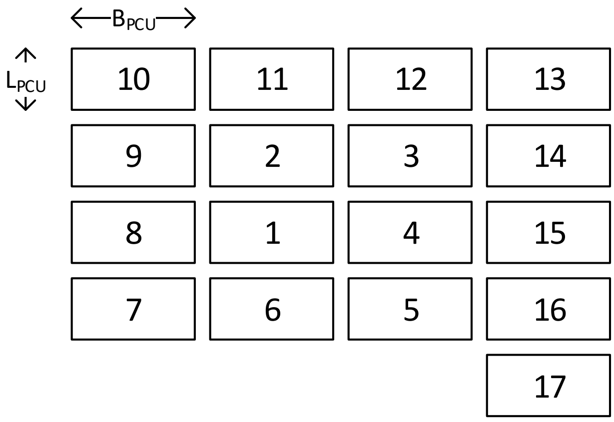


Figure 11: Illustration of 'net plant area' for a system with N_{PCU} = 17

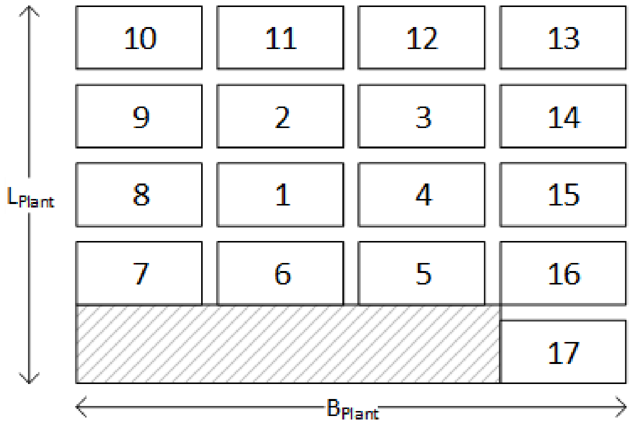


Figure 12: Illustration of 'effective plant area' for N_{PCU} = 17

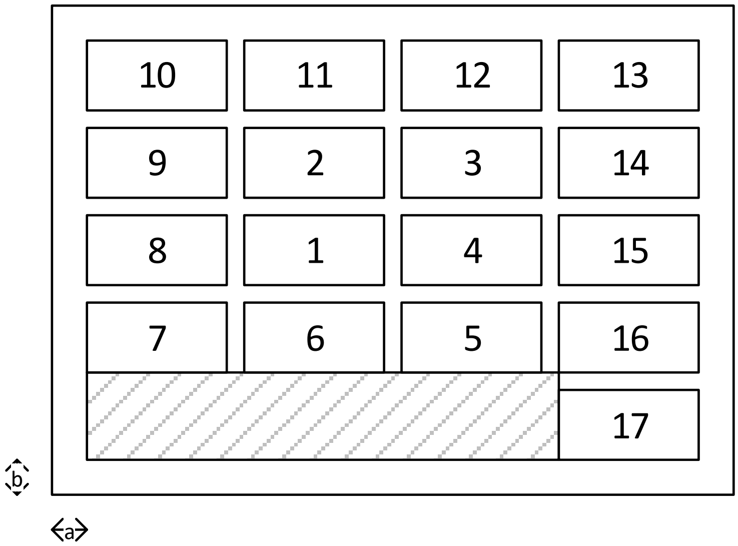


Figure 13: Illustration of 'Total plant area' for a system with N_{PCU} = 17

2.3.4 Packing Density and Deviation Factor

We define packing density (PD) as the ratio of active module area to total plant area for a given time window and configuration. This factor gives an indication of the active land area utilised for power generation.

$$\mathrm{PD} = \frac{\text{Active module area}}{\text{Total\_Plant\_Area\_with\_Aux}} = \frac{N_{mod} \times L_{mod} \times B_{mod}}{\text{Total\_Plant\_Area\_with\_Aux}}$$

In order to assess the extent of deviation in the estimated area, we introduce a deviation factor (DF), which is the ratio of the estimated total plant area to the benchmark area. In this study, we consider the benchmark area to be the norm suggested by CERC of 5 acres/MWp. DF is positive, if the estimated area is greater than benchmark area and negative if it is lesser

$$\mathrm{DF} = \frac{\text{Total\_plant\_Area\_with\_Aux (in acres)} - P_{plant} \times \text{Benchmark Area}}{P_{plant} \times \text{Benchmark Area}}$$

3. Results

3.1 Case Simulation to Illustrate the Proposed Approach

To illustrate the application of the proposed approach, we build the algorithm in Python and simulate a 1 MWp plant at location close Bengaluru (latitude 12.97 °N) with mono-crystalline, multi-crystalline, and thin-film technology options. To provide a fair comparison, modules of same power rating are considered. *Table 3* provides a summary of the simulation results. Appendix F provides details of spiral related parameters and specifics about the output.

Table 3: Summary of simulation results for technology comparison for a test case for a location at latitude of 12.97° N

Parameters ↓/Technology →	**Mono-crystalline**			**Multi-crystalline**			**Thin-Film (Amorphous Silicon)**		
Target Plant Capacity in MWp ($P_{plant\text{-}target}$)	1								
Module model	Adani Solar, ASM-7-PERC-350, Mono, 72 cells (Adani Solar, n.d.)			REC Solar, REC-350-TP2S 72, Multi-PERC, 144 cells (REC Solar, n.d.)			Moserbaer Solar, FS series A-Si, Thin film (Moserbaer Solar, 2010)		
Module power (Wp at STC)	350								
V_{mp} at STC (V)	38.59			38.9			133.6		
I_{mp} at STC (A)	9.08			9			2.62		
PCU Manufacturer	Eaton, Power Xpert Solar 250 kW Inverter (Eaton, 2015)								
No. of PCUs (N_{PCU})	4			4			4		
No. of modules strings/array (n)	6			6			3		
No. of modules in series/string (m)	11			11			3		
No. of arrays in parallel per PCU (y)	11			11			79		
Total no. of modules in plant (N_{plant})	2904			2904			2844		
Design Plant capacity (P_{Plant}) in MWp	1.016			1.016			0.995		
Time window wise parameters	**7 am to 5 pm**	**8 am to 4 pm**	**9 am to 3 pm**	**7 am to 5 pm**	**8 am to 4 pm**	**9 am to 3 pm**	**7 am to 5 pm**	**8 am to 4 pm**	**9 am to 3 pm**
D_r (m)	4.14	1.83	1.31	4.18	1.85	1.32	4.59	2.03	1.45
D_c (m)	8.32	2.97	1.60	8.40	2.99	1.61	9.23	3.29	1.77
Pure module area (acres)	1.407			1.440			4.020		
Net plant area (acres)	3.20	2.13	1.90	3.28	2.17	1.95	14.23	7.29	5.92
Effective plant area (acres)	3.20	2.13	1.90	3.28	2.17	1.95	14.23	7.29	5.92
Total plant area (acres)	4.53	3.23	2.96	4.61	3.30	3.02	16.76	9.10	7.55
Total plant area with Aux (acres)	4.53	3.23	2.96	4.61	3.30	3.02	17.00	9.10	7.55
PD	0.31	0.43	0.48	0.31	0.44	0.48	0.24	0.44	0.53
DF @ 5 acres/MWp	-0.11	-0.36	-0.42	-0.09	-0.35	-0.41	2.42	0.83	0.52

It can be seen that the thin-film module offers very high voltage addition and hence requires less modules to be connected in series; this is indicated by a reduced 'm'. However, its current addition is poor and therefore a large number of modules need to be connected in parallel, resulting in a large 'y'. This aspect affects the area requirements of the plant. The combined effect of all the plant scaling parameters is reflected in the plant area requirements. This is captured in Figure 14, here the estimated plant area is compared with the IREDA and CERC benchmarks. It can be seen that for all the three technologies, when considering time windows 8 am to 4 pm and 9 am to 3 pm the area estimates lie within, or are less than the IREDA and CERC estimates. It has to be noted that for a multi-crystalline plant the upper limit of IREDA and CERC benchmarks are the same (5 acres/MWp). It can be seen that, due to the module dimensions and hence the sizing parameters (n, m, y) the area estimates of mono and multi-crystalline technology based plants are very similar, but the thin film technology based plants differ significantly. It can be seen that for a given time window, the difference between the D_r and D_c components across technology options is not much. This is because of the cap on the maximum array structure height. The resulting higher area requirements due to sizing parameters are reflected in the PD and DF estimates appropriately in Figure 15. It is to be noted that DF is negative when the estimated area is lesser than the CERC benchmark. Since the number of PCUs in all cases is 4 (a perfect square) the 'Net plant area' and the 'Effective plant area' work out to be the same.

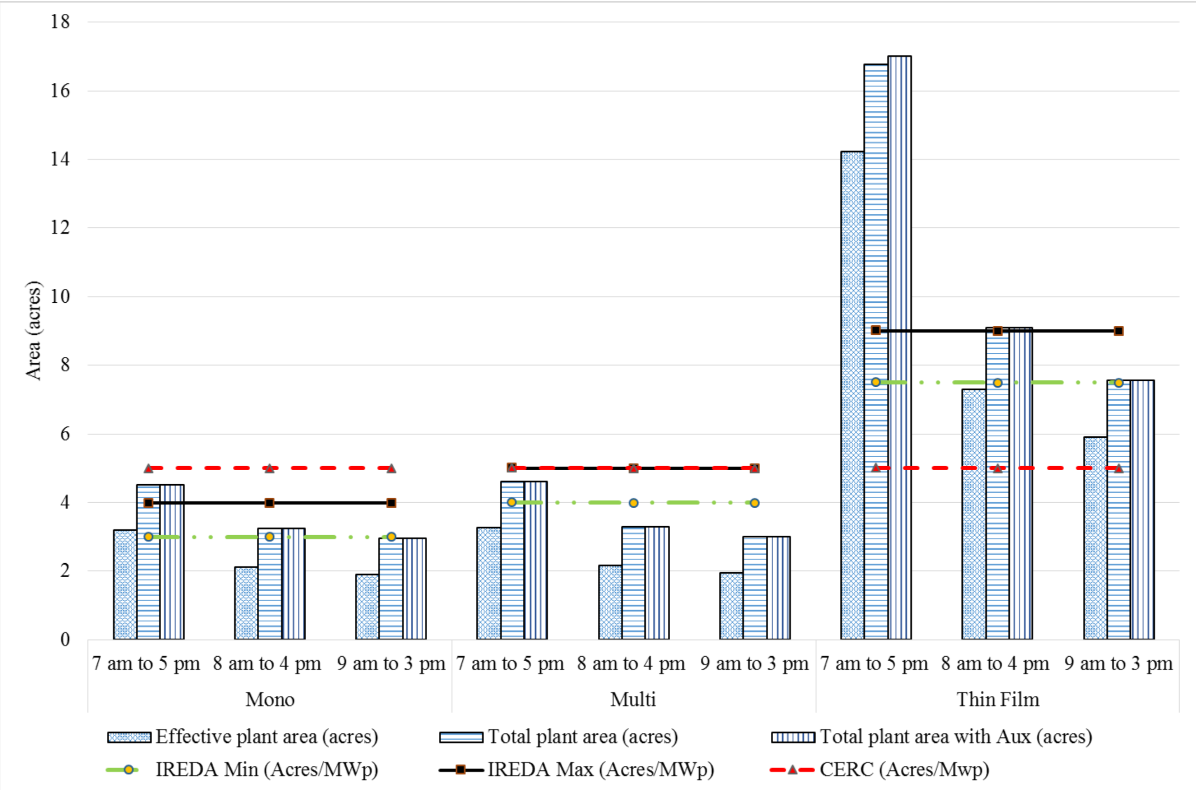


Figure 14: Area estimates for a 1MWp plant near Bengaluru for different technologies

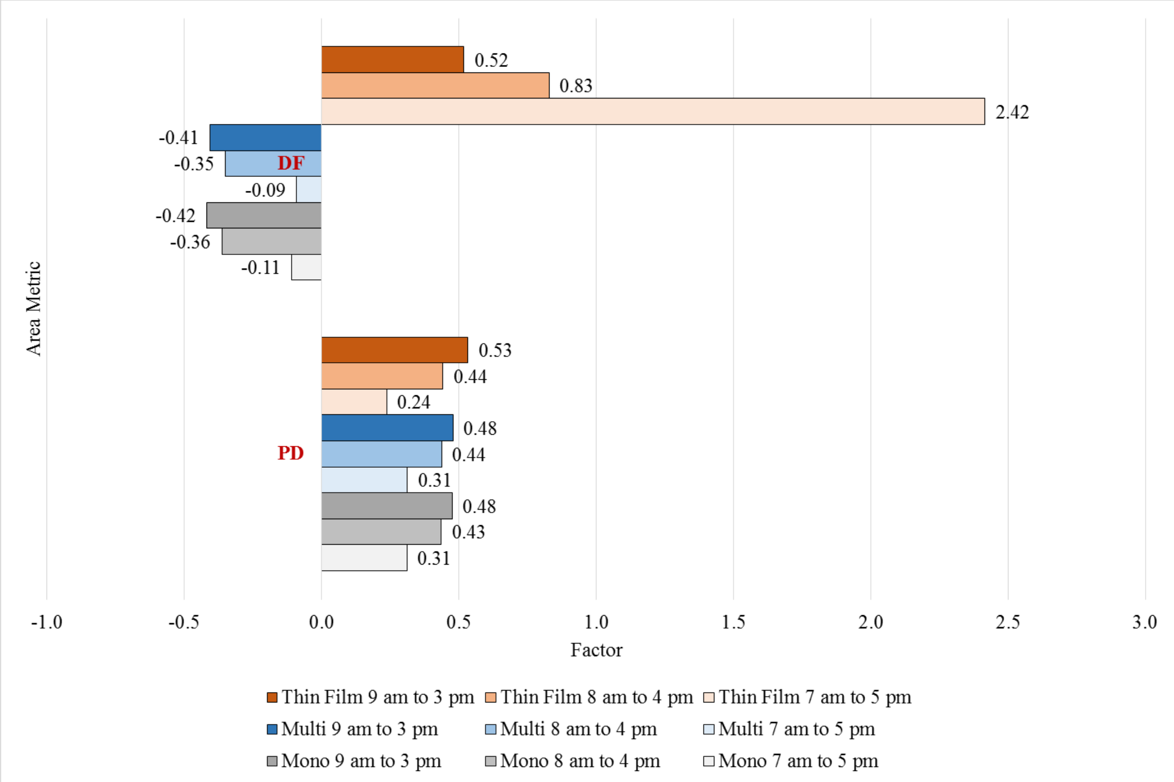


Figure 15: PD and DF for 1MWp plant near Bengaluru for different technologies

3.2 Testing the Approach to Predict Area of Active PV Plants

To check the robustness of the approach, we estimate the area of some existing plants and check the deviation margins when compared to their declared area. Table 4 provides a summary of the estimates. Appendix G details the relevant considerations and calculations. The deviation in the area could be attributed to applicability of assumption for estimating the auxiliary area, which is a plant specific criteria and a strong function of terrain undulations. Another factor, which could create variations in the estimate, is the tilt angle of the modules considered in design, since it could not be confirmed from public records, it is possible that $\beta \neq \varphi$ for plants which show positive deviation. It has to be noted that theoretically it is possible to design these plants in lesser area too (detailed in Appendix G).

Table 4: Summary of comparison of actual declared area of select existing plants and estimated area

Plant no.	Plant	Coordinates	Declared land area (Acres)	Estimated area (acres)	Deviation
1	Grid connected 3 MWp Solar PV power plant (UNFCCC - CDM, 2011)	16° 24' 03" N, 74° 39' 48" E	15	15.61	4%
2	5 MW Solar PV Power Project at NTPC Faridabad (UNFCCC - CDM, 2014)	28° 17' 08" N, 77° 19' 02" E	20	19.33	-3%
3	5 MW Solar PV Power Project at Port Blair (A&N) (UNFCCC - CDM, 2012b)	11° 36' 40" N, 92° 42' 36" E	24.71	21.58	-13%

4	15 MW Solar Photovoltaic Power Plant in Gujarat (UNFCCC - CDM, 2012a)	23° 21’ 37” N, 70° 03’ 15” E	106	92.17	-13%
5	5 MW_{AC} (~ 5.75 MWp) Grid Connected Solar PV based power generation at Naini, Allahabad (UNFCCC - CDM, 2012c)	25° 22’ 22” N, 81° 52’ 18” E	27	28.28	5%

3.3 India-Specific Insights

India is spread across latitudes 8.067 ºN to 37.1 ºN. When applying the proposed approach, due to β = φ, the ‘n’ in an array would be different across latitudes, since the array height is capped at 2m. This would lead to varying inter-row and inter-column spacing at different latitudes. To shed some light on the land area requirements for a PV plant across the latitudinal spread, we size the plant details as needed for different locations (illustrated in Figure 16). Here a 1 MWp system is sized using Tata Power multi-crystalline TS250 - 250 Wp module (Tata Power Solar, 2014) and a 250 kW Eaton power conditioning unit (Eaton, 2015) and the base assumptions mentioned earlier are simulated across the latitude range 8ºN to 37ºN at 1º resolution. For time windows 7 am to 5 pm and 8 am to 4 pm, results for only those latitudes whose area falls below 5 acres is plotted. For 9 am to 3 pm however, the results are plotted for the entire range. If we consider the upper limit of area requirement/MWp to be 5 acres/MWp, from Figure 16 it can be seen that, a 7 am to 5 pm time window would be suitable for latitudes up to 11ºN and 8 am to 4 pm time window is suited up to 23º N, beyond this 9 am to 3 pm seems like the most suitable time window. *The kinks in the profile is attributed to the change in ‘n’* as indicated in Figure 17. Also the decreasing trend in area needs from 8ºN to 10ºN and again from 12ºN to 14ºN is due to asymmetry in sizing introduced by ‘y’.

Another aspect of focus, is to consider the area requirements with increase in plant capacity. To capture the extreme cases, we estimate the area requirements for the extreme latitudes of 8ºN and 37ºN from 1 to 100 MWp. Figure 18 captures this for a 9 am to 3 pm solar time window. It could be seen that, when comparing it with the benchmark area estimates as per CERC, the area estimates for latitude of 37ºN only slightly exceed the benchmark area requirements. Whereas, the area estimates for latitude of 8ºN are significantly much less than the CERC estimates. This indicates that the CERC norms over-estimate the area requirements at lower latitudes. As a support to this claim the 3 MW Yelasandra plant (Mitavachan, H; Srinivasan, J; Gokhale, 2011) at (12.883ºN, 78.15ºE) occupies only 10.3 acres of land against the CERC estimate and allotted land area of 15 acres. This translates to 3.43 acres/MWp. Considering a rough estimate from Figure 16, it can be seen that the area estimate at 13ºN (closest latitude) works out to be 3.45 acres/MWp for a time window of 8 am to 4 pm and 3.16 acres/MWp for a time window of 9 am to 3 pm. The step pattern observed in the Figure 18 is due to the correction applied to minimise auxiliary area assignment as explained in Appendix E. The analysis indicated in section 3.1 can be extended to the extreme latitudes (8ºN and 37ºN) and results are presented in Appendix H.

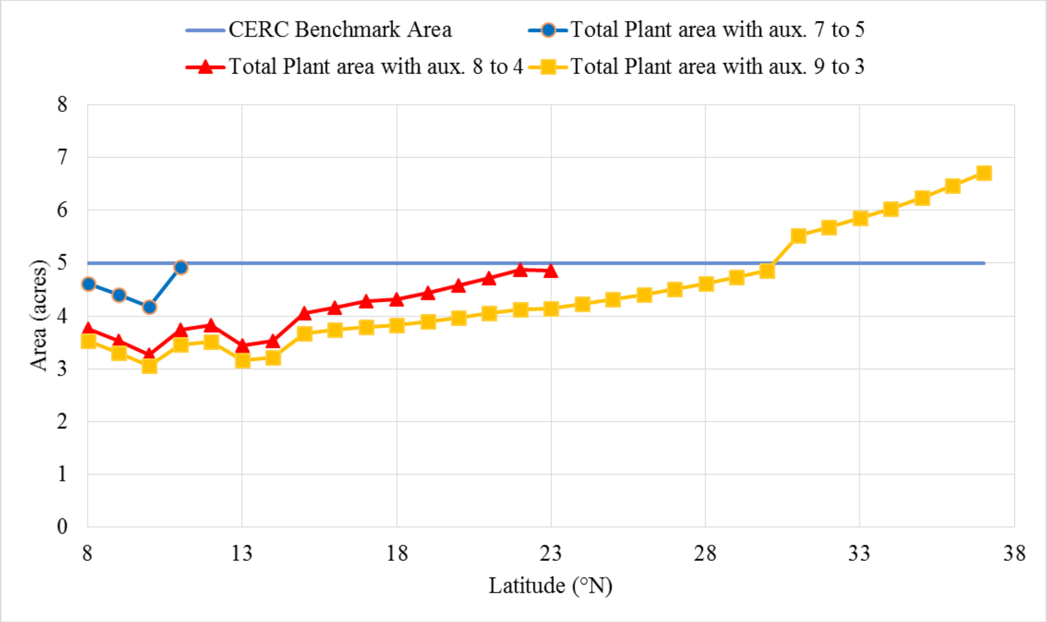


Figure 16: Total plant area including auxiliary area requirements for 1MWp plant across time windows

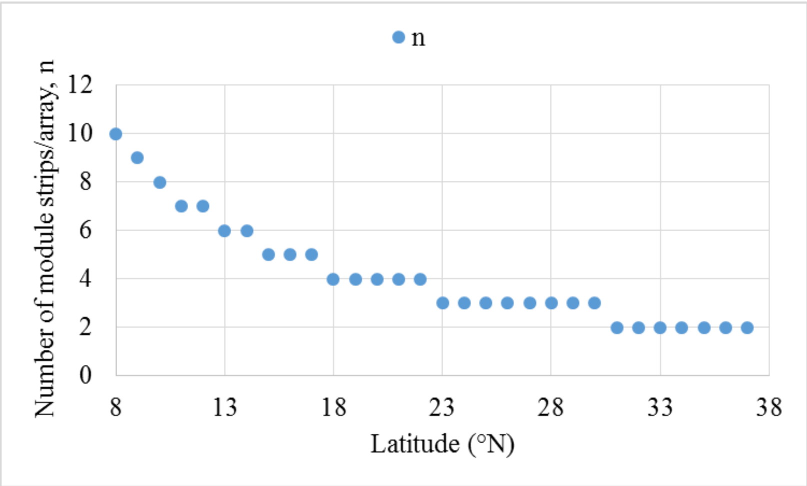


Figure 17: Variation of 'n' across latitude

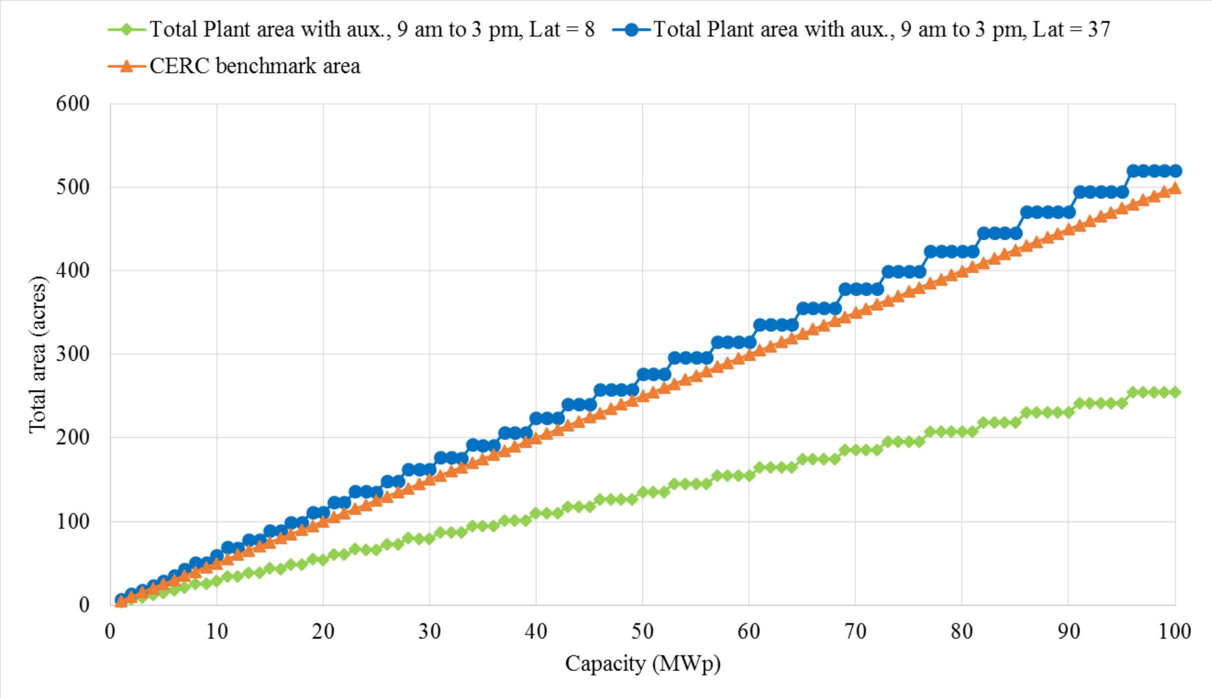


Figure 18: Capacity wise Total plant area (including auxiliary area) for 9 am to 3 pm window for latitudes 8 and 37 ºN

4. Estimating the Solar Power Potential for India

In this report, so far we have presented a method for estimating land area requirements of a solar PV plant factoring various design considerations. Further, we presented results of a hypothetical case comparing different module technologies. To check the robustness of the approach we compared the estimated area requirements from the method to the reported area of currently operational plants. The basis for the deviations was ascertained. In this context, we now aim to assess the solar PV potential in India using the land data from 2011-12 provided in the 'Bhuvan – Geo platform' by the Indian Space Research Organisation (ISRO, 2014)

The total land cover of India is about 3.287 Million km^2 and the percentage share of the various land types is indicated in Figure 19. Typically wastelands are considered for installation of RE plants. The wastelands constitute to about 12.10% of the total land cover, this translates to 0.34 Million km^2. The percentage share of these wastelands is indicated in Figure 20. The definition of land use land cover categories considered for this analysis is as defined by ISRO (ISRO, NRSC, RSAA, LRUMG, & LUCMD, 2014).

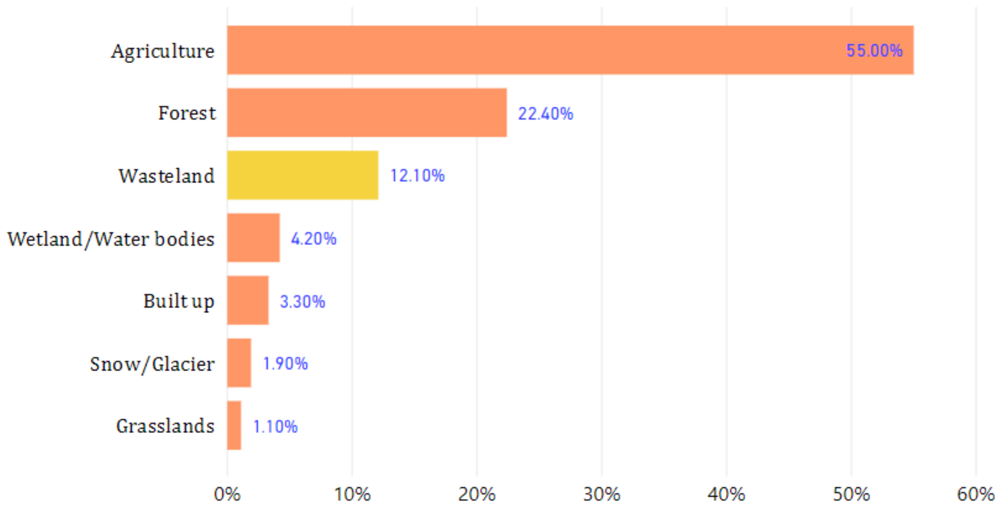


Figure 19: Percentage share of land categories for India

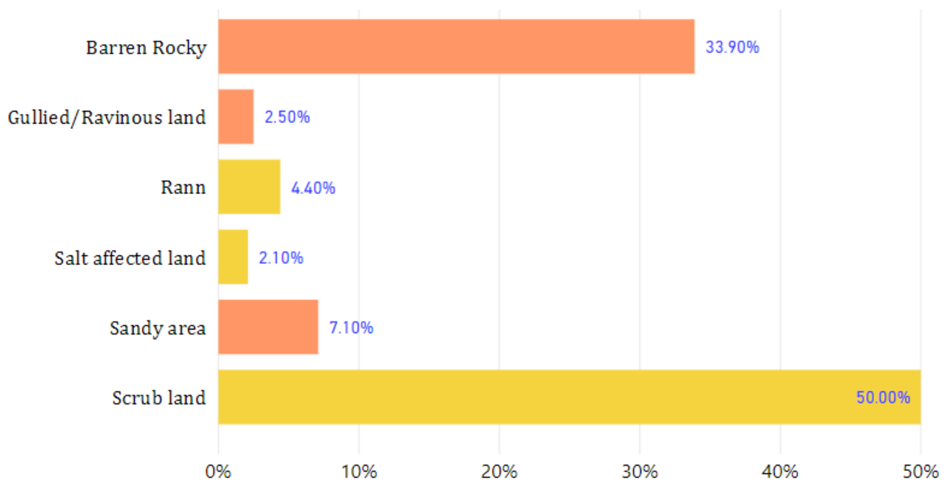


Figure 20: Percentage share of wasteland categories in India

Communications with sector experts reveal that, in context of installing utility scale ground mounted solar plants, rocky areas, gullied/ravenous land and sandy areas are not preferred due to loose and unstable soil cover. In this context, the aggregate of the remaining categories (Rann, Salt affected land and scrub land) which are suitable for RE installation translates to about 0.22 million km^2. It has to be acknowledged that each state has a distinct mix of land area and wasteland share. Figure 21 gives a perspective of state-wise land share, the supplementary material (excel sheet) provides the associated data. The idea of land availability has been sieved through in terms of total wasteland and 'Tappable' wasteland. Due to the unique mix of land cover of each state, the three maps in Figure 21 presents some interesting insights. Majority of the eastern states have relatively less available area for setting up solar plants. Jammu and Kashmir presents an interesting case, the scale of available wasteland significantly reduces when the rocky land component is not considered. The percentage of available land area in Gujarat, Madhya, Andhra Pradesh, Telangana and Maharashtra is slightly higher in the select wasteland set.

Our next step is to translate the available land area to potential solar plant capacity. In an exercise conducted by the National Institute of Solar Energy (NISE), they had estimated the national solar power potential to be about 750 GW (NISE & MNRE, 2014). This includes both utility scale and roof top installation. The assumptions considered for estimating ground mounted solar power plant potential is as follows:

- About 3% of wasteland in the state is used
- In 1 km^2 of wasteland, 50 MWp of solar PV power plant can be installed. This translates to about 4.95 acres/MWp
- The average solar PV module efficiency is assumed to be 15%

We recollect that CERC has a norm of 5 acres/MWp, which is an approximated version of the above assumption. Considering the latitudinal spread of the country, the area requirements for solar PV plants across this spread has been illustrated in section 3.3. To take this idea further, we applied the proposed method to estimate state-wise benchmarks for land area requirements. To estimate this we simulate the area requirements for a 1 MWp solar PV plant at a 0.01° latitudinal resolution (indicated in Figure 23).The kinks in the curve are due to variations in 'n' as explained in section 3.3. We next consider the latitudinal spread of each state and arrive at the average area requirement for a 1 MWp plant. Here we consider the same system configuration as indicated in section 3.3. A visual representation of this is presented in Figure 22 and the estimated data is presented in the supplementary material. From Figure 22, it can be noted that only five states have a benchmark area greater than 5 acres/MWp. The national average benchmark area works out to be 4.29 acres/MWp. Figure 24 and Figure 25 provides a summary of the estimated capacity as per assumptions considered by NISE (PM refers to considering state-wise estimates as per proposed method). The supplementary material provides the details of the state-wise estimated potentials. From Figure 24, it can be seen that by considering select wasteland categories the estimates based on CERC and NISE are reduced by about 35% and those based on PM are reduced by 31%. Due to the considerations of PM, the potential solar capacity is estimated to be about 20% and 19% higher that estimated by the CERC and NISE norms respectively. From Figure 25, it can be seen that the scrub lands contribute to about 88% of the estimated potential, salt affected areas and areas under rann contribute to the remaining 12%. Figure 26 (based on PM) it can be inferred that Rajasthan, Gujarat, Madhya Pradesh and Maharashtra constitute to about 56% and the seven union territories contribute to a meagre 0.06%.When we shift our consideration from all wastelands to select wasteland categories some states see significant dip estimates. Dip in potentials of Jammu and Kashmir, Himachal Pradesh and Uttarakhand can be attributed to discarding rocky areas for consideration and those of Rajasthan is attributed due to discarding both rocky and sandy land areas. The supplementary material provides relevant raw data.

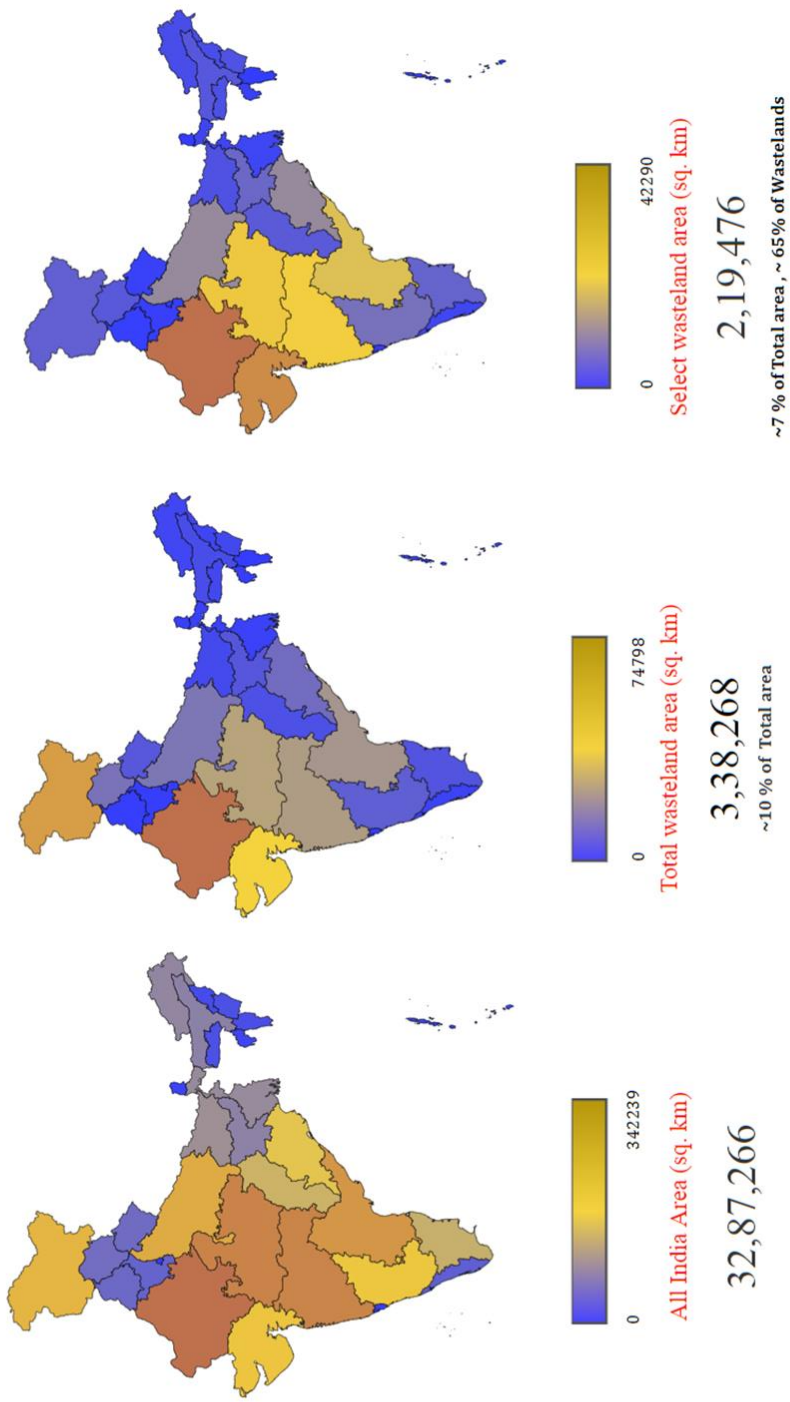


Figure 21: State-wise land share in India

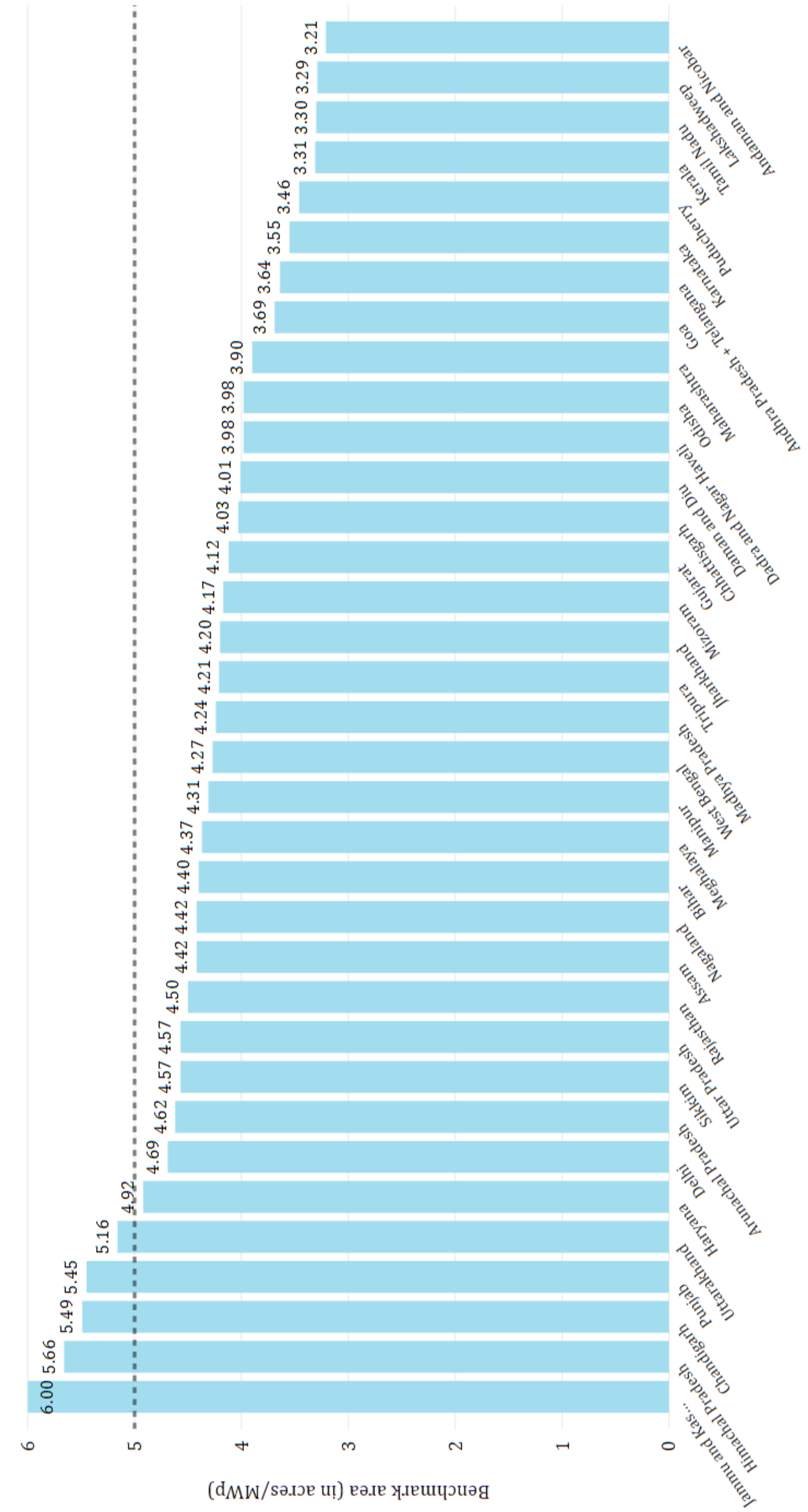


Figure 22: State-wise benchmark area for 1 MWp plant considering the Proposed Method (PM)

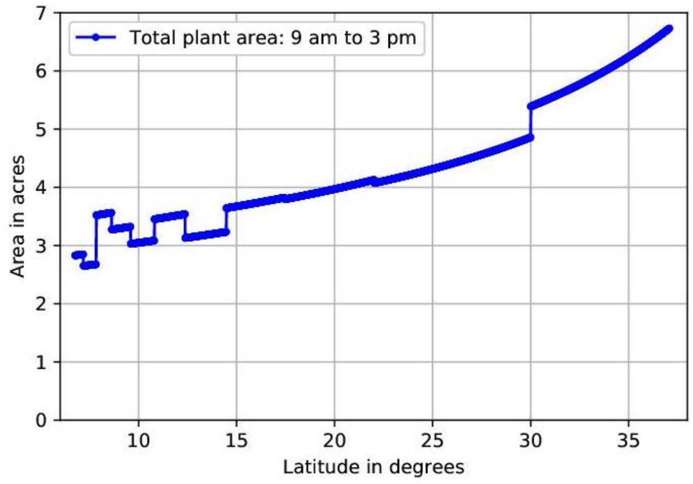


Figure 23: Latitude wise estimate of 1 MWp PV plant area for a time window of 9 am to 3 pm using the proposed method

Figure 24: Estimated solar potential for 3% of all wasteland and select wasteland areas

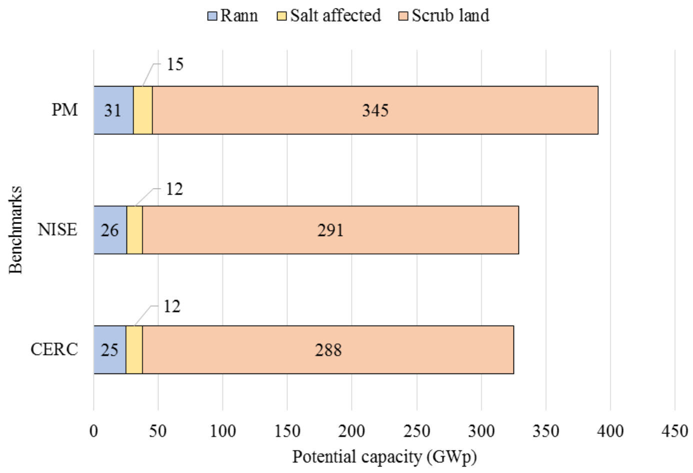


Figure 25: Category wise potential for 3% of select wasteland areas

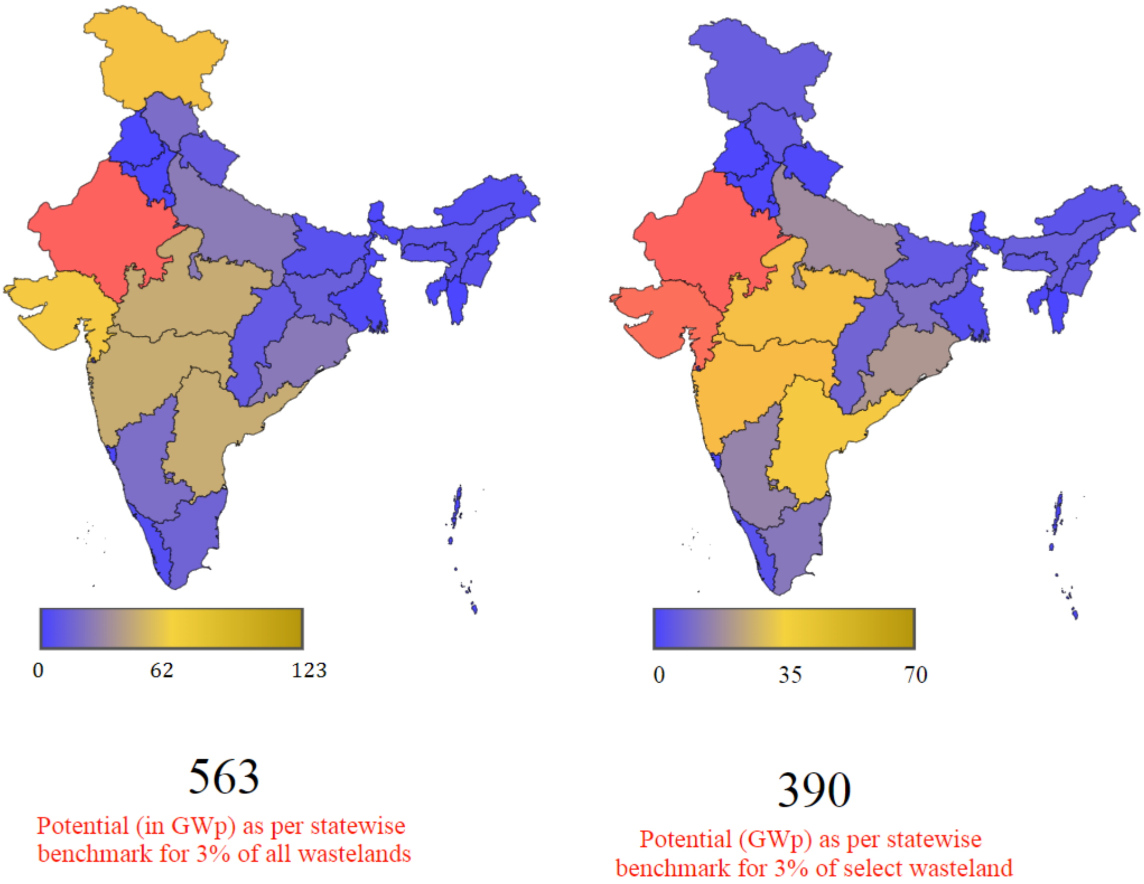


Figure 26: State-wise solar power plant potential estimated based on the proposed method

5. Conclusions and Policy Implications

Land availability is one of the critical aspects of interest for pursuing a high RE based electricity system. The approach proposed here provides a theoretical means to arrive at the optimal land area requirement for setting up a utility scale PV plant. This method factors the electrical, maintenance, and shading aspects and provides a generic approach to estimate plant area for a given location, capacity, and PV technology. The proposed approach would help in better planning, considering the land resource requirements for large scale deployment of solar PV plants. The land area estimates using this approach have been compared with declared land area of select existing plants and have found to be within an acceptable margin of deviation for planning purpose. To assess the impact of the proposed approach, it was observed that the CERC benchmark tends to overestimate land area requirements for latitudes less than 30° N. The proposed method can be used as a generic reference for estimating land area requirements for setting future utility scale solar PV plants across the country.

An area of refinement in the model for future work would be to create a revised basis for auxiliary area considerations factoring the terrain undulations. Another aspect would be the inclusion of optimal tilt and surface azimuth angle for a given location. Also, the mesh/grid created by this approach can be intersected with irregularly shaped land area contours to design module area cover for a prospective plant.

To summarise the policy commentary: the total wasteland area in India constitutes to about 12.10% of the total land cover. Out of this, 56.5% constitute the select wasteland area suitable for installing ground mounted solar plants. We apply the proposed method for area estimation to arrive at state-wise benchmark area for a 1 MWp plant. It was found that national average land area requirement is about 4.29 acres/MWp which is less than the CERC norms of 5 acres/MWp. Further, the tappable ground mounted utility scale solar power potential for India when considering select wasteland categories is estimated to be about ~391 GWp as per the proposed method and ~330 GWp and ~326 GWp when considering the NISE and CERC benchmarks respectively. The 20% gain in solar potential can be attributed to better land utilisation. This approach also emphasises the importance of considering state-wise benchmark areas.

In conclusion the proposed method is robust enough to accommodate and aid in informing policy related implications for aspects such as improved module efficiency and locational specific land area utilisation for setting up future solar plants. The refined land area estimates could lead to better use of the finite land resource available.

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Appendices

7. Appendix A

Nomenclature

Model related details

Table A.1: List of symbols and conventions

Symbol	Description
a	Boundary spacing along N-S direction (m)
b	Boundary spacing along E-W direction (m)
B_{mod}	Breadth of the module (m)
Day_{Hour}	An array which indicates hour values ranging from 1 to 24^{th} hours of the day
D_c	Inter-column spacing set (three elements of D_{col}, one for each time window) (m)
D_{col}	Inter-column spacing between 2 array strips (E-W direction) for a given time window (m)
D_r	Inter-row spacing set (three element of D_{row}, one for each time window) (m)
D_{row}	Inter-row spacing between 2 array strips (N-S direction) for a given time window (m)
h	Array height not factoring ground clearance (m)
I_{mid}	Current at V_{mid} to provide the rated PCU power (A)
I_{mp}	Current at maximum module power under Standard Testing Conditions - STC (A)
L_{col}	Hourly Inter-column spacing between 2 array strips (E-W direction) (A)
L_{mod}	Length of the module (m)
L_{row}	Hourly Inter-row spacing between 2 array strips (NS direction) (m)
m	No. of panels in series (for Voltage addition) = 1 module string
N	Day number as per Julian calendar
n	No. of module strings in parallel (for Current addition) in 1 array
N_{mod}	Total number of modules in the plant
N_{PCU}	Number of PCUs/inverter in the plant
P_{mod}	Module power rating under STC (Wp)
P_{nomDC}	Nominal DC power rating of the PCU (kW)
P_{plant}	Designed plant capacity (MWp)
$P_{plant\text{-}target}$	Desired plant capacity to be designed (MWp)
V_{maxDC}	Maximum DC voltage limit of the PCU (V)
V_{mid}	Midpoint of maximum power point (MPP) voltage range of the PCU (V)
V_{mp}	Voltage at maximum module power at STC (V)
V_{mppmax}	Maximum MPP voltage limit of PCU (V)
V_{mppmin}	Minimum MPP voltage limit of PCU (V)
V_{start}	Start-up voltage of PCU (V)
y	No. of arrays in parallel (for Current addition)
α_s	Solar altitude angle in º Convention: Negative before sunrise, 0 º at sunrise and increases to 90 º at solar noon and decreases to 0 º at sunset (Range: –90 º to + 90 º)
β	Tilt of the module in º Convention: Always positive (Range: 0º to 90º)
γ	Surface azimuth angle in º Convention: 0 º due south, negative towards East, positive towards West (Range: –180 º to 180 º)
γ_s	Solar azimuth angle in º

	Convention: 0 º due south, negative towards East, positive towards West (Range: –180 º to 180 º)
δ	Declination angle in º Convention: Positive for North (Range: –23.45 º to 23.45 º)
θ	Incidence angle in º Convention: 90 º at sunrise, $\lvert\delta\rvert$ at solar noon (minimum for that day) and 90 º at sunset (Range: 0 º to 90 º)
θ_z	Zenith angle in º Convention: ~90 º at sunrise and sunset, decreases from 90 º after sunrise, $\theta z = \lvert\delta-\Phi\rvert$ º at solar noon, increases beyond 90 º after sunset (Range: 0 º to 180 º)
φ	Latitude of the location of interest Convention: Positive for º North, negative for º South (Range: –90 º to + 90 º)
ω	Hour angle in º Convention: –90 º at sunrise, 0 º at solar noon , 90 º at sunset (Range: –180 º to 180 º)

Table A.2: Nomenclature used in generic spiral application algorithm

Symbol	**Description**
A_BDr	Counter for tracing the area component of a unit due to its breadth and inter-row spacing, B × Dr
A_BDr_temp	Counter for tracing the B × Dr area components of the transition set
A_{block}	Area for a generic set of X units arranged in spiral, representing sum of area due to enclosed and outlying set
A_LB	Counter for tracing the Area component of a unit due to its dimensions L × B
A_LDc	Counter for tracing the Area component of a unit due to its length and inter-column spacing, L × Dc
A_LDc_temp	Counter for tracing the L × Dc area components of the transition set
A_e	Area of the enclosed set
A_o	Area of the outlying set
Area_BS_along_length	Area of the boundary spacing component along length
Area_BS_along_breadth	Area of the boundary spacing component along breadth
A_{unit}	Area of the generic unit
Aux_{land}	Auxiliary land area requirements
B	Breadth of a generic unit
$B\_array_{e/o}$	Breadth of the array units for the enclosed or outlying set
B_flag	Flag to trace the addition of outlying set along breadth
$B\_PCU_{e/o}$	Breadth of the PCU block for the enclosed or outlying set
BDrow	Consolidated coefficient accounting for contribution due to B × Drow area component for all units
B_{PCU}	Effective breadth of the PCU block
B_{Plant}	Breadth of the area constituting the effective plant area
count	Counter to trace if the first element of the transition set is reached
DrowDcol	Consolidated coefficient accounting for contribution due to Drow × Dcol area component for all units
Effective_PCU_area	Effective area of the PCU block
Effective_Plant_Area	Effective area of the plant not including boundary spacing and auxiliary area

L	Length of a generic unit
$L\_array_{e/o}$	Length of the array units for the enclosed or outlying set
L_flag	Flag to trace the addition of outlying set along length
$L\_PCU_{e/o}$	Length of the PCU block for the enclosed or outlying set
L_{Plant}	Length of the area constituting the effective plant area
LB	Consolidated coefficient accounting for contribution due to L × B area component for all units
LDcol	Consolidated coefficient accounting for contribution due to L × Dcol area component for all units
L_{PCU}	Effective length of the PCU block
Net_Area_PCU	Net area of the PCU block
N_B	Number of generic units along breadth for X units
N_{Be}	Number of units along breadth contributing to enclosed set
N_{Bo}	Number of units along breadth contributing to outlying set
N_{Ce}	Number of inter-column spacing sections along breadth contributing to enclosed set
N_{Co}	Number of inter-column spacing sections along breadth contributing to outlying set
N_L	Number of generic units along length for X units
N_{Le}	Number of units along length contributing to enclosed set
N_{Lo}	Number of units along length contributing to outlying set
N_o	Number of outlying units
N_{Re}	Number of inter-row spacing sections along length contributing to enclosed set
N_{Ro}	Number of inter-row spacing sections along length contributing to outlying set
R	Counter to trace the growth of units along length (y – axis) and rectangular matrix formation, by default unit is assumed to be a rectangular matrix
S	Counter to trace the growth of units along breadth (x – axis) and square matrix formation
Total_Plant_Area	Total plant area not including auxiliary area
X	Number of blocks/units

8. Appendix B

Assumptions

The broad assumptions for the model are listed as follows:

1. The time period of reference is based on solar time
2. PV modules are of fixed-tilt configuration. It is also a general practice to consider the tilt of the module (and hence array) β, to be equal to the latitude of the location φ. Further, the arrays are considered to face due south in case of northern hemisphere and due north in case of the southern hemisphere (Antonio and Hegedus, 2003; Markvart and Castaner, 2013), this makes the surface azimuth angle, $\gamma = 0°$.
3. The maximum allowable height of the array structure is limited to 2m (~ 6.5 feet). This is to accommodate the ease of maintenance and upkeep of the arrays. Also, a 0.5m (1.64 feet) ground clearance is provided to protect the panels from effects of soiling.
4. The initial land area available is an infinite plane with no undulations and has a flat terrain profile.
5. The auxiliary area requirement factors the need for additional land area for placement of the inverter/PCU, office buildings and extended pathways inside plant. These have been considered based on consultation with sector experts. To account for this in the model, a curve fit equation is generated to estimate the auxiliary land area requirement as a function the capacity of the plant (MWp)
6. A boundary spacing of 10m is considered between the plant inner periphery and the outer plant boundary.
7. An important consideration while performing the electrical sizing of the system is that:
    a. The combined voltage of modules in series should not exceed the maximum tolerable Direct Current (DC) voltage of the inverter
    b. The combined current of the module arrays in parallel should not exceed the maximum rated DC current of the inverter

    These considerations are fundamental to deciding the system design point for the PCU (Antonio and Hegedus, 2003). In this model we consider the midpoint voltage in the Maximum Power Point (MPP) range and the corresponding current to achieve the rated PCU power rating.

9. Appendix C

Solar Angles

Formulae relevant to various solar angles computation:

$$B = (N - 1) \times 360/365$$

$$\omega = -15(12 - Day_{hour})$$

$$\delta = \frac{180}{\pi} \times (0.006918 - 0.399912 \times \cos(B) + 0.070257 \times \sin(B) - 0.006758 \times \cos(2B) + 0.000907 \times \sin(2B) - 0.002697 \times \cos(3B) + 0.00148 \times \sin(3B))$$

$$\theta = \cos^{-1}(\sin\delta \times \sin\Phi \times \cos\beta - \sin\delta \times \cos\Phi \times \sin\beta \times \cos\gamma + \cos\delta \times \cos\Phi \times \cos\beta \times \cos\omega + \cos\delta \times \sin\Phi \times \sin\beta \times \cos\gamma \times \cos\omega + \cos\delta \times \sin\beta \times \sin\gamma \times \sin\omega)$$

$$\theta_z = \cos^{-1}(\cos\Phi \times \cos\omega \times \cos\delta + \sin\Phi \times \sin\delta)$$

$$\alpha_s = 90 - \theta_z$$

$$\gamma_s = sign(\omega) \times \left|\cos^{-1}\left(\frac{\cos\theta_z.\sin\Phi - \sin\delta}{\sin\theta_z.\cos\Phi}\right)\right|$$

10. Appendix D

Generic equation for plant area

A more generic representation of the plant in terms of a single variable for each of the area components:
($L \times B$, $L \times D_c$, $B \times D_r$, and $D_r \times D_c$) can be illustrated as follows:

A_{plant} (sq. m) = $p \times L \times B + q \times B \times D_r + r \times D_c \times L + s \times D_r \times D_c$

Here,

$p = N_{Le} \times N_{Be} + N_{Lo} \times N_{Bo}$

$q = N_{Re} \times N_{Be} + N_{Ro} \times N_{Bo}$

$r = N_{Le} \times N_{Ce} + N_{Lo} \times N_{Co}$,

$s = N_{Re} \times N_{Ce} + N_{Ro} \times N_{Co}$

By logic it could be stated that the coefficient of $L \times B$ term would be equal to number of units X, as in terms of area computation every block would contribute p = X

11. Appendix E

Auxiliary area requirements

The auxiliary area requirements accounts for land imperfections, additional spacing requirements for support infrastructure, etc. Since there is no standardised way for allocating land area for PCUs, administrative and monitoring building, power substation, and extended pathways etc. as needed in the plant; a criteria for auxiliary area requirement has been considered in consultation with sector experts. It has been conveyed by sector experts that for a 1 MWp plant, roughly 15% of the net plant area is required for auxiliary infrastructure and it decreases to 1% for a 100 MWp plant. A mathematical curve fit was adopted to capture this decreasing trend, and is illustrated by the following equations:

$$\mathrm{Aux_{land}} = 0.165 \times \mathrm{Total\_Plant\_Area} \qquad (P_{plant} < 1\ \mathrm{MW})$$

$$\mathrm{Aux_{land}} = 16.723 \times e^{-0.027*(P_{plant})} \times \mathrm{Total\_Plant\_Area} \qquad (P_{plant} = 1 \text{ to } 100\ \mathrm{MW})$$

$$\mathrm{Aux_{land}} = 0.01 \times \mathrm{Total\_Plant\_Area} \qquad (P_{plant} > 100\ \mathrm{MW})$$

$$\mathrm{Total\_Plant\_Area\_with\_Aux\ (in\ m^2)} = \mathrm{Total\_Plant\_Area} + \mathrm{Aux_{land}}$$

It is required to trace plant design with asymmetric sizing parameters and apply an area correction so as to avoid excess auxiliary area assignment. If the difference between effective plant area (Effective_Plant_Area) and Total plant area (Total_Plant_Area) is greater than the auxiliary area ($\mathrm{Aux_{land}}$), then there would be no need for any auxiliary area consideration. However, if the difference is less, the auxiliary area would be considered for evaluating the total area requirements.

12. Appendix F

Case details for technology comparison

Spiral related parameters for the case are indicated in Table F.1 and Table F.2

Table F.1: Area related parameters for arranging 'y' arrays in spiral

Parameters ↓/Technology →	Mono-crystalline	Multi-crystalline	Thin-Film (Amorphous Silicon)
Y	79	11	11
N_{Le}	9	3	3
N_{Be}	8	3	3
N_{Lo}	7	1	1
N_{Bo}	1	2	2
N_{re}	8	2	2
N_{ce}	7	2	2
N_{ro}	6	1	1
N_{co}	1	1	1
L_flag	1	0	0
B_flag	0	1	1

Table F.2: Area related parameters for arranging 'N_{PCU}' inverters in spiral

Parameters ↓/Technology →	Mono-crystalline	Multi-crystalline	Thin-Film (Amorphous Silicon)
N_{PCU}	4	4	4
N_{Le}	2	2	2
N_{Be}	2	2	2
N_{Lo}	0	0	0
N_{Bo}	0	0	0
N_{re}	1	1	1
N_{ce}	1	1	1
N_{ro}	0	0	0
N_{co}	0	0	0
L_flag	0	0	0
B_flag	0	0	0

13. Appendix G

Comparison of plant area with select existing plants

This section aims to estimate the area requirements of select operational plants and compare it with their reported land area coverage. The plants for the case study (listed Table G.1) were chosen such that they are spread across the country so as to get wide latitudinal spread. In order to have uniformity in design, same design considerations have been applied for all plants. Only plants which had reported the total land area covered were considered. The image of each plant is attached in the end of Appendix G for reference.

Table G.1: Plant details

Plant no.	Plant	Promoter / Developer	Location	Coordinates (declared / As per google maps)	Declared Land area (Acres)
1	Grid connected 3 MWp Solar PV power plant (UNFCCC - CDM, 2011)	Karnataka Power Corporation Ltd. (KPCL)	Itnal, Belgaum, Karnataka	16° 26' 06" N, 74° 40' 30" E	15
				16° 24' 03" N, 74° 39' 48" E	
2	5 MW Solar PV Power Project at NTPC Faridabad (UNFCCC - CDM, 2014)	National Thermal Power Corporation (NTPC) Ltd.	Jajru, Faridabad, Haryana	28° 17' 08" N, 77° 19' 04" E	20
				28° 17' 08" N, 77° 19' 02" E	
3	5 MW Solar PV Power Project at Port Blair (A&N) (UNFCCC - CDM, 2012a)	NTPC Ltd.	Garacharma, Captain Town, Port Blair, Andaman Islands	11° 36' 00" N, 92° 42' 00" E	24.71
				11° 36' 40" N, 92° 42' 36" E	
4	15 MW Solar Photovoltaic Power Plant in Gujarat (UNFCCC - CDM, 2012b)	Welspun Urja Gujarat Pvt. Ltd.	Khisura, Anjar, Kutch, Gujarat	23° 21' 37" N, 70° 03' 15" E	106
				23° 21' 37" N, 70° 03' 15" E	
5	5 MW_{AC} (~ 5.75 MWp) Grid Connected Solar PV based power generation at Naini, Allahabad (UNFCCC - CDM, 2012c)	EMC Ltd.	Naini, Allahabad, Uttar Pradesh	25° 22' 00" N, 81° 51' 00" E	27
				25° 22' 22" N, 81° 52' 18" E	

Table G.2 indicates the details provided for module and PCU for this plant. Further, some plants indicated the number of modules, number of modules/string, and also the number of inverters. This is indicated in Table G.3.

Table G.2: Module and PCU details

Plant no.	Installed Capacity as per no of panels	Panel info	PCU info
1	2.99993	Titan Energy Systems Mono Crystalline, 225 Wp, Titan S6 – 60 (Titan Energy Systems, n.d.)	Details Unavailable - 250 kW, Assuming Eaton 250 kW (Eaton, 2015)
2	5.00112	Emmvee solar, poly crystalline, 230 Wp (Emmvee Photovoltaic Power Pvt. Ltd., 2012)	AEG 630 kW (AEG Power Solutions, n.d.)
3	5.00832	Photon Energy Systems Ltd 235 Wp C-Si, PMM0235 (Photon Energy Systems Limited, 2014)	SMA -Sunny Central 800 CP, 800 kW (SMA Solar Technology, n.d.)
4	14.99232	First Solar - Thin Film (CdTe) 80 Wp, FS380 (First Solar Inc., 2012)	SMA - 800 kW (SMA Solar Technology, n.d.)
5	5.76455	Unknown - Multi Crystalline - 235 Wp, Assuming TS235 Tata power module (Tata Power Solar, 2014)	unknown - 500 kW x 2 for each 1.15 MWp, Assuming ABB 500 kW, (ABB, 2014)

Table G.3: Additional details of plant as provided in reports

Plant no.	Latitude = tilt	Module Rating (Wp)	L_{mod} (m)	B_{mod} (m)	Inverter Rating (kW)	No. of modules	No. of modules/String	No. of PCU
1	16.40	3	225	28.63	7.93	13333	24	12
2	28.29	5	230	29.53	7.79	21744	24	8
3	11.61	5	235	29.6	8.06	21312	24	-
4	23.36	15	80	48.5	1.65	187404	14	16
5	25.37	5.75	235	29.6	7.95	24530	22	10

The possible combinations that can be considered while sizing the plant, are illustrated in Figure G.1, as the exact design point of each plant is not known. Considering all four permissible configurations, the number of modules at different levels were estimated (Table G.4) and the combination which gave the lowest deviation in terms of total number of modules relative to declared number of modules (Table G.5) was finalised for area estimation (marked in bold).

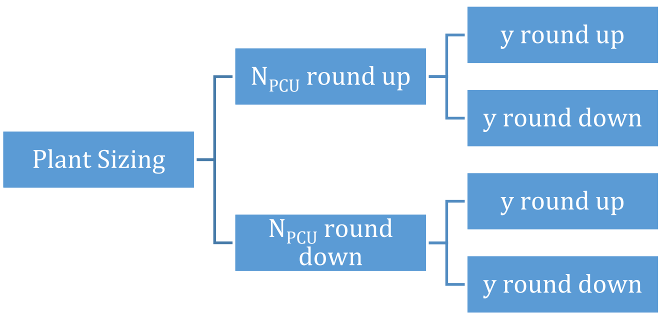

Figure G.1: Combinations of N_{PCU} and y

Spread of n, m, y, N_{PCU} for the five plants as indicated in Table G.6. Using these, the total number of modules and hence the effective MWp rating of the plant for each combination is calculated and is indicated Table G.4.

Table G.4: Estimated number of modules and plant capacity

Plant no.	Mod. Rating (Wp)	Declared		N_{PCU} round down				N_{PCU} round up			
		No of Modules	Plant Capacity	No of modules (y) round up	Plant Capacity	No of modules (y) round down	Plant Capacity	No of modules (y) round up	Plant Capacity	No of modules - (y) round down	Plant Capacity
1	225	13333	3.00	14400	3.24	12960	**2.92**	14400	3.24	12960	2.92
2	230	21744	5.00	20160	4.64	19656	4.52	23040	5.30	22464	**5.17**
3	235	21312	5.01	21168	**4.97**	20160	4.74	24696	5.80	23520	5.53
4	80	187404	14.99	189540	15.16	187920	**15.03**	200070	16.01	198360	15.87
5	235	24530	5.76	23958	**5.63**	23232	5.46	26136	6.14	25344	5.96

Table G.5: deviations with respect to total number of modules and final choice

Plant no.	Round down N_{PCU}		Round up N_{PCU}	
	y – round up	y – round down	y – round up	y – round down
1	8.00%	**-2.80%**	8.00%	-2.80%
2	-7.28%	-9.60%	5.96%	**3.31%**
3	**-0.68%**	-5.41%	15.88%	10.36%
4	1.14%	**0.28%**	6.76%	5.85%
5	**-2.33%**	-5.29%	6.55%	3.32%

Table G.6: Spread of n, m, y and N_{PCU}

Plant no	n	m	y –round up	y – round down	N_{PCU} round down	N_{PCU} round up
1	5	24	10	9	12	12
2	3	24	40	39	7	8
3	7	24	21	20	6	7
4	6	15	117	116	18	19
5	3	22	33	32	11	12

Based on the deviation indicated table G.5, the most suitable combination of module sizing parameters is indicated in the following Table G.7.

Table G.7: Suitable plant sizing parameters

Plant no.	Target Plant Capacity (MWp)	N_{PCU}	Plant rating as per PCU (MW)	n	m	y	Plant Rating (MWp)
1	3	12	3	5	24	9	2.92
2	5	8	5.04	3	24	39	5.17
3	5	6	4.8	7	24	21	4.97

4	15	18	14.4	6	15	116	15.03
5	5.75	11	5.5	3	22	33	5.63

Considering different time window of operations, the inter-row and inter-column spacing required for tilt of the module (equal to latitude), is indicated in Table G.8.

Table G.8: Time window wise inter-row and inter- column spacing

Plant no.	Module tilt (º)	7 am to 5 pm		8 am to 4 pm		9 am to 3 pm	
		D_{row} (m)	D_{col} (m)	D_{row} (m)	D_{col} (m)	D_{row} (m)	D_{col} (m)
1	16.40	5.41	10.69	2.17	3.38	1.54	1.77
2	28.29	31.40	60.16	3.70	5.19	2.42	2.38
3	11.61	4.00	8.10	1.82	3.00	1.31	1.63
4	23.36	10.85	20.95	2.96	4.30	2.03	2.11
5	25.37	13.40	25.77	2.93	4.18	1.97	2.01

An indication of benchmark area for comparison provided in Table G.9.

Table G.9: Declared and benchmarked area for comparison

Plant no.	Plant Rating		Area	Area as per CERC benchmark
	Target (MWp)	Estimated (MWp)	Declared (acres)	x 5 acre/MWp - Target capacity
1	3	2.92	15	15
2	5	5.17	20	25
3	5	4.97	24.71	25
4	15	15.03	106	75
5	5.75	5.63	27	28.75

The area estimated for all time windows is indicated in table G.10.

Table G.10: Estimated area for all time windows

Plant no.	Effective Area (acres)			Total Area (acres)		
	7 am to 5 pm	8 am to 4 pm	9 am to 3 pm	7 am to 5 pm	8 am to 4 pm	9 am to 3 pm
1	12.74	7.68	6.78	**15.61**	10.08	9.09
2	293.58	25.67	**19.33**	336.85	30.39	23.68
3	18.37	13.38	12.26	**21.58**	16.21	14.99
4	321.24	82.50	63.55	357.41	**92.17**	71.08
5	101.29	23.92	18.93	116.48	**28.28**	23.01

Although, the areas marked in bold indicate the closest area estimates to the declared area, it could be noted that, it is theoretically possible to set the same plant with area requirement lesser than that indicated by benchmark CERC norms. In this case, the area estimates for all plants in the 9 am to 3 pm window fall below the requirements posed by the benchmark CERC norms. Of course, with consideration of a narrower time window, the shading losses during time period beyond the specific window could reduce the energy generation. This trade-off is to be considered by the developer while designing the plant.

The effective dimensions of the plant based on spacing with respect to each time window is indicated in Table G.11.

Table G.11: Effective dimensions of plant for each reference time window

Plant no	Effective Length (m)			Effective Breadth (m)		
	7 am to 5 pm	8 am to 4 pm	9 am to 3 pm	7 am to 5 pm	8 am to 4 pm	9 am to 3 pm
1	116.29	80.70	73.77	443.40	384.93	372.09
2	682.92	129.01	103.25	1,739.77	805.30	757.66
3	157.77	127.29	120.10	471.30	425.41	413.06
4	767.91	341.73	291.28	1,692.97	977.08	882.92
5	373.29	132.36	110.36	1,098.16	731.25	694.23

By visually inspecting images of the plants (Figures G.2 to G.6), it could be observed that the module cover area and total plant area differs significantly and total plant area is a function of the land terrain undulations. The auxiliary area allotted for each plant varies and is case specific. Plant 1 and 3 have a fair portion of land, which is free from PV module cover. Plant 4 and 5 exhibit case of a well-packed plant.

Plant 2, especially is a case of interest, as here hardly any auxiliary area or boundary spacing is used by the plant. Hence, it would be apt for it to be compared to only the effective land area estimate instead of the total land area with auxiliary area estimate. For all other plants the comparison is done with the total land area with auxiliary area estimate. Since the basis for the tilt angle and inter-row and inter-column spacing is not explained in the UNFCCC reports, an effort has been made to address this issue with the concept of solar time windows as discussed earlier. The time window which provides the closest estimate to the declared area is considered. The entries which are the closest to the declared area in absolute terms are marked in bold in Table G.10. This is the reference area chosen for comparison and is summarised in Table G.12.

Table G.12: Summary of comparison of declared area and estimated area

Plant No.	Declared area (acres)	Computed reference area (acres)	Choice of area, time window	Deviation
1	15	15.61	Total Area, 7 am to 5 pm	4%
2	20	19.33	Effective Area, 9 am to 3 pm	-3%
3	24.71	21.58	Total Area, 7 am to 5 pm	-13%
4	106	92.17	Total Area, 8 am to 4 pm	-13%
5	27	28.28	Total Area, 8 am to 4 pm	5%

The mismatch in the area could be attributed to applicability of assumptions for estimating the auxiliary area. This is a plant specific criteria, as it is a strong function of terrain undulations. Another factor, which could create variations in the estimate, is the tilt angle of the modules considered in design.

It has to be reiterated that the proposed method is a theoretical approach to estimate the lower end of the area requirements for a given set of conditions, for a given capacity, at a specified location. The comparison with real plants is an effort to look at the closeness of the assumptions considered in this approach, to that of the conditions factored by an operational plant. It could be noted that it is theoretically possible to set up the same plant with lesser land area, than the specified norm as indicated in Table G.13.

Table G.13: A comparison of declared area and estimated theoretical minimum area

Plant No.	**Estimated (MWp)**	**Declared area (acres)**	**Minimum area required (acres)**	**Minimum area (acres/MWp)**
1	2.92	15	9.09	3.12
2	5.17	20	23.68	4.58
3	4.97	24.71	14.99	3.01
4	15.03	106	71.08	4.73
5	5.63	27	23.01	4.09

Images of various plants:

Figure G.2: Plant 1 – KPCL Belgaum plant

Figure G.3: Plant 2 – NTPC Faridabad plant

Figure G.4: Plant 3 – NTPC plant Port Blair

Figure G.5: Plant 4 – Welspun Urja plant

Figure G.6: Plant 5 – EMC plant at Naini

14. Appendix H

Comparison of land area requirements for extreme latitudes in India

Figure H.1 extends this technology comparison as illustrated in section 3.1 for the extreme latitudes (8ºN and 37ºN) encompassing India. Here, we estimate the total plant area with auxiliary area considerations for the 9 am to 3 pm window.

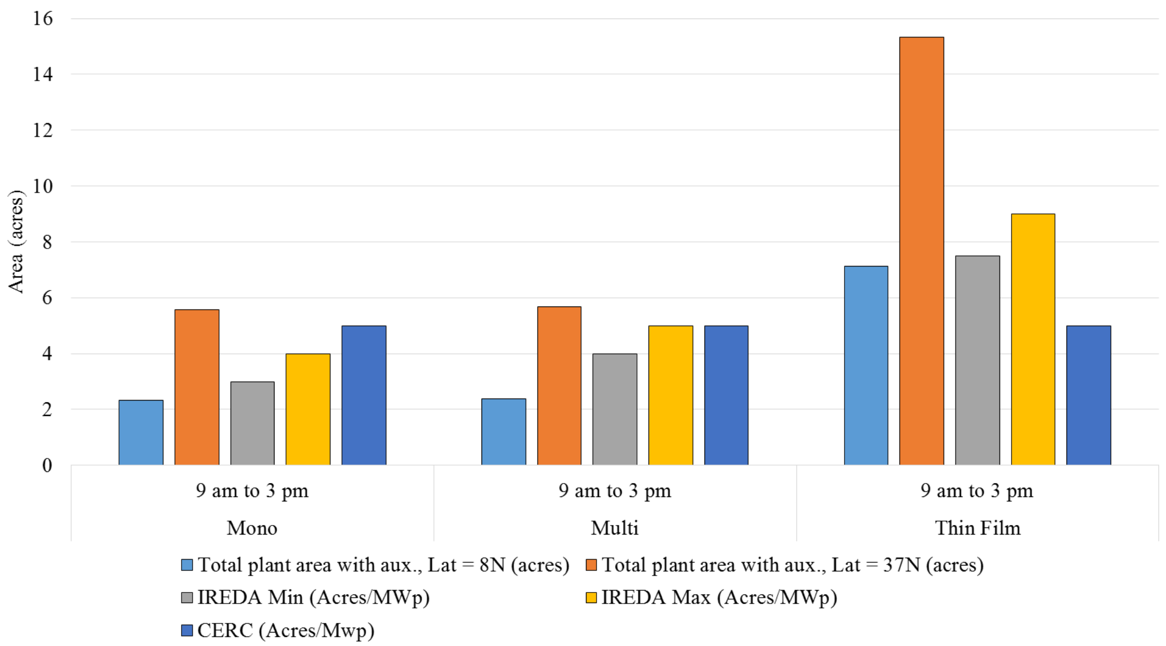

Figure H.1: Land area requirements for various technology options for 8ºN and 37ºN case

It can be seen that due to tilt angle considerations and plant sizing parameters (n, m, y) there is a noticeable difference between the area of the plant across the extreme latitudes, and the IREDA and CERC benchmarks. This is particularly predominant for thin film based set up and is in accordance with our earlier observations in section 3.1. In all cases there is significant difference between the area estimates of the plant at 8ºN and 37ºN. Further, it can be seen that the CERC benchmark over-estimates the land area requirement for lower latitudes for mono and multi-crystalline technologies. This reaffirms our inference from Figure 15 in section 3.3.

15. Reference for Appendices

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Supplementary Material

State / UT	Total State area (sq.km)	Total all wasteland (sq.km)	Select Wastelands (sq.km)				in acres/MWp
			Rann	Salt affected	Scrub land	Total (SWL)	benchmark area
Andaman and Nicobar	8249	8.94	0	0	1.29	1.29	3.21
Andhra Pradesh + Telangana	275068	22079.85	0	1608.74	16943.53	18552.27	3.64
Arunachal Pradesh	83743	2489.9	0	0	2297	2297	4.62
Assam	78438	4012.2	0	0	3780.27	3780.27	4.42
Bihar	94171	3229.08	0	0	3015.81	3015.81	4.4
Chandigarh	114	1.42	0	0	1.35	1.35	5.49
Chhattisgarh	135194	4963.62	0	0.29	4292.13	4292.42	4.03
Dadra and Nagar Haveli	491	42.35	0	0	42.35	42.35	3.98
Daman and Diu	112	8.99	0	0.85	7.72	8.57	4.01
Delhi	1483	68.48	0	0.15	62.18	62.33	4.69
Goa	3702	323.57	0	0	264.73	264.73	3.69
Gujarat	196024	37393.71	16995.29	970.36	18593.18	36558.83	4.12
Haryana	44212	507.17	0	27.64	378.1	405.74	4.92
Himachal Pradesh	55673	13530.65	0	2.47	3913.33	3915.8	5.66
Jammu and Kashmir	222236	57574.72	0	60.74	4937.85	4998.59	6
Jharkhand	79706	6569.29	0	0	6027.87	6027.87	4.2
Karnataka	191791	8617.44	0	525.4	6873.33	7398.73	3.55
Kerala	38863	1658.87	0	0	1398.17	1398.17	3.31
Lakshadweep	32	0.62	0	0	0	0	3.29
Madhya Pradesh	308252	25420.55	0	0	23534.51	23534.51	4.24
Maharashtra	307690	23773.96	0	8.12	22175.08	22183.2	3.9
Manipur	22330	3055.59	0	0	3055.59	3055.59	4.31
Meghalaya	22429	3102.98	0	0	2835.55	2835.55	4.37
Mizoram	21081	144.82	0	0	139.68	139.68	4.17
Nagaland	16579	2356.43	0	0	2355.57	2355.57	4.42
Odisha	155707	12057.93	0	15.52	10791.78	10807.3	3.98
Puducherry	492	10.81	0	0.1	8.24	8.34	3.46
Punjab	50362	547.46	0	25.64	357.53	383.17	5.45
Rajasthan	342239	74798.18	196.2	799.15	41294.37	42289.72	4.5
Sikkim	7096	842.08	0	0	19.71	19.71	4.57
Tamil Nadu	130058	6011.41	0	530.59	4967.59	5498.18	3.3
Tripura	10486	622.59	0	0	617.83	617.83	4.21
Uttar Pradesh	240928	14369.43	0	3741.69	7052.3	10793.99	4.57
Uttarakhand	53483	6744.36	0	0	695.67	695.67	5.16
West Bengal	88752	1329	0	0.97	1235.16	1236.13	4.27
Total/Average	**3287266**	**338268**	**17191**	**8318**	**193966**	**219476**	**4.29**

Supplementary Material

State / UT	3% Potential in GWp as per CERC 5 acres/MWp					3% Potential in GWp as per NISE 4.9421 acres/MWp					3% Potential in GWp as per estimated benchmark area				
	All wasteland	**Rann**	**Salt affected**	**Scrub land**	**Total (SWL)**	**All wasteland**	**Rann**	**Salt affected**	**Scrub land**	**Total (SWL)**	**All wasteland**	**Rann**	**Salt affected**	**Scrub land**	**Total (SWL)**
Andaman and Nicobar	0.013	0.000	0.000	0.002	0.002	0.013	0.000	0.000	0.002	0.002	0.021	0.000	0.000	0.003	0.003
Andhra Pradesh + Telangana	32.736	0.000	2.385	25.121	27.506	33.120	0.000	2.413	25.415	27.828	44.967	0.000	3.276	34.507	37.783
Arunachal Pradesh	3.692	0.000	0.000	3.406	3.406	3.735	0.000	0.000	3.446	3.446	3.995	0.000	0.000	3.686	3.686
Assam	5.949	0.000	0.000	5.605	5.605	6.018	0.000	0.000	5.670	5.670	6.729	0.000	0.000	6.340	6.340
Bihar	4.788	0.000	0.000	4.471	4.471	4.844	0.000	0.000	4.524	4.524	5.440	0.000	0.000	5.081	5.081
Chandigarh	0.002	0.000	0.000	0.002	0.002	0.002	0.000	0.000	0.002	0.002	0.002	0.000	0.000	0.002	0.002
Chhattisgarh	7.359	0.000	0.000	6.364	6.364	7.445	0.000	0.000	6.438	6.439	9.131	0.000	0.001	7.895	7.896
Dadra and Nagar Haveli	0.063	0.000	0.000	0.063	0.063	0.064	0.000	0.000	0.064	0.064	0.079	0.000	0.000	0.079	0.079
Daman and Diu	0.013	0.000	0.001	0.011	0.013	0.013	0.000	0.001	0.012	0.013	0.017	0.000	0.002	0.014	0.016
Delhi	0.102	0.000	0.000	0.092	0.092	0.103	0.000	0.000	0.093	0.093	0.108	0.000	0.000	0.098	0.099
Goa	0.480	0.000	0.000	0.392	0.392	0.485	0.000	0.000	0.397	0.397	0.650	0.000	0.000	0.532	0.532
Gujarat	55.441	25.198	1.439	27.567	54.203	56.091	25.493	1.456	27.890	54.838	67.283	30.580	1.746	33.455	65.781
Haryana	0.752	0.000	0.041	0.561	0.602	0.761	0.000	0.041	0.567	0.609	0.764	0.000	0.042	0.570	0.611
Himachal Pradesh	20.061	0.000	0.004	5.802	5.806	20.296	0.000	0.004	5.870	5.874	17.722	0.000	0.003	5.125	5.129
Jammu and Kashmir	85.362	0.000	0.090	7.321	7.411	86.362	0.000	0.091	7.407	7.498	71.135	0.000	0.075	6.101	6.176
Jharkhand	9.740	0.000	0.000	8.937	8.937	9.854	0.000	0.000	9.042	9.042	11.595	0.000	0.000	10.639	10.639
Karnataka	12.776	0.000	0.779	10.191	10.970	12.926	0.000	0.788	10.310	11.098	17.995	0.000	1.097	14.353	15.450
Kerala	2.459	0.000	0.000	2.073	2.073	2.488	0.000	0.000	2.097	2.097	3.715	0.000	0.000	3.131	3.131
Lakshadweep	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Madhya Pradesh	37.689	0.000	0.000	34.893	34.893	38.131	0.000	0.000	35.302	35.302	44.445	0.000	0.000	41.147	41.147
Maharashtra	35.248	0.000	0.012	32.877	32.889	35.661	0.000	0.012	33.263	33.275	45.190	0.000	0.015	42.151	42.166
Manipur	4.530	0.000	0.000	4.530	4.530	4.583	0.000	0.000	4.583	4.583	5.256	0.000	0.000	5.256	5.256
Meghalaya	4.601	0.000	0.000	4.204	4.204	4.654	0.000	0.000	4.253	4.253	5.264	0.000	0.000	4.810	4.810
Mizoram	0.215	0.000	0.000	0.207	0.207	0.217	0.000	0.000	0.210	0.210	0.257	0.000	0.000	0.248	0.248
Nagaland	3.494	0.000	0.000	3.492	3.492	3.535	0.000	0.000	3.533	3.533	3.952	0.000	0.000	3.951	3.951
Odisha	17.877	0.000	0.023	16.000	16.023	18.087	0.000	0.023	16.188	16.211	22.459	0.000	0.029	20.101	20.130
Puducherry	0.016	0.000	0.000	0.012	0.012	0.016	0.000	0.000	0.012	0.013	0.023	0.000	0.000	0.018	0.018
Punjab	0.812	0.000	0.038	0.530	0.568	0.821	0.000	0.038	0.536	0.575	0.745	0.000	0.035	0.486	0.521
Rajasthan	110.898	0.291	1.185	61.224	62.700	112.197	0.294	1.199	61.942	63.435	123.220	0.323	1.316	68.027	69.667
Sikkim	1.248	0.000	0.000	0.029	0.029	1.263	0.000	0.000	0.030	0.030	1.366	0.000	0.000	0.032	0.032
Tamil Nadu	8.913	0.000	0.787	7.365	8.152	9.017	0.000	0.796	7.451	8.247	13.504	0.000	1.192	11.159	12.351
Tripura	0.923	0.000	0.000	0.916	0.916	0.934	0.000	0.000	0.927	0.927	1.096	0.000	0.000	1.088	1.088
Uttar Pradesh	21.305	0.000	5.548	10.456	16.003	21.554	0.000	5.613	10.578	16.191	23.309	0.000	6.070	11.440	17.509
Uttarakhand	9.999	0.000	0.000	1.031	1.031	10.117	0.000	0.000	1.044	1.044	9.689	0.000	0.000	0.999	0.999
West Bengal	1.970	0.000	0.001	1.831	1.833	1.994	0.000	0.001	1.853	1.854	2.307	0.000	0.002	2.144	2.146
Total	**501.527**	**25.489**	**12.333**	**287.580**	**325.402**	**507.403**	**25.787**	**12.478**	**290.950**	**329.214**	**563.432**	**30.903**	**14.901**	**344.669**	**390.473**

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