



BSI Standards Publication

Land usage of photovoltaic (PV) farms - Mathematical models and calculation examples

National foreword

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TECHNICAL REPORT



Land usage of photovoltaic (PV) farms – Mathematical models and calculation examples

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.160

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**LAND USAGE OF PHOTOVOLTAIC (PV) FARMS –
MATHEMATICAL MODELS AND CALCULATION EXAMPLES**

FOREWORD

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The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
82/1319/DTR	82/1411/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

It is very important to calculate the land usage of PV power plants. If the plant is poorly designed, it would result in either a waste of land due to too large an area, or the loss of power generation because of shading between arrays. This TR gives a simple calculation for a quick guideline of the land usage of PV farms. For accurate and optimum land usage design, a more sophisticated numerical computation is encouraged.

The key factor to affect land usage of PV plants is the distance between PV arrays. The calculation of the distance between PV arrays is affected by the following factors:

- Sun-Earth relationship;
- solar declination angle (determining the date of a year);
- solar hour angle (determining the time of a day);
- latitude of the location of PV plant;
- azimuth of PV array;
- tilted angle of PV array;
- flat land or tilted land;
- efficiency of PV modules;
- mounting and tracking arrangements if used (e.g. fixed, single-axis tracking, double-axis tracking);
- the coordinates system (ground horizontal coordinates, equatorial coordinates);
- the ratio of length and width of PV array, and
- the possible maximum mechanical tilted angle of PV array, etc.

Increased land usage comes with power generation. To maximise generation and minimise land usage has many advantages including decreasing cost.

LAND USAGE OF PHOTOVOLTAIC (PV) FARMS – MATHEMATICAL MODELS AND CALCULATION EXAMPLES

1 Scope

This document is aimed at building mathematical models for calculation of the distance between arrays, to farthest avoid shading and reasonably reduce the land usage of PV farms.

In general, there will be longest south-north shading on the day of the winter solstice. The boundary condition to calculate the south-north (*S-N*) distance between PV arrays used in this document is based on winter solstice. The longest east-west (*E-W*) shading is on the time when the sun is in the east. The users can change the boundary conditions (date and time) depending on local conditions (latitude, land limitation, facing direction, etc.), the formulas are all the same.

The shading distance calculation is based on date and time boundaries, not based on shading energy losses that may be very complicated. The no-shading distance calculation in this document is only for the distance between PV arrays, not for other surrounding objects, but the formula can also be used to calculate the no-shading distance between the objects and PV arrays. Where shading occurs on the PV array site other calculations are required that are not within the scope of this document. The no-shading distance calculation is based on the northern hemisphere in this document, but all formulas can also be used for the southern hemisphere.

The no-shading calculation model is different for fixed PV arrays and PV systems with solar trackers. This document derives mathematical models for both fixed PV arrays and solar trackers.

For solar trackers, there are 2 different coordination systems: the Ground Horizontal Coordinates (*GHC*) and Equatorial Coordinates (*EC*).

This document provides land usage calculations of PV farms for the following array types:

- Fixed PV array on flat-land and face to the south
- Fixed PV array on flat-land and face to non-south direction
- Fixed PV array on tilted land and face to the south
- Horizontal *E-W* tracking in Equatorial Coordinates
- Tilted *E-W* tracking in Equatorial Coordinates
- Pole-Axis tracking in Equatorial Coordinates
- Double tracking in Equatorial Coordinates
- Solar Azimuth tracking in ground horizontal coordinates
- Manual solar altitude tracking in ground horizontal coordinates
- Double tracking in ground horizontal coordinates

In the following clauses, the different coordinates systems are introduced and the land usage calculations for different operational models are provided.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62727:2012, *Photovoltaic systems – Specification for solar trackers*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

array azimuth

angle between a line due south at northern hemisphere (or due north at southern hemisphere) and the shadow cast by the normal of PV array on Earth. It defines in which direction the normal of PV array is. This convention states the angle is positive if the line is east of south and negative if it is west of south. It equals to zero when pointing to south at northern hemisphere and to north at southern hemisphere.

Note 1 to entry: Solar azimuth is denoted by γ .

3.2

array tilted angle

angle between horizontal ground and the plane of PV array

Note 1 to entry: *S-N* tilted angle is denoted by Z and the *E-W* tilted angle is denoted by A .

3.3

cosine losses

in-plan solar irradiance equal to the direct irradiance times $\cos\theta$ (θ is incidence angle), so the cosine losses coefficient is equal to $1-\cos\theta$

Note 1 to entry: For incidence angle see 3.8, and incidence angle is denoted by θ .

3.4

day length

time period from sunrise to sunset

Note 1 to entry: Unit: hours.

3.5

Equatorial Coordinates

EC

show the relationship of earth and sun referenced on equatorial plane. The sun position is determined by solar declination and hour angles.

3.6

Ground Horizontal Coordinates

GHC

show the relationship of earth and sun referenced on ground horizontal plane. The sun position in the sky is determined by solar altitude and solar azimuth.

3.7**hour angle**

is one of the coordinates used in the equatorial coordinate system to give the direction of a point on the celestial sphere. The hour angle of a point is the angle between two planes: one containing the Earth's axis and the zenith (the meridian plane), and the other containing the Earth's axis and the given point (the hour circle passing through the point).

Note 1 to entry: The angle is expressed as positive east of the meridian plane and negative west of the meridian plane. The angle may be measured in degrees or in time, with $24 \text{ h} = 360^\circ$ exactly. The hour angle is denoted by ω .

Note 2 to entry: The solar hour angle is paired with the solar declination to fully specify the location of the sun in the equatorial coordinate system.

3.8**incidence angle**

angle between solar beam and the normal of PV panel. The smaller of the incidence angle the less of cosine losses of the incidence solar power.

Note 1 to entry: Angle of incidence is denoted by θ .

3.9**latitude**

angle which ranges from 0° at the Equator to 90° (North or South) at the poles. Lines of constant latitude, or parallels, run east–west as circles parallel to the equator.

Note 1 to entry: Latitude is denoted by φ .

3.10**longitude**

meridians (lines running from the North Pole to the South Pole) connect points with the same longitude. By convention, one of these, the Prime Meridian, which passes through the Royal Observatory, Greenwich, UK, was allocated the position of zero degrees longitude. The longitude of other places is measured as the angle east or west from the Prime Meridian, ranging from 0° at the Prime Meridian to $+180^\circ$ eastward and -180° westward.

Note 1 to entry: Longitude is denoted by λ .

3.11**no-shading distance**

distance between PV arrays at specific time when the back array is not shaded by front array and this distance is used in the design to install PV arrays

Note 1 to entry: The main purpose of this document is to calculate the *S-N* no-shading distance and *E-W* no-shading distance between PV arrays.

3.12**shading distance**

shading projections behind PV arrays produced by solar beam

Note 1 to entry: Shading distance is denoted by L' .

3.13**solar altitude**

refers to the angle of the sun relative to the Earth's horizon

Note 1 to entry: Solar altitude is measured in degrees. Solar altitude is denoted by α and the formula is: $\sin \alpha = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega$.

3.14**solar azimuth**

angle between a line due south at northern hemisphere (or due north at southern hemisphere) and the shadow cast by a vertical rod on Earth. It defines in which direction the sun is. This convention states the angle is positive if the line is east of south and negative if it is west of

south. It equals to zero when pointing to south at northern hemisphere and to north at southern hemisphere.

Note 1 to entry: Solar azimuth is denoted by β and the formula is: $\sin\beta = \cos\delta\sin\omega/\cos\alpha$ (for $\beta \leq 90^\circ$) or $\cos\beta = (\sin\phi\sin\alpha - \sin\delta)/(\cos\alpha\cos\phi)$ (for $\beta = 0 - 180^\circ$).

3.15

solar declination

the declination of the sun is the angle between the equator and a line drawn from the centre of the Earth to the centre of the sun. The declination angle, denoted by δ , varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun. If the Earth were not tilted on its axis of rotation, the declination would always be 0° . However, the Earth is tilted by $23,45^\circ$ and the declination angle varies plus or minus this amount. Only at the spring and fall equinoxes is the declination angle equal to 0° . The declination is zero at the equinoxes, positive during the northern hemisphere summer and negative during the northern hemisphere winter. The declination reaches a maximum of $23,45^\circ$ on summer solstice in the northern hemisphere and a minimum of $-23,45^\circ$ on winter solstice in the northern hemisphere.

Note 1 to entry: Abbreviated as dec; symbol δ .

Note 2 to entry: The formula is: $\delta = 23,45\sin(360 \times (284+N)/365)$ (known as Cooper equation) where N is the number of days from Jan. 1st.

3.16

solar time

calculation of the passage of time based on the position of the sun in the sky. The fundamental unit of solar time is the day. Two types of solar times are local true solar time (sundial time) and mean solar time (clock time). The length of mean solar day based on mean solar time is 24 h and the length of true solar day is not exactly 24 h, the length of a solar day varies through the year.

Note 1 to entry: Since shading is always produced by the true sun, the time in this document is the true solar time.

Note 2 to entry: The difference between local standard time and true solar time can be calculated by the formula:

True solar time = local standard time + discrepancy between two kinds of solar times

+4 x (longitude of local standard time – local longitude).

Note 3 to entry: Local standard time is based on time zone.

Note 4 to entry: Discrepancy between two kinds of solar times can be found in any text book of sun-earth relationship.

4 Azimuth and hour angle coordinates

There are several definitions for azimuth coordinates:

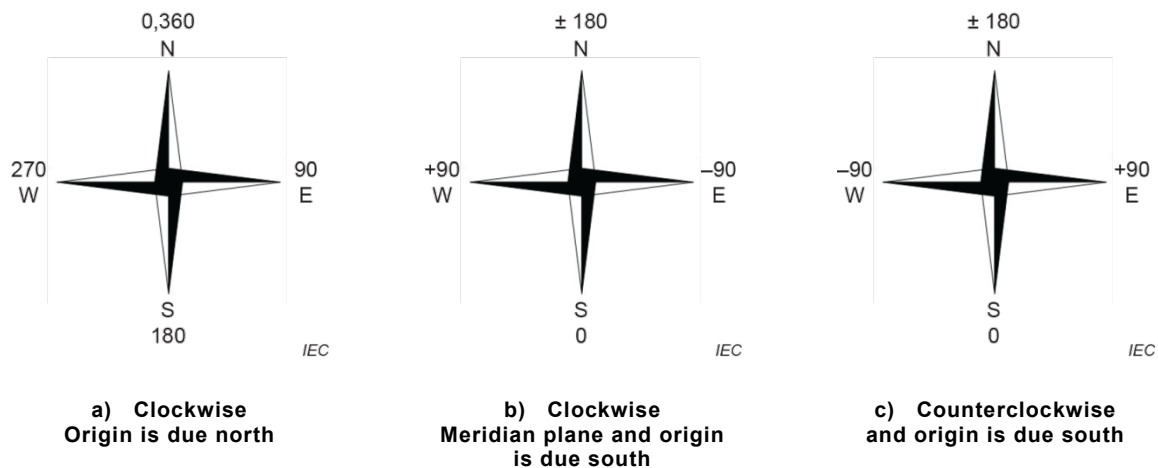


Figure 1 – Current definition of azimuth and hour angle coordinates

The most popular azimuth and hour-angle coordinates is the middle one which is used by PVSyst and RETScreen design software. In this document, it is proposed that (c) in Figure 1 be used for calculation to make less confusion because the results of the azimuth formula ($\cos \beta$) and hour-angle formula ($\cos \omega$) are always positive, never negative. Solar hour-angle, solar azimuth and PV array azimuth all follow the same definition, see Figure 2.

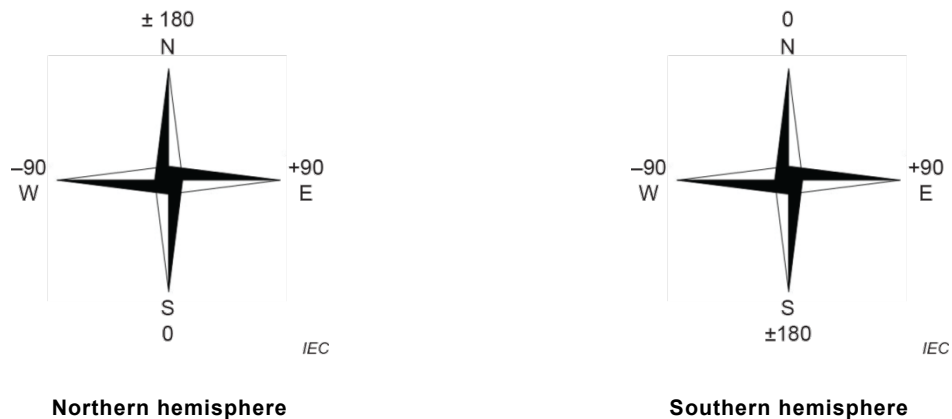
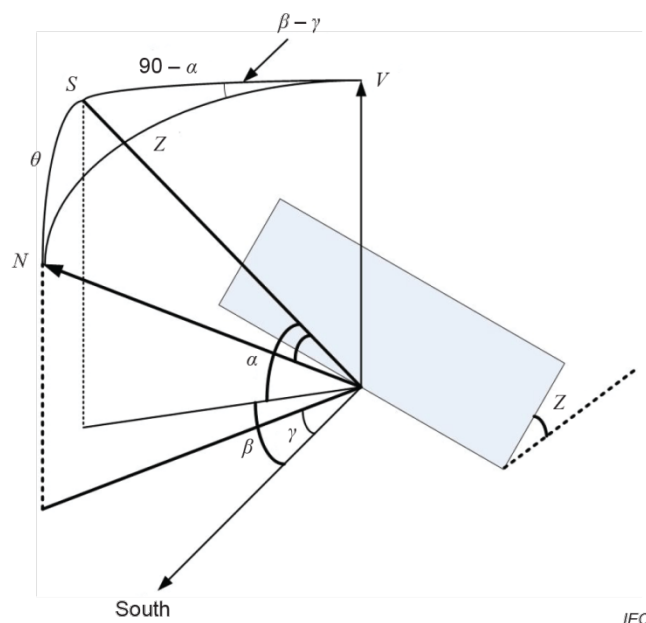


Figure 2 – Definition of azimuth and hour angle coordinates for this document

All examples in this document are based on northern hemisphere.

5 Coordinate systems (Figures 3 to 6)

5.1 Ground Horizontal Coordinates (*GHC*)



Key

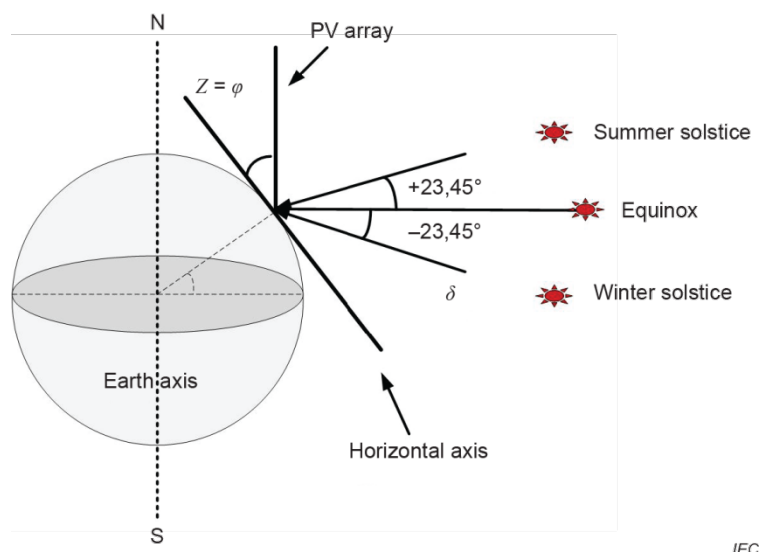
- V Vertical axis from ground to sky
- N Normal of PV array
- Z Tilted angle of PV array
- S Solar beam
- α Solar altitude
- β Solar azimuth
- r PV array azimuth

Figure 3 – PV array in ground horizontal coordinates

The solar trackers based on *GHC* take the ground horizontal plane as the reference. The sun position is defined by solar altitude and solar azimuth. There are four types of operations in these coordinates: fixed PV arrays, altitude tracking (usually manual adjustment), single axis azimuth tracking and double axis tracking:

- For fixed PV arrays, the tilted angle of arrays is always fixed and the azimuth of the arrays can be zero (face to south) or face to non-south directions. The PV arrays are installed either on flat land or on sloped land.
- For double axis tracking (2-axis) system, the tracker follows two variables: the solar altitude and solar azimuth. The function is achieved by adjusting the tilted angle and azimuth of the PV arrays.
- For single axis azimuth tracking, the tracker simply follows the solar azimuth by adjusting the azimuth angle of PV array and the tilted angle of PV array remains fixed.
- For altitude-tracking (usually manual-adjustment), the tracker follows the solar altitude by adjusting the tilted angle of PV array and the azimuth of the array is always facing to the south in the northern hemisphere and north in the southern hemisphere.

5.2 Equatorial Coordinates (EC)

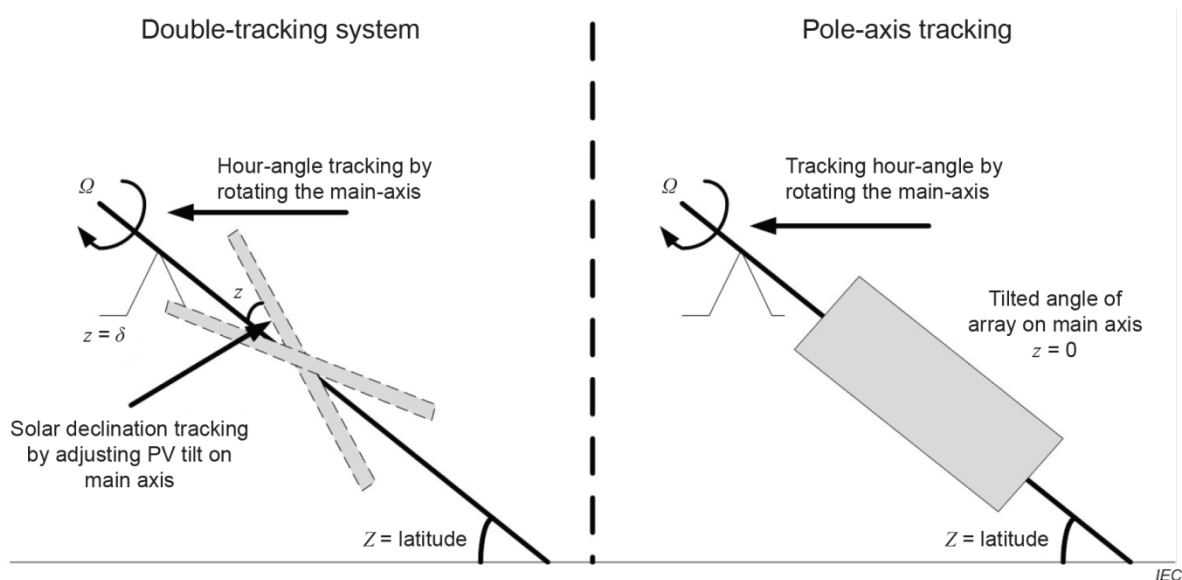


IEC

Key

- Z Tilted angle of PV array
- φ Latitude of the location
- 1 PV array will be parallel with earth axis if the tilt equals to latitude
- 2 Solar incidence angle (δ) varied $\pm 23,45^\circ$ during a year

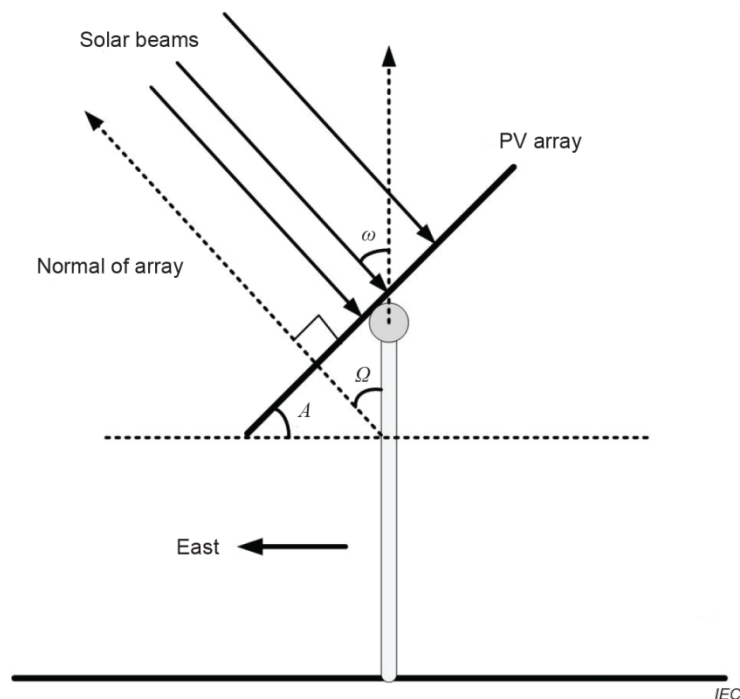
Figure 4 – PV array in equatorial coordinates



IEC

Figure 5 – Equatorial tracking systems

Solar trackers based on Equatorial Coordinates take the Earth's axis and the Earth's equatorial plane as the reference. The sun position is defined by solar hour angle and solar declination. There are four types of trackers in these coordinates: horizontal *E-W* tracking, tilted *E-W* tracking with tilted PV array on horizontal axis, pole-axis tracking with main-axis tilted angle equal to latitude, and double axis tracking.

**Key** A E-W Tilt of array Ω Turning angle ω Solar hour angle $\Omega = A$ Hour angle tracking means: make $A = \omega$ **Figure 6 – Relationship between A , Ω and ω**

- For pole-axis tracking, the S - N tilted angle of main axis is equal to latitude, so the main axis is parallel with the earth-axis that connects the south-pole and north-pole. The tracker simply follows the solar hour-angle by rotating the main-axis from east to west.
- For horizontal axis E - W tracking, the tracker simply follows the solar hour-angle by rotating the main-axis from east to west. PV arrays are installed horizontally on the main-axis. This type of solar trackers is very popular due to low cost, but it is not suitable for locations in high latitude ($\geq 35^\circ$) due to higher cosine losses during the winter season.
- For tilted E - W tracking, the tracker operates the same as horizontal E - W tracking and rotates the main-axis to follow solar hour angle from east to west. PV modules have a fixed tilted angle on the horizontal main-axis.
- For double-tracking systems, the tracker follows two variables: solar declination and the solar hour angle. It follows solar declination angle by adjusting the S - N tilted angle of PV modules and follows the hour angle by rotating the main-axis.

6 Boundary conditions

The longest S - N shading between PV arrays is on winter solstice and the longest E - W shading is at the time when the sun is in the east. Decoupled calculation for S - N and E - W no-shading distance is necessary. So the boundary conditions for both S - N and E - W distance calculations need to be provided.

In fact, optimization between land usage and power generation is required in design. For example, when the land cost is high, boundary conditions may need to change to reduce the

land usage. The proposed conditions for calculation of no-shading distance are provided below. Users may change the condition depending on the situation of the projects.

- a) For *S-N* distance, the no-shading period between arrays is set at the time of 75 % of day length (suitable for all latitudes) or from 9:00am to 3:00pm on winter solstice (for locations within 20° – 40° of latitude). See Table 1.

Table 1 – No-shading set time on winter solstice for various latitudes

Latitude φ °	Degradation δ °	Sunrise hour angle °	Sunrise time	Day length h	No-shading period 75 % day length h	Set hour angle °	Set time
0	-23,45	90,000	6:00:00	12,000	9,000	67,500	7:30:00
10	-23,45	85,613	6:17:33	11,415	8,561	64,210	7:43:09
20	-23,45	80,916	6:36:20	10,789	8,092	60,687	7:57:15
30	-23,45	75,496	6:58:01	10,066	7,550	56,622	8:13:31
36,25	-23,45	71,455	7:14:11	9,527	7,145	53,591	8:25:38
40	-23,45	68,655	7:25:23	9,154	6,866	51,491	8:34:02
50	-23,45	58,872	8:04:31	7,850	5,887	44,154	9:03:23
60	-23,45	41,295	9:14:49	5,506	4,130	30,971	9:56:07

- b) There shall be some day and sometime when solar altitude reaches 20° and the sun is just in the east when the *E-W* shading is the longest during a year. So, for *E-W* distance, no-shading condition is set at 20° of solar altitude and the solar azimuth is 90°. See Table 2.

Table 2 – Date and time when solar altitude is 20° and the sun is in the east

Latitude φ	Solar declination δ	Date	Sunrise time	Sunrise Hour angle	Sunrise azimuth	Set solar altitude α	Set solar azimuth β	Set hour angle ω	Set time
0	0,00	Mar.21	6:00:00	90,00	90,00	20,00	90,00	70,00	7:20:00
10	3,50	Mar.29	5:57:28	90,62	93,55	20,00	90,00	70,30	7:18:11
20	6,75	Apr.7	5:50:53	92,47	97,19	20,00	90,00	71,13	7:15:30
30	9,75	Apr.15	5:37:47	95,69	101,28	20,00	90,00	72,45	7:10:48
36,25	11,75	Apr. 20	5:24:05	98,77	104,63	20,00	90,00	73,70	7:05:48
40	12,75	Apr. 24	5:16:47	100,95	106,74	20,00	90,00	74,45	7:02:48
50	15,25	May. 2	4:44:50	108,96	114,15	20,00	90,00	76,90	6:52:36
60	17,25	May. 9	3:49:08	122,54	126,38	20,00	90,00	79,72	6:41:53

- c) No-shading distance does not only depend on solar altitude, but also on tilted angle of PV arrays. The earlier the array faces to the sun, the higher the array tilted angle is. The tilted angle of the PV array is also limited by the mechanical ability. The tilted angle of PV arrays in this document is defined as the *S-N* tilted angle and the *E-W* tilted angle.
- d) No-shading distances can be decoupled into *S-N* distance and *E-W* distance. The *S-N* distance is only relevant with length of PV array and the *S-N* tilt of PV array; the *E-W* distance is only relevant with width of PV array and the *E-W* tilt of PV array.
- e) The boundary conditions can be changed depending on certain situations to optimize the power generation and land usage, they are local latitude, land limitation, land cost, feed-in

tariff (FIT), etc., the calculation method and all formulas for different conditions are all the same.

- f) The calculation method and all formulas can also be used for CPV land usage, the only difference is the boundary conditions.
- g) The proposed boundary conditions for *S-N* distance and *E-W* distance calculations of all types of PV operations are listed in Table 3:

Table 3 – Proposed boundary conditions

Ground-horizontal coordinates					
Type of operation	S-N distance	Array tilt	E-W distance	Array azimuth	Remarks
Fixed PV arrays	75 % day length, or 9:00am to 3:00pm on winter solstice	φ	NA	0°	
Manual-regulated arrays	75 % day length, or 9:00am to 3:00pm on winter solstice	2 times or 4 times	NA	0°	No more than 4 times
Azimuth tracking	75 % day length, or 9:00am to 3:00pm on winter solstice	φ	Solar altitude 20° Solar azimuth 90°	= solar azimuth	L:K Ratio 1:1 ~ 1:2
Double axis tracking (for flat-plate panels)	75 % day length, or 9:00am to 3:00pm on winter solstice	60°	Solar altitude 20° Solar azimuth 90°	= solar azimuth	L:K Ratio 1:1 ~ 1:2
Double axis tracking (for HCPV and LCPV)	Solar altitude reaches 20°, on winter solstice	70°	Solar altitude 20° Solar azimuth 90°	= solar azimuth	L:K Ratio 1:1 ~ 1:2
Equatorial Coordinates					
Type of operation	S-N distance	Array tilt	E-W distance	Array tilt	Remarks
Horizontal E-W tracking	NA		Solar altitude 20° Solar azimuth 90°	60°	
Tilted E-W tracking	75 % day length, or 9:00am to 3:00pm on winter solstice	$1/2 \varphi$	Solar altitude 20° Solar azimuth 90°	60°	
Pole-axis tracking (for flat-plate panels)	75 % day length, or 9:00am to 3:00pm on winter solstice	φ	Solar altitude 20° Solar azimuth 90°	60°	
Pole-axis tracking (for line-focus LCPV)	75 % day length, or 9:00am to 3:00pm on winter solstice	φ	Solar altitude 20° Solar azimuth 90°	70°	
Double axis tracking (for flat-plate panels)	75 % day length, or 9:00am to 3:00pm on winter solstice	$\varphi+23,45$	Solar altitude 20° Solar azimuth 90°	60°	
Double axis tracking (for HCPV and LCPV)	Solar altitude reaches 20°, on winter solstice	$\varphi+23,45$	Solar altitude 20° Solar azimuth 90°	70°	

7 Land use calculations for fixed PV arrays on flat land (Figure 7)



IEC

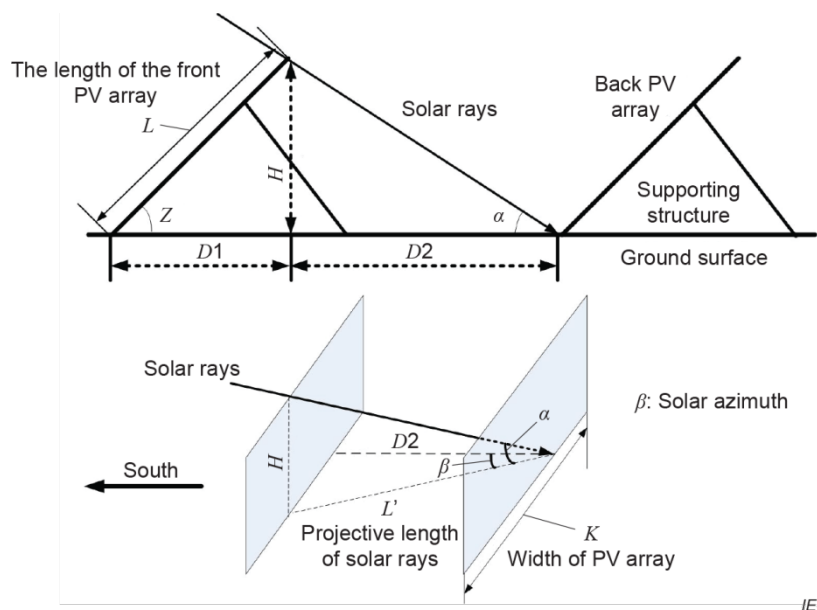
Figure 7 – Fixed PV array on flat land

7.1 Boundary conditions

- a) Fixed PV arrays faces to the south;
- b) No need for calculation of *E-W* distance, just calculate the *S-N* distance between arrays;
- c) No-shading period is based on 75 % of day length on winter solstice;
- d) The arrays are installed on flat land, not sloped land.

7.2 Calculation models for the fixed PV arrays on flat land

Figure 8 shows the relationship of solar beam and PV array and the distance between arrays.



IEC

Figure 8 – Relationship of solar beam and PV array

From Figure 8:

$$D1 = L \times \cos Z, H = L \times \sin Z$$

$$D2 = \cos\beta \times L', L' = H / \tan\alpha$$

S-N distance between arrays:

$$D = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) \times \cos\beta / \tan\alpha$$

where

β is solar azimuth;

α is solar altitude;

L' is shading distance behind PV arrays produced by solar beam;

H is the height of front PV arrays

L is the length of PV array;

Z is the tilted angle of PV array;

K is the width of PV array.

Formula of solar altitude α :

$$\sin\alpha = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega$$

Formula of solar azimuth β :

$$\cos\beta = (\sin\varphi \sin\alpha - \sin\delta) / (\cos\alpha \cos\varphi)$$

where

φ is the latitude of the location;

δ is the solar declination, $-23,45^\circ$ on winter solstice;

ω is the solar hour angle.

7.3 Example of land usage for fixed PV arrays on flat land

Location: Anywhere (if the latitude is the same, the calculation is the same)

Latitude φ : $36,25^\circ N$

Fixed PV arrays facing to the south

Date: on winter solstice, solar declination $\delta = -23,45^\circ$

No-shading set time: hour angle $\omega = 53,59^\circ$ at 8:25:38am (75 % of day length)

Day length of winter solstice (from sunrise to sunset): 9,53 h

Sunrise at 7:14:11 (solar time)

Solar altitude $\alpha = 11,76^\circ$ at 8:25:38 am (solar time)

Solar azimuth $\beta = 48,95^\circ$ at 8:25:38 am (solar time)

Array azimuth $\gamma = 0^\circ$

Tilted angle of array: $36,25^\circ$

255 W C-Si Module: Length = 1,685 m, Width = 0,997 m, Module efficiency = 15,18 %

Module configuration of PV Array: 4 in length: $L = 3,988$ m; 22 in width: $K = 37,07$ m and 88 modules in total.

Rated power of array: 22,44 kW

Calculation results:

Relative height $H = L \times \sin Z = 3,988 \times \sin 36,25^\circ = 2,358$ m

$D1 = 3,216$ m, $D2 = 7,44$ m

Distance = $D1 + D2 = 10,65$ m

Array width $K = 37,07$ m

Net land occupation = $394,96$ m²

PV array = 22,44 kW

Unit land occupation = $17,60$ m² /kW

Considering the gap between PV modules, the gap between PV arrays and the road within PV farm and the inverter/transformer areas within the PV farm, an additional 15 % of land is required. So the final unit land usage of PV farm is:

$$17,60 \text{ m}^2 / \text{kW} \times 1,15 = 20,24 \text{ m}^2 / \text{kW}$$

NOTE The land usage outside the PV farm by control buildings, warehouse, high-voltage transformer station, living areas and surrounding fence is not included.

8 Special consideration of non-south direction and sloped land

8.1 General

Where the PV array does not face directly south and/or the land is not horizontal, the calculation needs to be changed as follows.

8.2 Boundary conditions

- Fixed PV arrays and face to $\pm 15^\circ$ of the south;
- No-shading between arrays during 75 % of day length on winter solstice;
- The arrays are installed on sloped land;

d) The relative height between arrays is known.

8.3 Calculation models

Figure 9 shows the relationship of solar beam and PV array and the distance between arrays:

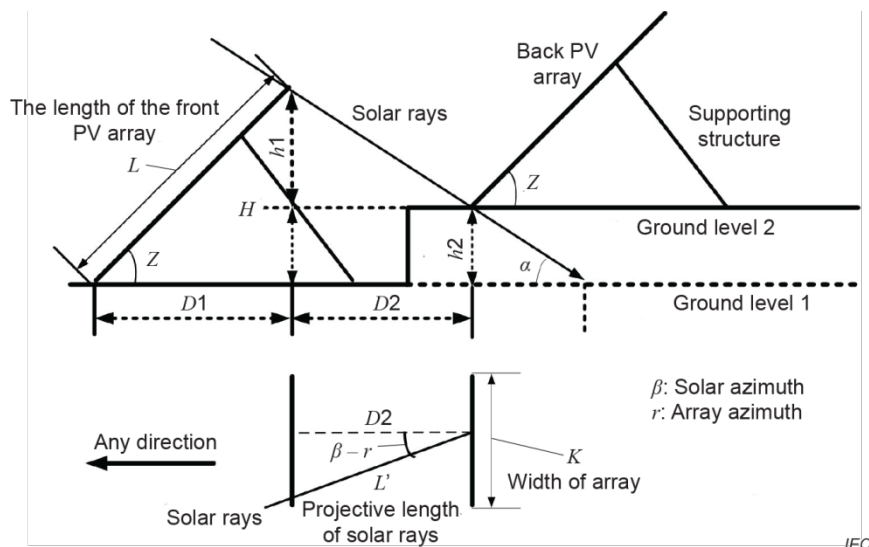


Figure 9 – Relationship of solar beam and PV array and the distance between arrays

From Figure 9:

$$D1 = L \times \cos Z$$

$$H = L \times \sin Z = h1 + h2, h1 = H - h2$$

$$D2 = \cos(\beta - r) \times L', L' = h1 / \tan \alpha$$

$$\text{Distance } D = D1 + D2 = (L \times \cos Z) + (L \times \sin Z - h2) \times \cos(\beta - r) / \tan \alpha$$

where

β is the solar azimuth;

γ is the array azimuth;

α is the solar altitude;

L' is the shading distance behind PV arrays produced by solar beam;

H is the height of front array $H = h1 + h2$;

$h1$ is the relative height between arrays;

$h2$ is the height difference of the land (available);

L is the length of PV array;

Z is the S-N tilted angle of PV array;

K is the width of PV array.

Formula of solar altitude α :

$$\sin \alpha = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega$$