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TECHNICAL REPORT

colour inside

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

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

FOREWORD

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IEC TR 63149, which is a technical report, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

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- withdrawn,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.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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 fomulas 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 cosθ (θ is incidence angle), so the cosine losses coefficient is equal to 1-cosθ

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 h = 360° 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° 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 $\beta \leq 90°$) or $\cos\beta = (\sin\varphi\sin\alpha - \sin\delta)/(\cos\alpha\cos\varphi)$ (for $\beta = 0$ -180°).

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° 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° on summer solstice in the northern hemisphere and a minimum of -23,45° 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

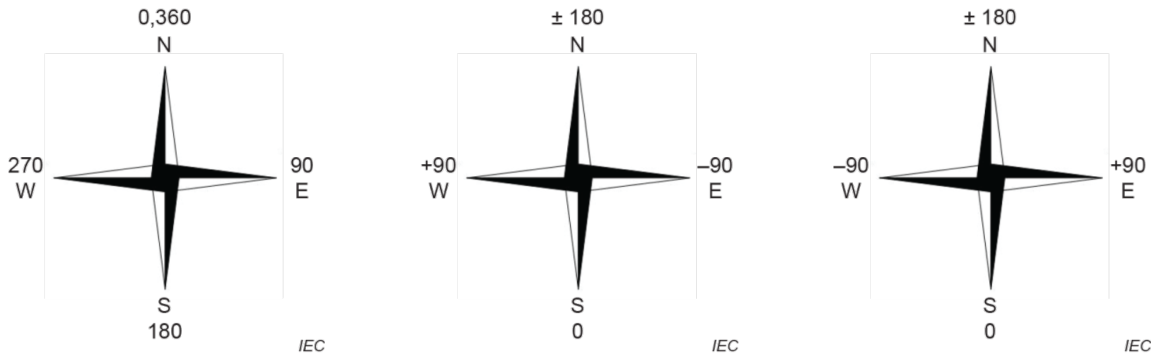
+4 x (longitude of local standard time – local longitude).

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:



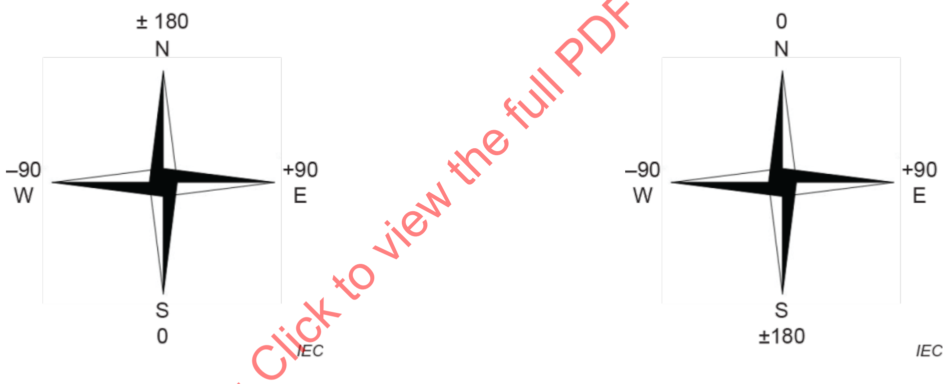
a) **Clockwise**
Origin is due north

b) **Clockwise**
Meridian plane and origin is due south

c) **Counterclockwise and origin is due south**

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 β) and hour-angle formula (cos ω) are always positive, never negative. Solar hour-angle, solar azimuth and PV array azimuth all follow the same definition, see Figure 2.



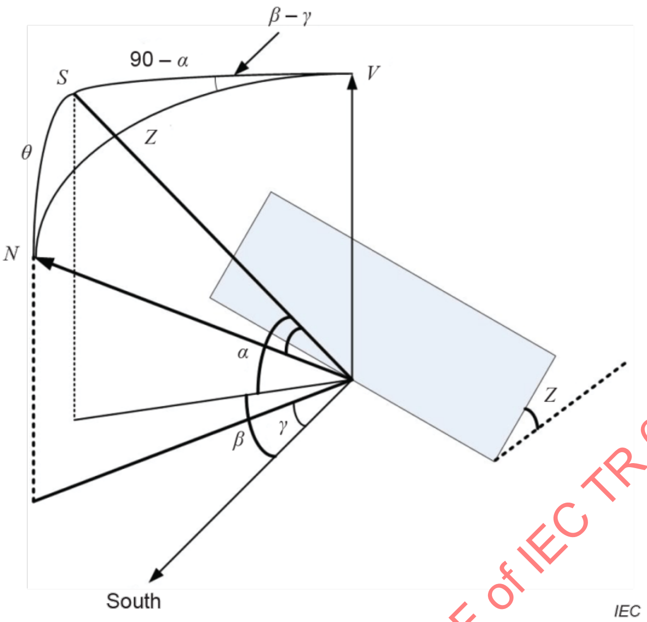
Northern hemisphere **Southern hemisphere**

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

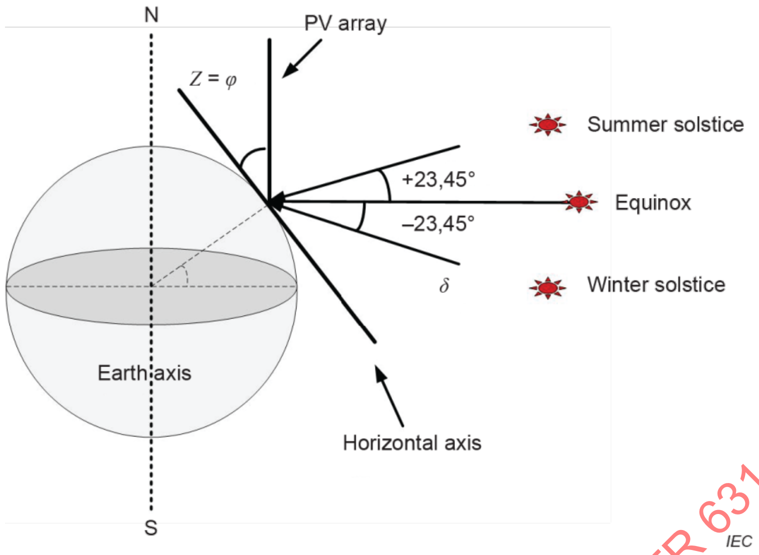
r PV array azimuth

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*)



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 ± 23,45° during a year

Figure 4 – PV array in equatorial coordinates

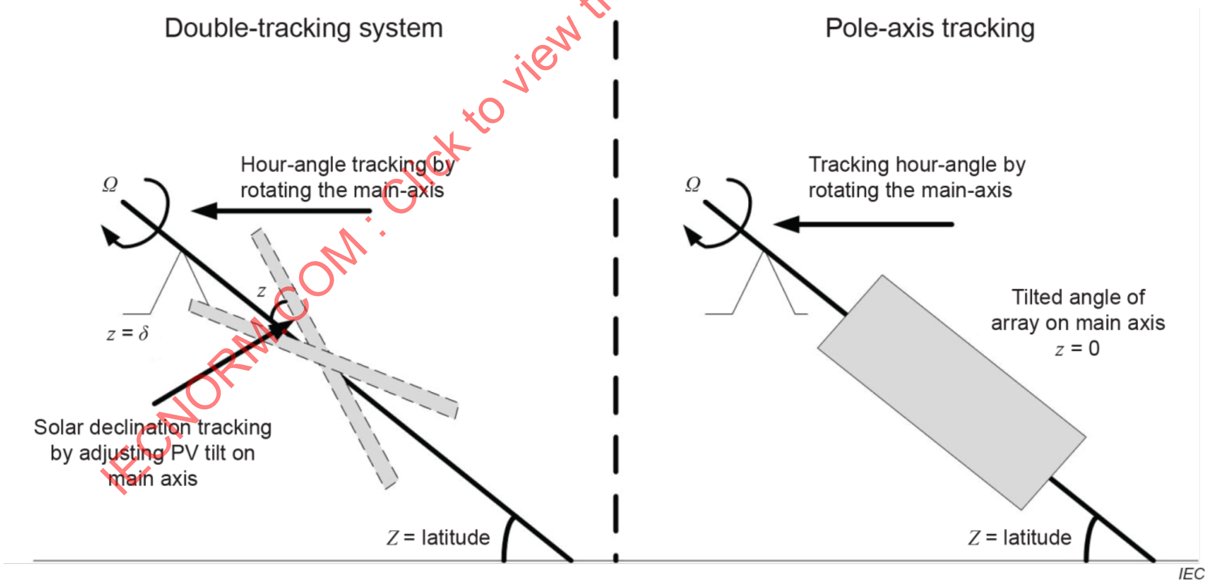
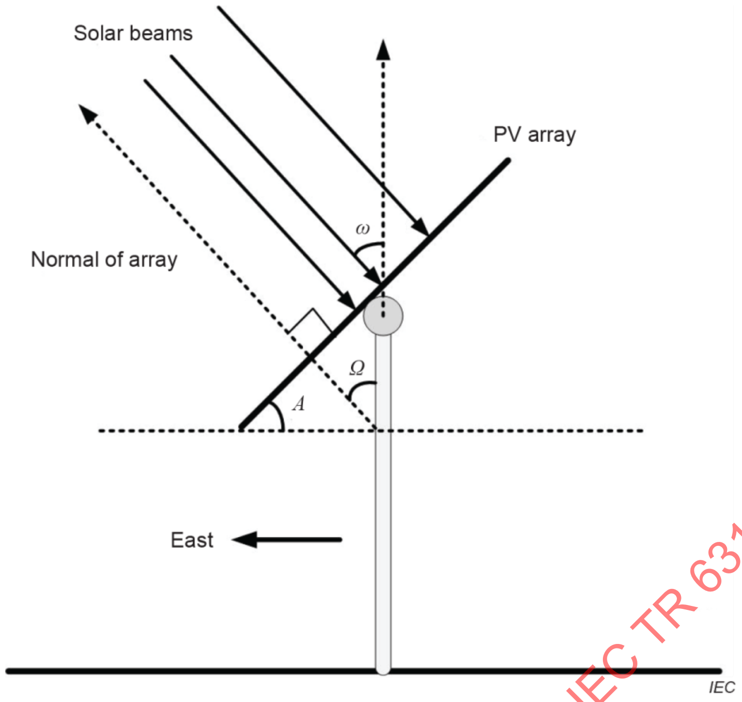


Figure 5 – Equatorial tracking systems

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 (≥ 35°) 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 ω °	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 φ	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	φ+23,45	Solar altitude 20° Solar azimuth 90°	60°	
Double axis tracking (for HCPV and LCPV)	Solar altitude reaches 20°, on winter solstice	φ+23,45	Solar altitude 20° Solar azimuth 90°	70°	

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

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.

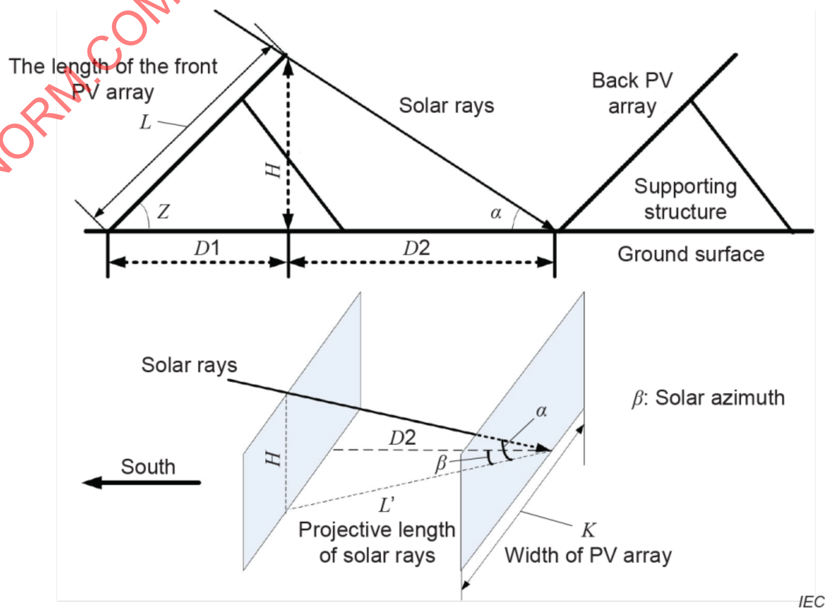


Figure 8 – Relationship of solar beam and PV array

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° 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° N

Fixed PV arrays facing to the south

Date: on winter solstice, solar declination δ = –23,45°

No-shading set time: hour angle ω = 53,59° 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 α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Array azimuth γ = 0°

Tilted angle of array: 36,25°

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 × sin 36,25° = 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 m^2

PV array = 22,44 kW

Unit land occupation = 17,60 m^2 /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 surounding 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

a) Fixed PV arrays and face to ±15° of the south;

b) No-shading between arrays during 75 % of day length on winter solstice;

c) 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:

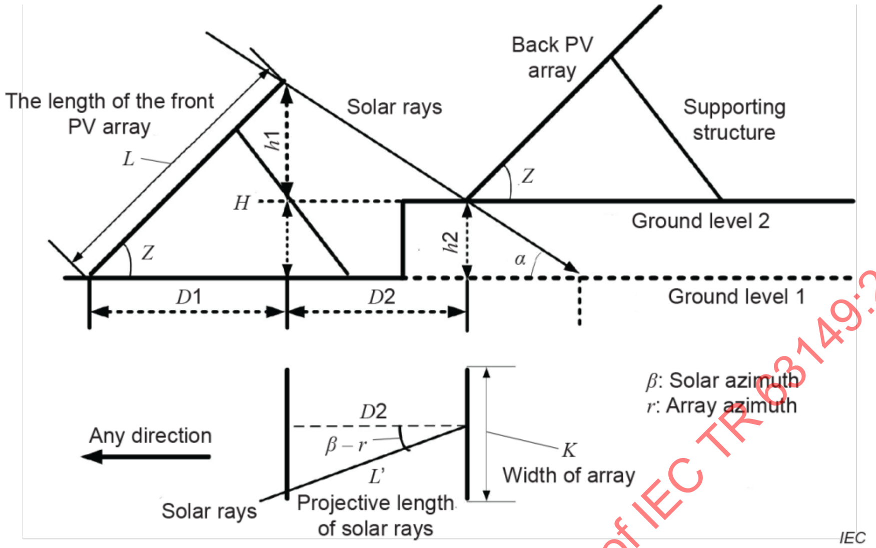


Figure 9 – Relationship of solar beam and PV array and the distance between arrays

From Figure 9:

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

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

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

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

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 eight 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:

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

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;

ω is the solar hour angle.

8.4 Example for fixed PV arrays with non-south direction

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

Latitude: 36,25° N

Fixed PV arrays and face to 10° deviate from the south

Date: on winter solstice, solar declination δ = –23,45°

No-shading set time: hour angle ω = 53,59° at 8:25:38am (75 % of daylength)

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

Sunrise at 7:14:11 (solar time)

Solar altitude α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Array azimuth γ = 10°

Tilted angle of array Z = 36,25°N

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:

$H = L \times \sin Z$ = 3,988 × sin 36,25 = 2,358 m

$\beta - \gamma$ = 38,95°

$D1$ = 3,216 m

$D2$ = 8,809 m

Distance = $D1+D2$ = 12,025 m

Array width K = 37,07 m

Net land occupation = 445,759 m^2

PV array = 22,44 kW

Unit land occupation = 19,86 m^2 /kW (this is larger land usage than the example facing to the south).

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:

19,86 m^2 / kW x 1,15 = 22,84 m^2 / kW

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

8.5 Example for fixed PV arrays on sloped land

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

Latitude: 36,25° N

Fixed PV arrays and face to the south

Date: on winter solstice, solar declination δ = -23,45°

No-shading set time: hour angle ω = 53,59° at 8:25:38am (75 % of daylength)

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

Sunrise at 7:14:11 (solar time)

Solar altitude α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Array azimuth γ = 0°

$h2$ = 0,4 m (the relative height between arrays)

Tilted angle of array Z = 36,25°N

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

$H = L \times \sin Z$ = 3,988 × sin 36,25 = 2,358 m

$h1 = H - h2$ = 2,358 – 0,4 = 1,958 m

Calculation results:

$D1$ = 3,216 m

$D2$ = 6,177 m

Distance = $D1+D2$ = 9,393 m

Array width K = 37,07 m

Net land occupation = 348,188 m^2

PV array = 22,44 kW

Unit land occupation = 15,516 m^2 / kW (it is less land usage than flat land)

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:

15,52 m^2 / kW x 1,15 = 17,84 m^2 / kW

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

9 Land usage for solar altitude tracking in ground horizontal coordinates (Figures 10 and 11)

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Figure 10 – Manual adjusted supporting structure

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Figure 11 – Manual adjusted PV array

9.1 Boundary conditions

a) Solar altitude tracking system in ground horizontal coordinates only tracks the solar altitude by adjusting PV tilt.

b) The azimuth of PV array faces to south at the location where the latitude is higher than the tropic line. For the location where the latitude is within the tropic line, PV azimuth may face to north during summer season.

c) This type of tracking system is often used as manual adjustment, not the automatic tracking.

d) PV tilt is adjusted to make incidence angle as small as possible to have lowest cosine losses during a year. The adjustment of PV tilt can be 2 times, 4 times or 6 times during a year. For certain locations, for example, in case of 2 times adjustment, the annual PV output will be 4,81 % higher than fixed PV arrays; for 4 times adjustment, the annual PV output will be 7,12 % higher than fixed PV arrays. For 6 times adjustment, the increased output of PV arrays is no more than 8,5 %, but too much work on adjustment. So, people use no more than 4 times adjustment to get more annual PV output with reasonable adjustment work. Please note that when we talk about shading distance, it is only relevent with local latitude, but when we talk about PV energy output, it is not only relevent with latitude, but also relevent with local climate, elevation, irradiation level, direct and diffuse irradiation ratio, etc., the energy output is different location by location.

e) The caculation model for the manual adjustment is the same with the fixed array. It only needs to consider the maximum tilted angle of PV arrays on winter solstice. See Table 4.

Table 4 – Adjustment rules for solar altitude tracking

2 times adjustment with 2 tilted angles		**6 times adjustment with 4 tilted angles**	
Date of adjustment	Position and tilted angle	Date of adjustment	Position and tilted angle
Mar. 21	Position 1: Latitude – 12,0°	Mar. 21	Position 1: Latitude – 6,0°
Sep. 23	Position 2: Latitude + 12,0°	May 06	Position 2: Latitude – 18,0°
4-time adjustment with 3 tilted angles		Aug. 06	Position 2: Latitude – 6,0°
Date of adjustment	Position and tilted angle	Sep. 23	Position 3: Latitude + 6,0°
Apr. 20	Position 1: Latitude – 16,0°	Nov. 08	Position 4: Latitude + 18,0°
Aug. 21	Position 2: Latitude	Feb. 05	Position 3: Latitude + 6,0°
Oct. 23	Position 3: Latitude + 16,0°		
Feb. 20	Position 2: Latitude		

The principles for the adjustment of PV tilted angles are shown below:

Specific dates: Spring equinox is on March 21
Autumn equinox is on Sep. 23
Winter solstice is on Dec. 21
Summer solstice is on Jun. 21

And δ ≈ ± 24,00° during a year

If the tilt of PV array equals to the local latitude, the PV array will be in parallel with earth-pole.

1) 2 times adjustment is shown in Figure 12:

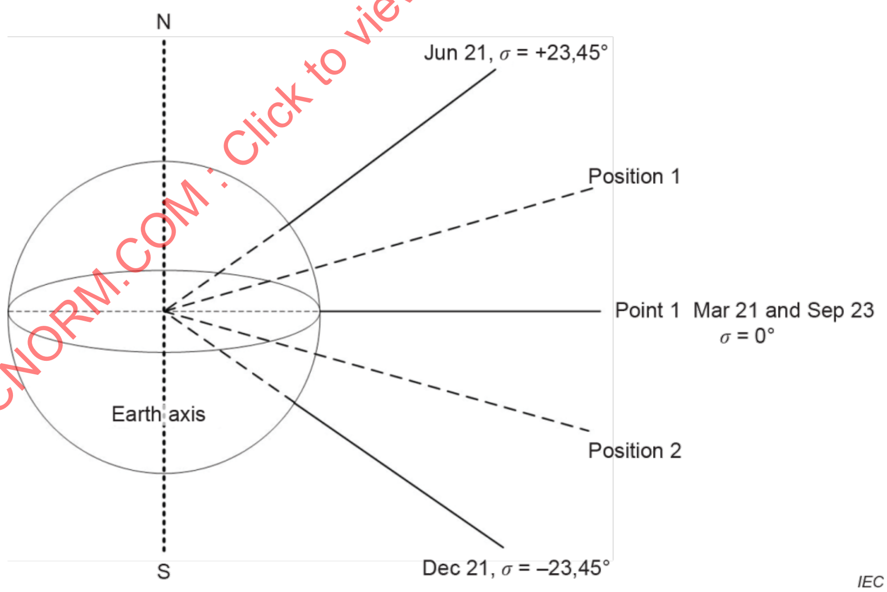

Figure 12 – 2 times adjustment rules

Process:

i) When the sun moves to Point 1 on Mar. 21, PV tilt is adjusted to Position 1 (latitude – 12°);

ii) When the sun turns back to Point 1 on Sep. 23, PV tilt is adjusted to Position 2 (Latitude + 12°);

iii) When the sun runs to Point 1 again on Mar. 21 next year, PV tilt is adjusted to Position 1 again.

2) 4 times regulation is shown in Figure 13:

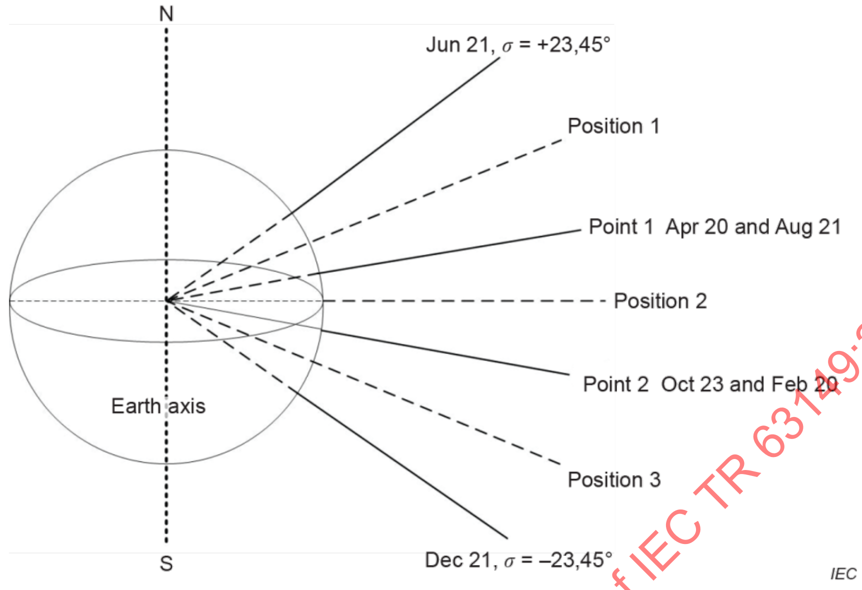

Figure 13 – 4 times adjustment rules

Process:

i) When the sun moves to Point 1 on Apr. 20, PV tilt is adjusted to Position 1 (latitude – 16°);

ii) When the sun turns back to Point 1 on Aug. 21, PV tilt is adjusted to Position 2 (Latitude);

iii) When the sun runs to Point 2 on Oct. 23, PV tilt is adjusted to Position 3 (latitude + 16°);

iv) When the sun goes back to Point 2 again on Feb. 20 next year, PV tilt is adjusted to Position 2 (Latitude);

v) The process goes to i) again.

9.2 Calculation models for solar altitude tracking

The calculation formula is the same as for fixed PV arrays:

$$D = D1 + D2,\ D1 = L \times \cos Z$$

$$D2 = \cos(\beta-\gamma) \times L'$$

$$L' = H / \tan\alpha,\ H = L \times \sin Z$$

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

9.3 Example of land usage for 4-times adjustment

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

Latitude: 36,25° N

Mannual regulated PV arrays and face to the south

Largest tilted angle on winter solstice: 36,25° + 16,0°

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 53,59° 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 α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Array azimuth γ = 0°

Tilted angle of array Z = 52,25°*N*

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 rower of array: 22,44 kW

Calculation results:

Relative height = 3,15 m

$D1$ = 2,44 m

$D2$ = 9,95 m

Distance = $D1$+$D2$ = 12,39 m

Array width K = 37,07 m

Net land occupation = 459,22 m^2

PV array = 22,44 kW

Unit land usage = 20,46 m^2 /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:

20,46 m^2 /kW x 1,15 = 23,53 m^2 /kW. The land usage is larger than ordinary fixed PV arrays (20,24 m^2 /kW), but the output will be 5 %-7 % higher than the fixed arrays.

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

10 Land usage calculation for horizontal *E*-*W* tracking in equatorial coordinates (Figure 14)

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Figure 14 – Horizontal *E*-*W* tracking

10.1 Boundary conditions

a) The PV modules are installed horizontally on the main axis and the *S*-*N* tilted angle of the modules is 0°. This is the single axis tracker, the main-axis tracks the solar hour angle, so it is only necessary to calculate the *E*-*W* distance between PV arrays and no need to calculate *S*-*N* no-shading distances.

b) The boundary condition: The longest *E*-*W* shading distance is at the time when the sun is in the east. The boundary condition for *E*-*W* distance set at solar altitude is 20° and the sun is in the east.

c) 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 tilted angle of the array is. The tilted angle of the array is also limited by the mechanical ability. In this document, the maximum *E*-*W* tilted angle of PV arrays is 60° for flat-plate PV modules and 70° for CPV systems.

d) The horizontal *E*-*W* tracking is only suitable for the regions below 35° latitude. For the locations where the latitude is higher than 35°N, the cosine losses will be too high during winter time because the solar altitude is too low in winter time.

10.2 Calculation models

The distance between PV arrays is shown in Figure 15.

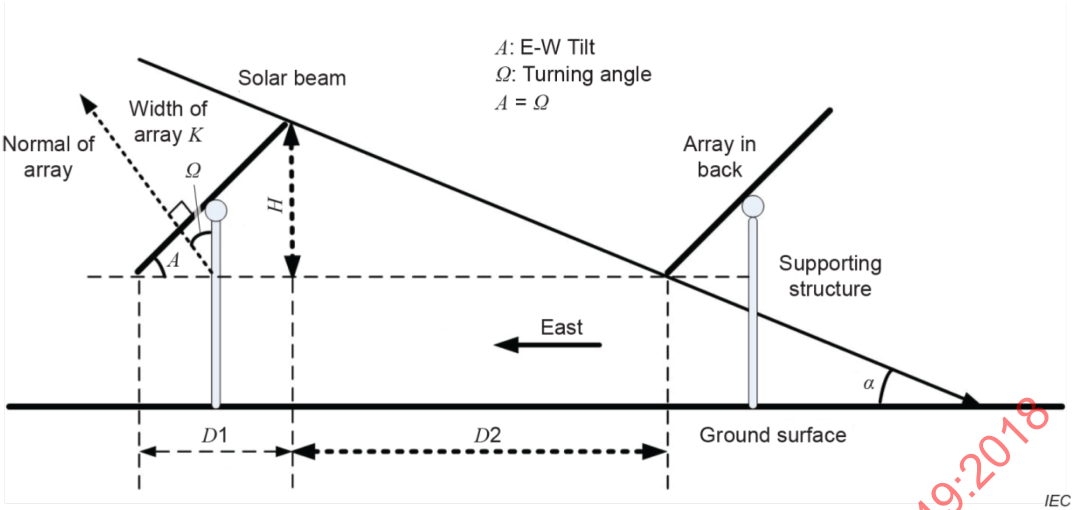

Figure 15 – Horizontal *E-W* tracking

$$D1 = K \times \cos A$$

$$D2 = H / \tan\alpha,\ H = K \times \sin A$$

$$D = D1 + D2 = (K \times \cos A) + (K \times \sin A) / \tan\alpha$$

$$\alpha = \arcsin(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega)$$

where

α is the solar altitude;

A is the E-W tilted angle of PV arrays;

H is the height of front PV arrays;

K is the width of PV array;

φ is the local latitude;

δ is the solar declination angle;

ω is the solar hour angle.

10.3 Example – Land usage for horizontal *E-W* tracking

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

Latitude:36,25° *N*

From Table 2, the right date and time can be found when the solar altitude is 20° and the sun is in the east:

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

Time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 60°

255 W C-Si Module: length is 1,68 m,width is 0,997 m, module efficiency is 15,18 %

Module configuration of PV array (see Figure 14 as example): 1 module installed in E-W direction, the width of the array: K = 1,68 m; 20 modules in series along the S-N main-axis, the length of the array is 19,94 m. 20 modules in total.

Total power is 5,1 kW

Calculation:

$$H = K \times \sin A = 1{,}68 \times \sin 60 = 1{,}45 \text{ m}$$

$$D2 = H / \tan \alpha = 1{,}45 / \tan 20 = 4{,}00 \text{ m}$$

The results: $D1$ = 0,84 m, $D2$ = 4,00 m,E-W distance between arrays is 4,84 m,knowing the length of arry is 19,94 m, so the pure land usage is 96,46 m^2.

The total power is 5,1 kW, the unit land usage is 19,25 m^2 / kW.

Considering the gap between PV modules, the road within the 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:

$$19{,}25 \times 1{,}15 = 22{,}14 \text{ m}^2 / \text{kW}$$

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

11 Land usage for pole-axis tracking (Figure 16)

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(a) (b)

Figure 16 – Pole-axis tracking

11.1 Boundary conditions

a) Pole-axis tracking is that the main axis is tilted equal to latitude. In this case, the main axis is parallel with the earth pole.

b) The PV modules are installed on tilted main axis. The main axis rotates to track the hour angle from east to west. For such trackers, it is not only necessary to consider the *E-W* distance between arrays, but also the *S-N* distance.

c) For *S-N* no-shading distance, the condition is set at the time of 75 % of day length or from 9:00am to 3:00pm on winter solstice. The calculation formula is the same with fixed PV arrays since *S-N* tilt of main axis never changes.

d) For *E-W* no-shading distance, the condition is set at 20° of solar altitude and the sun is in the east. The calculation formula is the same with horizontal *E-W* tracking since solar beams are all in parallel.

e) The pole-axis tracking is suitable for any latitude. There is no problem of higher cosine losses in winter for the places at high latitude.

11.2 The calculation for *E-W* distance

The calculation of *E-W* distance is the same as the horizontal *E-W* tracking system.

The distance between arrays is shown in Figure 15 which is for horizontal *E-W* tracking.

See Figure 16 (b) as example.

The boundary conditions for *E-W* distance calculation are as follows:

$$D1 = K \times \cos A$$

$$D2 = H / \tan\alpha,\ H = K \times \sin A$$

$$D = D1 + D2 = (K \times \cos A) + (K \times \sin A) / \tan\alpha$$

$$\alpha = \arcsin(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega)$$

Latitude:36,25° *N*

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

Time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 60°

255 W C-Si Module: length is 1,68 m, width is 0,997 m, efficiency is 15,18 %

Module configuration of PV array: 1 module installed in E-W direction, the width of the array: K = 0,997 m; 4 modules are installed along the S-N main-axis, the length of the array is 6,72 m. 4 modules in total.

Total power is 1,02 kW

The calculation results:

$$D2 = H / \tan\alpha = 2{,}37 \text{ m } (H = 0{,}86 \text{ m}, \alpha = 20°)$$

$$D1 = K \times \cos A = 0{,}997 \times \cos 60° = 0{,}499 \text{ m}$$

The E-W distance between arrays: $D = D1 + D2 = 2{,}87$ m.

11.3 The calculation for *S-N* distance

The calculation of S-N distance is the same as for the fixed PV arrays, the S-N tilted angle of PV array is always the same during operation.

The distance between arrays is shown in Figure 8 which is for the fixed PV arrays.

See Figure 16 (b) as example.

The boundary conditions for S-N distance calculation are as follows:

From Figure 8:

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

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

South-North distance between arrays:

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

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

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

where

β is the solar azimuth;

α is the solar altitude;

L' is the 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 S-N tilted angle of main axis.

11.4 Example 1: no-shading distance is set within 75 % day length on winter solstice

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

Latitude φ: 36,25° N

Main axis of PV arrays is facing to the south

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 53,59° 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 α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Main axis azimuth γ = 0°

Tilted angle of array: 36,25°

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

Module configuration of PV array: 1 moduls installed in E-W direction, the width of the array: K = 0,997 m; 4 modules are installed along the S-N main-axis, the length of the array is 6,72 m. 4 modules in total.

Total power is 1,02 kW

Calculation results:

Relative height H = 3,97 m

L' = 19,09 m

$D1$ = 5,42 m, $D2$ = 12,53 m,

S-N Distance $D = D1 + D2$ = 17,95 m

11.5 Example 2: no-shading period is from 9:00am to 3:00pm on winter solstice

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

Latitude φ: 36,25° N

Main axis of PV arrays is facing to the south

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 45,00° at 9:00:00am (solar time).

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

Sunrise at 7:14:11 (solar time)

Solar altitude α = 16,73°

Solar azimuth β = 42,64°

Main axis azimuth γ = 0°

Tilted angle of array: 36,25°

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

Module configuration of PV array: 1 moduls installed in *E*-*W* direction, the width of the array: K = 0,997 m; 4 modules are installed along the *S*-*N* main-axis, the length of the array is 6,72 m. 4 modules in total.

Total power is 1,02 kW

Calculation results:

Relative height H = 3,97 m

L' = 13,22 m

$D1$ = 5,42 m, $D2$ = 9,73 m,

S-*N* Distance $D = D1 + D2$ = 15,15 m

11.6 Example 3: Calculation for high-efficiency PV modules

285 W C-Si Module: Length = 1,665 m, Width = 0,992 m, Module efficiency = 17,26 % (11,37 % higher than 255 W modules).

Module configuration of PV array: 1 module is installed in *E*-*W* direction, the width of the array: K = 0,992 m; 4 modules are installed along the *S*-*N* main-axis, the length of the array is 6,66 m. 4 modules in total.

Total power is 1,14 kW

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

Latitude φ: 36,25° *N*

S-*N* distance calculation:

Main axis of PV arrays is facing to the south

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 45,00° at 9:00:00am (solar time)

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

Sunrise at 7:14:11 (solar time)

Solar altitude α = 16,73°

Solar azimuth β = 42,64°

Main axis azimuth γ = 0°

Tilted angle of array: 36,25°

Relative height H = 3,94 m

L' = 13,10 m

$D1$ = 5,37 m, $D2$ = 9,64 m,

S-N Distance $D = D1 + D2$ = 15,01 m

E-W distance calculation:

$D1 = K \times \cos A$

$D2 = H / \tan\alpha$, $H = K \times \sin A$

$D = D1 + D2 = (K \times \cos A) + (K \times \sin A) / \tan\alpha$

$\alpha = \arcsin(\sin\varphi\sin\delta+\cos\varphi\cos\delta\cos\omega)$

Latitude:36,25° N

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

Time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 60°

Array width: K = 0,992 m

The calculation results:

$D2 = H / \tan\alpha$ = 2,36 m (H = 0,859 m, α = 20°)

$D1 = K \times \cos A$ = 0,992 × cos 60° = 0,496 m

The E-W distance between arrays: $D = D1 + D2$ = 2,856 m.

11.7 Land usage for pole-axis tracking

Example 1: no-shading period is set within 75 % day length on winter solstice

The *E*-*W* distance between arrays is 2,87 m, and the *S*-*N* distance is 17,95 m, so the total land usage of PV array is 51,52 m^2.

The array power is 1,02 kW, the unit land usage is 50,51 m^2 / kW.

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

$$50{,}51 \times 1{,}15 = 58{,}09 \text{ m}^2 / \text{kW}$$

Example 2: no-shading period is from 9:00am to 3:00pm on winter solstice

The *E*-*W* distance between arrays is 2,87 m, and the *S*-*N* distance is 15,15 m, so the total land usage of PV array is 43,47 m^2.

The array power is 1,02 kW, the unit land usage is 42,61 m^2 / kW.

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

$$42{,}61 \times 1{,}15 = 49{,}01 \text{ m}^2 / \text{kW}$$

Example 3: Calculation for high-efficiency PV modules

The *E*-*W* distance between arrays is 2,856 m, and the *S*-*N* distance is 15,01 m, so the total land usage of PV array is 42,87 m^2.

The array power is 1,14 kW, the unit land usage is 37,60 m^2 / kW. (11,76 % less land usage than low-efficiency PV modules)

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

$$37{,}60 \times 1{,}15 = 43{,}24 \text{ m}^2 / \text{kW}$$

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

12 Land usage calculation for double-axis tracking in equatorial coordinates (Figure 17)

Figure 17 – Double tracking systems (hour-angle and solar declination)

12.1 Boundary conditions

a) Double axis tracking in equatorial coordinates should track both solar declination and solar hour angle, so it is not only necessary to consider the *E*-*W* distance between arrays, but also the *S*-*N* distance.

b) For double-axis tracking, PV modules shall track the solar declination δ by adjusting *S*-*N* tilt of PV modules, which changes only about 0,25° per day. On winter solstice, the *S*-*N* tilte equals to local latitude plus 23,45° and the tilt will not change all day. So, *S*-*N* distance calculation is the same as fixed PV arrays.

c) For *S*-*N* no-shading distance, the condition is set at the time of 75 % of day length or from 9:00am to 3:00pm on winter solstice. The calculation formula is the same with fixed PV arrays since *S*-*N* tilt of PV modules is never changed during the day of winter solstice.

d) For *E*-*W* distance calculation, it is based on 20° of solar altitude and the sun is in the east. The calculation formula is the same with horizontal *E*-*W* tracking since solar beams are all in parallel.

e) Equatorial double-axis tracking is usually used for concentrating PV (CPV), the no-shading distance calculation is the same with flat-plate modules, but the boundary conditions are different. The examples in this document are for flat-plate modules.

12.2 Calculation model for *E*-*W* distance

The calculation of *E*-*W* distance is the same as the horizontal *E*-*W* tracking system.

The distance between arrays is shown in Figure 15 which is for horizontal *E*-*W* tracking.

The boundary conditions for *E*-*W* distance calculation are as follows:

$$D1 = K \times \cos A$$

$$D2 = H / \tan\alpha,\ H = K \times \sin A$$

$$D = D1 + D2 = (K \times \cos A) + (K \times \sin A) / \tan\alpha$$

$$\alpha = \arcsin(\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega)$$

Latitude: 36,25° N

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

Time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 60°

See Figure 17 as example.

Take flat-plate PV modules as calculation model: 255 W C-Si Module: length is 1,68 m,width is 0,997 m, efficiency is 15,18 %.

Like in Figure 17, two modules installed in parallel in E-W direction, the width of the array: K = 1,994 m; two rows of 2 modules along the S-N main-axis, the length of the array: L = 3,36 m. 4 modules in total in one block. Total power of the block is 1,02 kW. 10 blocks make a PV array and the total power of one array is 10,2 kW with 40 modules in total.

Calculation results:

$$K = 1{,}994 \text{ m},\ Z = 60°,\ H = 1{,}73 \text{ m}$$

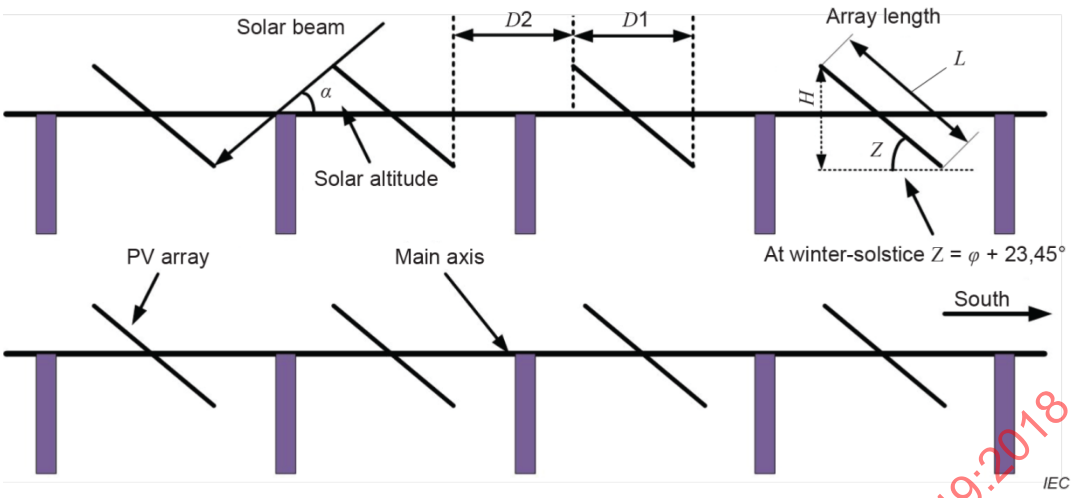
$$D2 = H / \tan\alpha = 4{,}74 \text{ m}$$

$$D1 = K \times \cos A = 0{,}997 \text{ m}$$

The E-W distance between arrays is $D = D1 + D2$ = 5,74 m.

12.3 Caculation for S-N distance

The south-north distance between arrays is as shown in Figure 18:



From sunrise to sunset, the main axis will rotate to follow the solar hour angle.

The PV array will face to the sun within 75 % of day-length or from 9:00 to 3:00 pm.

On certain days PV array will have the same S-N tilted angle from sunrise to sunset.

On winter solstice, the S-N tilt of PV array is: Z = φ + 23,45°.

E-W distance between PV array: follow the same rule of horizontal E-W tracking.

S-N distance between PV arrays: follow the same rule of fixed PV arrays.

Figure 18 – PV array and solar beam for double-axis tracking

The *S-N* distance between PV modules (*D*) is as follows:

$$D = D1 + D2$$

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

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

$$H = L \times \sin Z$$

South-North distance between arrays:

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

where

β is the solar azimuth;

α is the solar altitude;

L' is the 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 *S-N* tilted angle of PV array;

K is the width of PV array.

Formula of solar altitude α: $\sin\alpha = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega$

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° on winter solstice;

ω is the hour angle.

12.4 Example 1: no-shading distance is set within 75 % day length on winter solstice

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

Latitude φ: 36,25° N

Main axis of PV arrays is facing to the south.

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 53,59° 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 α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Main axis azimuth γ = 0°

S-N tilted angle of array: $Z = \varphi$ + 23,45° = 59,7°

255 W C-Si Module: length is 1,68 m,width is 0,997 m, efficiency is 15,18 %.

Like in Figure 17, two modules installed in parallel in E-W direction, the width of the array: K = 1,994 m; two rows of 2 modules along the S-N main-axis, the length of the array: L = 3,36 m. 4 modules in total in one block. Total power of the block is 1,02 kW.

Calculation results:

$$L = 3{,}36 \text{ m}, Z = 59{,}7°, \tan\alpha = 0{,}208$$

$$H = L \times \sin Z = 2{,}901 \text{ m}, L' = H / \tan\alpha = 13{,}934 \text{ m}$$

$$D1 = L \times \cos Z = 1{,}695 \text{ m}, D2 = \cos\beta \times L' = 9{,}150 \text{ m}$$

The S-N distance between blocks $D = D1 + D2$ = 10,846 m.

12.5 Example 2: no-shading period is from 9:00am to 3:00pm on winter solstice

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

Latitude φ: 36,25° N

Main axis of PV arrays is facing to the south.

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 45,00° at 9:00:00am (solar time).

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

Sunrise at 7:14:11 (solar time)

Solar altitude α = 16,73°

Solar azimuth β = 42,64°

Main axis azimuth γ = 0°

S-N tilted angle of array: $Z = \varphi$ + 23,45° = 59,7°

Array azimuth γ = 0°

255 W C-Si Module: length is 1,68 m,width is 0,997 m, efficiency is 15,18 %.

Like in Figure 14, two modules installed in parallel in E-W direction, the width of the array: K = 1,994 m; two rows of 2 modules along the S-N main-axis, the length of the array: L = 3,36 m. 4 modules in total in one block. Total power of the block is 1,02 kW.

Calculation results:

$$H = L \times \sin Z = 2{,}901 \text{ m},\ L' = H / \tan\alpha = 9{,}652 \text{ m}$$

$$D1 = L \times \cos Z = 1{,}695 \text{ m},\ D2 = \cos\beta \times L' = 7{,}101 \text{ m}$$

The S-N distance between blocks $D = D1 + D2$ = 8,796 m.

12.6 Land usage for equatorial double-axis tracking

Example 1: no-shading puriod is set within 75 % day length on winter solstice

The E-W distance between arrays is 5,74 m, and the S-N distance is 10,85 m, so the total land usage of PV array is 62,25 m^2.

The array power is 1,02 kW, the unit land usage is 61,03 m^2 / kW.

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

$$61{,}03 \times 1{,}15 = 70{,}19 \text{ m}^2 / \text{kW}$$

Example 2: no-shading period is from 9:00am to 3:00pm on winter solstice

The E-W distance between arrays is 5,74 m, and the S-N distance is 8,796 m, so the total land usage of PV array is 50,49 m^2.

The array power is 1,02 kW, the unit land usage is 49,50 m^2 / kW.

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

$$49{,}50 \times 1{,}15 = 56{,}92\ m^2 / kW$$

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

13 Land usage calculation for tilted *E*-*W* tracking

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Figure 19 – Tilted *E*-*W* tracking (horizontal main axis)

13.1 Boundary conditions

a) The tilted *E*-*W* tracking is that the main axis is horizontal and the PV modules are installed on the horizontal main axis with a fixed tilted angle (refer to Figure 19).

b) The main-axis rotates to track the hour angle from east to west. For such trackers, it is not only necessary to consider the *E*-*W* distance between arrays, but also the *S*-*N* distance between PV modules on main axis;

c) For *S*-*N* distance calculation, it should be based at noon time when PV module has the largest tilted angle during a day. At sunrise time, the *S*-*N* tilted angle of PV module is zero.

d) The optimized *S*-*N* tilted angle of PV module on the horizontal main axis is equal to 1/2 latitude.

e) For *E*-*W* distance calculation, it is based on 20° of solar altitude and the sun is in the east. The maximum *E*-*W* tilt of PV array (*A*) is 60°. The calculation formula is the same with horizontal *E*-*W* tracking since solar beams are all in parallel.

13.2 Why optimized *S*-*N* tilt is equal to 1/2 latitude

The smaller of the incidence angle is the less of cosine losses of solar power. The average incidence angle is calculated for different latitudes and typical days (equinox, winter solstice and summer solstice). For typical days, the average incidence angle is the average value between sunrise time and noontime. The calculation results are given in Table 5.

Table 5 – Annual average incidence angle for different latitudes and different tilts

Latitude	Tilt	Annual average incidence angle θ	Latitude	Tilt	Annual average incidence angle θ
0	0	15,63	30	0	24,12
0	0	15,63	30	15	21,94
0	0	15,63	30	30	22,82
10	0	17,43	36,25	0	27,98
10	5	17,43	36,25	18,125	23,72
10	10	17,43	36,25	36,25	25,94
20	0	19,50	40	0	30,43
20	10	19,50	40	20	24,92
20	20	19,50	40	40	27,82

For the places within tropic line, just putting PV arrays horizontally, since the annual average incidence angle is the same for different tilts, means the cosine losses are the same whether PV array has tilt or not. For the places outside of tropic line, the optimized tilt of PV array is 1/2 latitude to get the smallest incidence angle, to have lowest cosine losses during a year.

13.3 The calculation model for *E-W* distance

The calculation of east-west distance is the same as for the horizontal *E-W* tracking system.

The distance between arrays is shown in Figure 20:

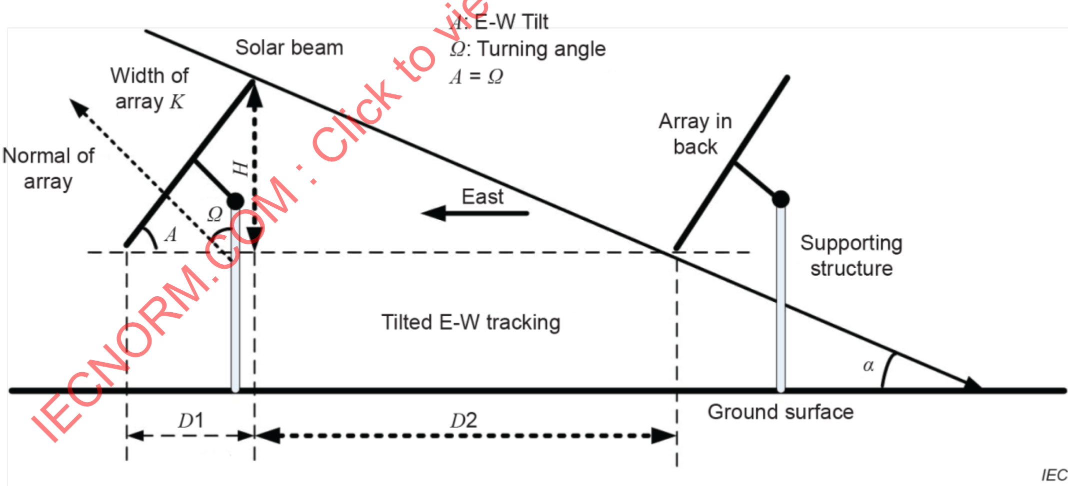


Figure 20 – *E-W* distance for tilted *E-W* tracking

13.4 Example of *E-W* distance calculation

The calculation formulas are the same as the horizontal *E-W* tracking system.

The distance between arrays is shown in Figure 20.

The boundary conditions for *E-W* distance calculation are as follows:

$$D1 = K \times \cos A$$

$$D2 = H / \tan\alpha,\ H = K \times \sin A$$

$$D = D1 + D2 = (K \times \cos A) + (K \times \sin A) / \tan\alpha$$

$$\alpha = \arcsin(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega)$$

Latitude: 36,25° N

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

Time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 60°

See Figure 19 as example.

Take flat-plate PV modules as calculation model: 255 W C-Si Module: length is 1,68 m,width is 0,997 m, efficiency is 15,18 %.

Module configuration of PV array: like in Figure 19, 1 module installed in *E-W* direction, the width of the array: K = 1,68 m; the length of PV array is 0,997 m.

Calculation results:

$$K = 1{,}68\ \text{m},\ Z = 60°,\ H = 1{,}455\ \text{m}$$

$$D2 = H / \tan\alpha = 3{,}997\ \text{m}$$

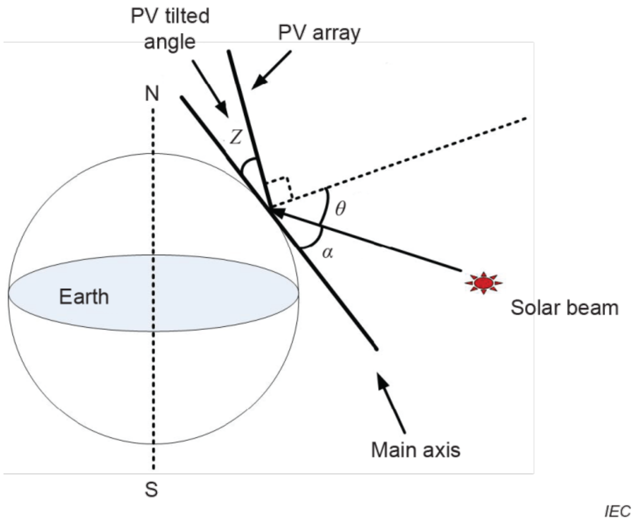
$$D1 = K \times \cos A = 0{,}84\ \text{m}$$

The *E-W* distance between arrays is $D = D1 + D2$ = 4,837 m.

13.5 The calculation model for *S-N* distance

Note that the south-north tilted angle of PV modules of this tracking system changes during tracking the hour angle. At noon time, the tilted angle is the largest one during a day. Therefore, the shading distance is calculated based on noon time. If the latitude is φ = 36,25°, the optimized *S-N* tilted angle of PV modules is equal to 1/2 of latitude, Z = 18,125°. See Figure 21.

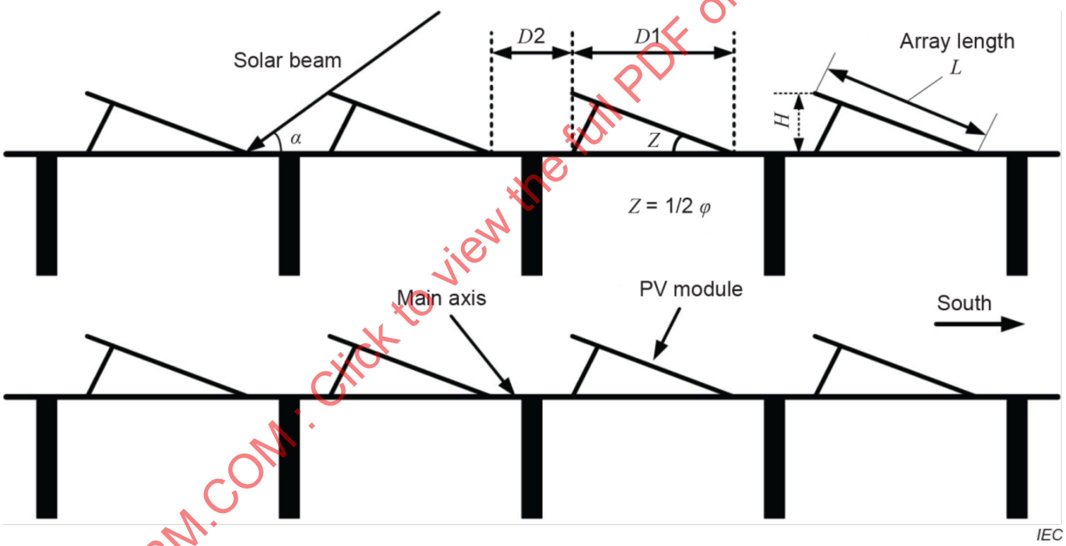
South-north distance between PV modules is shown in Figure 22:



The tilted angle of PV modules on horizontal main axis is equal to ½ latitude.

At noon time, the tilted angle is the highest during the day, so the S-N no-shading distance is calculated at noon time.

Figure 21 – The relationship between PV array and solar beam



The largest S-N tilted angle of the PV modules is at noon time during a day.

The optimized S-N tilt of PV modules on horizontal main axis is ½ latitude.

Distance betwwen PV array: $D1 = L \times \cos Z$, $D2 = H / \tan\alpha = L \times \sin Z / \tan\alpha$ (α is solar altitude).

Figure 22 – *S-N* distance between PV modules

The distance between PV modules (D) at noon time on winter solstice is as follows:

$$D = D1 + D2$$

$$D1 = L \times \cos Z \text{ (}L\text{:length of PV module)}$$

$$D2 = H / \tan\alpha, \; H = L \times \sin Z$$

On winter solstice, at noon time (hour angle ω = 0°):

$$\sin\alpha = \sin\varphi\sin\delta + \mathrm{con}\varphi\cos\delta = \cos(\varphi - \delta) = \sin(90° - (\varphi - \delta))$$

$$\alpha = 90° - \varphi - 23{,}45 \text{ (solar declination } \delta = -23{,}45)$$

$$D = D1 + D2 = L \times \cos Z + L \times \sin Z / \tan(90° - \varphi - 23{,}45)$$

13.6 Example of *S*-*N* distance calculation

Latitude: 36,25° *N*

Date: Dec. 21, winter solstice

Day length: 9 h and 31,6 min,

Solar altitude at noon time: 30,30°

Solar azimuth at noon time: β = 0°

S-*N* tilted angle of array: 36,25° x 1/2 = 18,125°

Array azimuth at noon time: γ = 0°

255 W C-Si Module: length is 1,68 m,width is 0,997 m, efficiency is 15,18 %.

See Figure 16 as an example.

Module configuration of PV array: 1 module installed on main axis, the width of the array: K = 1,68 m and the length of PV array L = 0,997 m.

Total power is 0,255 kW

Calculation results:

$$L = 0{,}997 \text{ m}, Z = 18{,}125°, H = L \times \sin Z = 0{,}503 \text{ m}$$

$D1 = L \times \cos Z$ = 0,948 m, $D2 = H / \tan\alpha$ = 0,531 m, the south-north distance between modules

$$D = D1 + D2 = 1{,}479 \text{ m}.$$

13.7 Land usage of tilted *E*-*W* tracking

The *E*-*W* distance between arrays is 4,837 m, and the *S*-*N* distance is 1,479 m, so the total land usage of one PV block is 7,151 m^2.

The array power is 0,255 kW, the unit land usage is 28,04 m^2 /kW.

Considering the gap between PV modules, the road within the 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:

$$28{,}04 \times 1{,}15 = 32{,}25 \text{ m}^2 / \text{kW}$$

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

14 Land usage calculation of double-axis tracking in ground horizontal coordinates (Figure 23)

Figure 23 – Double axis-tracking in ground gorizontal coordinates

14.1 Boundary conditions

a) Double-axis tracking in ground horizontal coordinates tracks the solar altitude and solar azimuth.

b) The azimuth of PV array can rotate 360°, so the system can track the solar azimuth from sunrise to sunset, the azimuth of PV array is equal to solar azimuth (β = γ) all day; and the tilted angle of array is equal to complementary solar altitude, namely Z = 90-α since the sun rays should be perpendicular to PV plane, but the tilted angle of array is constrained by the mechanical structure, so it is assumed that the largest designed tilt of PV array is 60° for flat-plate modules and 70° for CPV.

c) Decoupled calculation is required for E-W distance and S-N distance separately.

d) For S-N no-shading distance, the condition is set at the time of 75 % of day length or from 9:00am to 3:00pm on winter solstice.

e) For E-W distance calculation, it is based on 20° of solar altitude and the sun is in the east.

f) Double-axis tracking is usually used for concentrating PV (CPV), the no-shading distance calculation is the same with flat-plate modules, but the boundary conditions are different.

14.2 Calculation model for S-N distance

To calculate S-N distance, 5 distances need to be known. The 5 distances between PV arrays are shown in Figure 24.

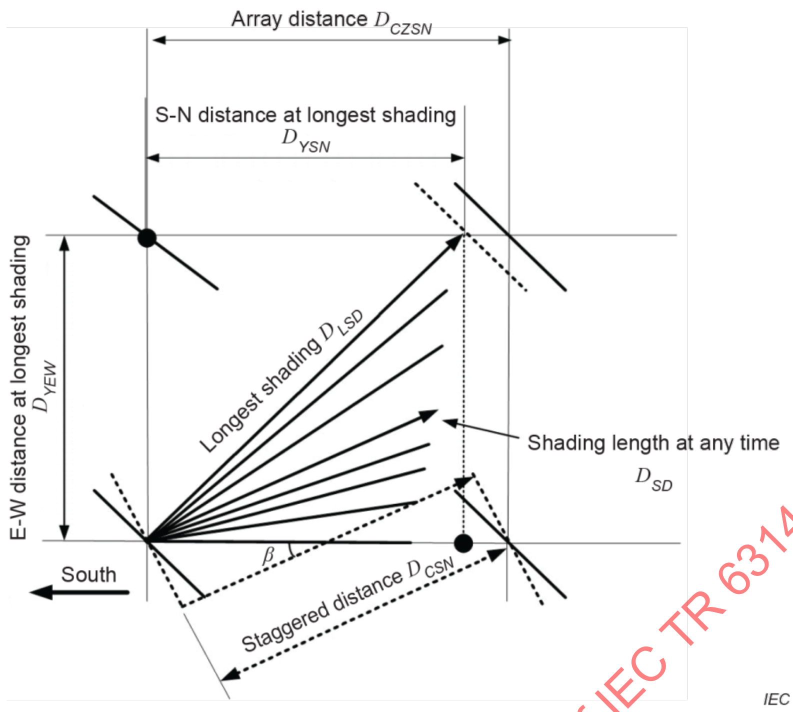


Figure 24 – Distance items relevent with no-shading distance calculation

a) D_{LSD}: the north-west (*N-W)* distance at longest shading, $D_{LSD} = D1+D2$ at set time;

b) D_{YSN}: *S-N* distance at longest shading, $D_{YSN} = D_{LSD} \times \cos\beta$;

c) D_{SD}: the front array shading length at any time, $D_{SD} = D1 + D2$, the value is from large to small (smallest at noon time);

d) D_{CSN}: *S-N* staggered distance, it is from small to large till ∞, when $D_{SN} = D_{CSN}$, it is the required D_{CSN};

$D_{CSN} = K / \tan\beta$;

e) D_{CZSN}: the *S-N* distance of arrays D_{CZSN}, it can be derived from D_{CSN}, $D_{CZSN} = D_{CSN} / \cos\beta$.

For above formulas:

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

where

L is the length of PV array;

K is the width of PV array;

Z is the tilted angle of PV array;

α is solar altitude;

β is solar azimuth.

NOTE D_{YEW} is *E-W* distance at longest shading, $D_{YEW} = D_{LSD} \times \sin\beta$, will be used for *E-W* distance calculation.

The calculation process is as follows:

a) calculate the longest *N-W* distance between PV arrays D_{LSD} at 75 % day-length or from 9:00am to 3:00pm;

b) calculate *S-N* distance at longest shading D_{YSN};

c) calculate the shading distance D_{SD} and the staggered distance D_{CSN} step by step and to find the point when the shading distance is equal to the staggered distance ($D_{SD} = D_{CSN}$). Record the staggered distance D_{CSN};

d) calculate the PV array *S-N* distance D_{CZSN} from D_{CSN};

e) compare D_{CZSN} and D_{YSN}, take the larger as the final *S-N* distance D_{SN}.

14.3 Example 1: calculation for *S-N* distance at 75 % day-length on winter solstice (Table 6)

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

Latitude: 36,25°*N*

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 53,59° at 8:25:38am (75 % of day length)

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

Solar altitude α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Tilted angle of array: Z = 60°

C-Si 255 W Module: length is 1,685 m, width is 0,997 m, and its efficiency is 15,18 %.

Module configuration of PV array: longitudinal 5 modules, length is L = 4,985 m; lateral 4 modules, width is K = 6,74 m; total 20 modules.

Total power of PV array is 5,1 kW

a) $D_{LSD} = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) / \tan\alpha$ = 23,23 m;

b) $D_{YSN} = D_{LSD} \times \cos\beta$ = 15,25 m;

c) $D_{SD} = D_{CSN}$ = 12,05 m at hour angle is 29°;

d) D_{CZSN} = 13,81 m which is smaller than D_{YSN}, so the final *S-N* distance D_{SN} is equal to D_{YSN} = 15,25 m.

Table 6 – *S-N* distances calculation at 75 % day length on winter solstice

φ °	*Z* °	*δ* °	*ω* °	*α* °	*β* °	*L* m	*K* m
36,25	60	-23,45	53.59	11,76	48,95	4,985	6,74
36,25	60	-23,45	45	16,73	42,64	4,985	6,74
36,25	60	-23,45	40	19,36	38,68	4,985	6,74
36,25	60	-23,45	30	23,92	30,12	4,985	6,74
36,25	60	-23,45	29	24,32	29,21	4,985	6,74
36,25	60	-23,45	23	26,47	23,61	4,985	6,74
36,25	60	-23,45	15	28,64	15,70	4,985	6,74
36,25	60	-23,45	10	29,56	10,55	4,985	6,74
36,25	60	-23,45	5	30,11	5,30	4,985	6,74
36,25	60	-23,45	0	30,30	0,00	4,985	6,74
	H m	*D2* m	*D1* m	D_{LSD}/D_{SD} m	D_{YSN} m	D_{CSN} m	D_{CZSN} m
	4,32	20,74	2,49	23,23	**15,25**	5,87	8,94
	4,32	14,36	2,49	16,86		7,32	9,95
	4,32	12,29	2,49	14,78		8,42	10,78
	4,32	9,73	2,49	12,23		11,62	13,43
	4,32	9,55	2,49	**12,05**		**12,05**	**13,81**
	4,32	8,67	2,49	11,16		15,42	16,83
	4,32	7,90	2,49	10,40		23,98	24,91
	4,32	7,61	2,49	10,11		36,18	36,80
	4,32	7,44	2,49	9,94		72,61	72,92
	4,32	7,39	2,49	9,88		∞	∞

14.4 Example 2: calculation for *S-N* distance at 9:00am on winter solstice (Table 7)

Latitude: 36,25°*N*

Date: on winter solstice, solar declination δ = -23,45°

Time: hour angle ω = 45,0° at 9:00am.

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

Solar altitude α = 16,73° at 9:00 am (solar time)

Solar azimuth β = 42,64° at 9:00 am (solar time)

Tilted angle of array: Z = 60°

C-Si 255 W Module: length is 1,685 m, width is 0,997 m, and its efficiency is 15,18 %.

Module configuration of PV array: longitudinal 5 modules, length is L = 4,985 m; lateral 4 modules, width is K = 6,74 m; total 20 modules.

Total power of PV array is 5,1 kW

a) $D_{LSD} = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) / \tan\alpha$ = 16,86 m;

b) $D_{YSN} = D_{LSD}$ x $\cos\beta$ = 12,40 m;

c) $D_{SD} = D_{CSN}$ = 12,05 m at hour angle is 29°;

d) D_{CZSN} = 13,81 m which is larger than D_{YSN}, so the *S-N* distance (D_{SN}) is equal to D_{CZSN} = 13,81 m.

Table 7 – *S-N* distances calculation at 9:00am on winter solstice

φ °	Z °	δ °	ω °	α °	β °	L m	K m
36,25	60	-23,45	45	16,73	42,64	4,985	6,74
36,25	60	-23,45	40	19,36	38,68	4,985	6,74
36,25	60	-23,45	30	23,92	30,12	4,985	6,74
36,25	60	-23,45	**29**	**24,32**	**29,21**	4,985	6,74
36,25	60	-23,45	23	26,47	23,61	4,985	6,74
36,25	60	-23,45	15	28,64	15,70	4,985	6,74
36,25	60	-23,45	10	29,56	10,55	4,985	6,74
36,25	60	-23,45	5	30,11	5,30	4,985	6,74
36,25	60	-23,45	0	30,30	0,00	4,985	6,74
	H m	$D2$ m	$D1$ m	D_{LSD}/D_{SD} m	D_{YSN} m	D_{CSN} m	D_{CZSN} m
	4,32	14,36	2,49	16,86	**12,40**	7,32	9,95
	4,32	12,29	2,49	14,78		8,42	10,78
	4,32	9,73	2,49	12,23		11,62	13,43
	4,32	**9,55**	**2,49**	**12,05**		**12,05**	**13,81**
	4,32	8,67	2,49	11,16		15,42	16,83
	4,32	7,90	2,49	10,40		23,98	24,91
	4,32	7,61	2,49	10,11		36,18	36,80
	4,32	7,44	2,49	9,94		72,61	72,92
	4,32	7,39	2,49	9,88		∞	∞

14.5 Example of *E-W* distance calculation

For *E-W* distance calculation, it is based on 20° of solar altitude and the sun is in the east.

For horizontal double-axis tracking, solar azimuth is equal to array azimuth all day ($\beta = \gamma$). Distance calculations are based on array length L and array tilt Z.

The boundary conditions are as follows:

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

$$D2 = H / \tan\alpha,\ H = L \times \sin Z$$

$$D_{HEW} = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) / \tan\alpha$$

D_{HEW}: the calculated *E-W* distance in horizontal coordinates

$$\alpha = \arcsin(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega)$$

Latitude: 36,25° N

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

No-shading time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 60°

C-Si 255 W Module: length is 1,685 m, width is 0,997 m, and its efficiency is 15,18 %.

Module configuration of PV array: longitudinal 5 modules, length is L = 4,985 m; lateral 4 modules, width is K = 6,74 m; total 20 modules.

Total power of PV array is 5,1 kW

Calculation results:

$$L = 4{,}985 \text{ m}, Z = 60°, H = 4{,}32 \text{ m}$$

$$D2 = H / \tan\alpha = 11{,}86 \text{ m}$$

$$D1 = L \times \cos Z = 2{,}49 \text{ m}$$

The E-W distance between arrays is $D_{HEW} = D1 + D2$ = 14,35 m.

a) Calculation for E-W distance at longest shading at 75 % day-length on winter solstice:

   $D_{YEW} = D_{LSD} \times \sin\beta$ = 17,52 m which is larger than D_{HEW} above (14,35 m), so the final E-W distance of array $D_{EW} = D_{YEW}$ = 17,52 m for the boundary condition of 75 % day-length.

b) Calculation for E-W distance at longest shading at 9:00am on winter solstice:

   $D_{YEW} = D_{LSD} \times \sin\beta$ = 11,42 m which is smaller than D_{HEW} above (14,35 m), so the final E-W distance of array $D_{EW} = D_{HEW}$ = 14,35 m for the boundary condition of 9:00am.

14.6 Land usage for horizontal double-axis tracking

Example 1: no-shading period is set within 75 % day length on winter solstice

The E-W distance between arrays is 17,52 m, and the S-N distance is 15,25 m, so the total land usage of PV array is 267,21 m^2.

The array power is 5,10 kW, the unit land usage is 52,39 m^2 /kW.

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

$$52{,}39 \times 1{,}15 = 60{,}25 \text{ m}^2 / \text{kW}$$

Example 2: no-shading period is from 9:00am to 3:00pm on winter solstice

The *E*-*W* distance between arrays is 14,35 m, and the *S*-*N* distance is 13,81 m, so the total land usage of PV array is 198,17 m^2.

The array power is 5,10 kW, the unit land usage is 38,86 m^2 /kW.

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

38,86 x 1,15 = 44,69 m^2 / kW

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

15 Land usage calculation for azimuth tracking in ground horizontal coordinates (Figure 25)

Figure 25 – Solar azimuth tracking (fixed PV tilt)

15.1 Boundary conditions

a) Azimuth tracking in ground horizontal coordinates tracks the solar azimuth ($\beta = \gamma$), and array tilted angle is fixed, in general, the array tilt Z is ≤ latitude φ.

b) Decoupled calculation is required for *E*-*W* distance and *S*-*N* distance separately.

c) For *S*-*N* no-shading distance, the condition is set at the time of 75 % of day length or from 9:00am to 3:00pm on winter solstice.

d) For *E*-*W* distance calculation, it is based on 20° of solar altitude and the sun is in the east.

15.2 Calculation model for *S*-*N* distance

To calculate *S*-*N* distance, 5 distances need to be known. The 5 distance between PV arrays is shown in Figure 24.

a) D_{LSD}: the north-west (*N*-*W*) distance at longest shading, $D_{LSD} = D1 + D2$ at set time;

b) D_{YSN}: *S*-*N* distance at longest shading, $D_{YSN} = D_{LSD} \times \cos\beta$;

c) D_{SD}: front array shading length at any time D_{SD}: $D_{SD} = D1 + D2$, the value is from large to small (smallest at noon time);

d) D_{CSN}: *S-N* staggered distance, it is from small to large till ∞, when $D_{SN} = D_{CSN}$, it is the required D_{CSN};

$D_{CSN} = K / \tan\beta$;

e) D_{CZSN}: the *S-N* distance of arrays D_{CZSN}, it can be derived from D_{CSN}, $D_{CZSN} = D_{CSN} / \cos\beta$.

For above formulas:

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

where

L is the length of PV array;

K is the width of PV array;

Z is the tilted angle of PV array;

α is solar altitude;

β is solar azimuth.

NOTE D_{YEW} is *E-W* distance at longest shading, $D_{YEW} = D_{LSD} \times \sin\beta$, will be used for *E-W* distance calculation.

The calculation process is as follows:

a) calculate the longest *N-W* distance between PV arrays D_{LSD} at 75 % day-length or from 9:00am to 3:00pm;

b) calculate *S-N* distance at longest shading D_{YSN};

c) calculate the shading distance D_{SD} and the staggered distance D_{CSN} step by step and to find the point when the shading distance is equal to the staggered distance ($D_{SD} = D_{CSN}$). Record the staggered distance D_{CSN};

d) calculate the PV array *S-N* distance D_{CZSN} from D_{CSN};

e) compare D_{CZSN} and D_{YSN}, take the larger as the final *S-N* distance.

15.3 Example 1: calculation for *S-N* distance at 75 % day-length on winter solstice (Table 8)

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

Latitude: 36,25° *N*

Date: on winter solstice, solar declination δ = –23,45°

Time: hour angle ω = 53,59° at 8:25:38am (75 % of day length)

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

Solar altitude α = 11,76° at 8:25:38 am (solar time)

Solar azimuth β = 48,95° at 8:25:38 am (solar time)

Tilted angle of array: Z = 36,25°

C-Si 255 W Module: length is 1,685 m, width is 0,997 m, and its efficiency is 15,18 %.

Module configuration of PV array: longitudinal 5 modules, length is L = 4,985 m; lateral 4 modules, width is K = 6,74 m; total 20 modules.

Total power of PV array is 5,1 kW

a) $D_{LSD} = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) / \tan\alpha$ = 18,18 m;

b) $D_{YSN} = D_{LSD} \times \cos\beta$ = 11,94 m;

c) $D_{SD} = D_{CSN}$ = 10,91 m at hour angle is 31,79°;

d) D_{CZSN} = 12,82 m which is larger than D_{YSN}, so the final *S-N* distance D_{SN} is equal to D_{CZSN} = 12,82 m.

Table 8 – *S-N* distances calculation for azimuth tracking at 75 % day length

Φ °	Z °	δ °	ω °	α °	β °	L m	K m
36,25	36,25	-23,45	53,59	11,76	48,95	4,985	6,74
36,25	36,25	-23,45	45	16,73	42,64	4,985	6,74
36,25	36,25	-23,45	35	19,36	38,68	4,985	6,74
36,25	36,25	-23,45	**31,77**	**23,92**	**30,12**	4,985	6,74
36,25	36,25	-23,45	25	24,32	29,21	4,985	6,74
36,25	36,25	-23,45	20	26,47	23,61	4,985	6,74
36,25	36,25	-23,45	15	28,64	15,70	4,985	6,74
36,25	36,25	-23,45	10	29,56	10,55	4,985	6,74
36,25	36,25	-23,45	5	30,11	5,30	4,985	6,74
36,25	36,25	-23,45	0	30,30	0,00	4,985	6,74
	H m	$D2$ m	$D1$ m	D_{LSD}/D_{SD} m	D_{YSN} m	D_{CSN} m	D_{CZSN} m
	2,95	14,16	4,02	**18,18**	**11,94**	5,87	8,94
	2,95	9,81	4,02	13,83		7,32	9,95
	2,95	7,38	4,02	11,40		9,80	11,90
	2,95	**6,88**	**4,02**	**10,91**		**10,91**	**12,82**
	2,95	6,10	4,02	10,12		14,13	15,65
	2,95	5,69	4,02	9,71		17,84	19,07
	2,95	5,40	4,02	9,42		23,98	24,91
	2,95	5,20	4,02	9,22		36,18	36,80
	2,95	5,08	4,02	9,10		72,61	72,92
	2,95	5,04	4,02	9,06		∞	∞

15.4 Example 2: calculation for S-N distance at 9:00am on winter solstice (Table 9)

Latitude: 36,25°*N*

Date: on winter solstice, solar declination δ = –23,45°

Time: hour angle ω = 45,0° at 9:00am

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

Solar altitude α = 16,73° at 9:00 am (solar time)

Solar azimuth β = 42,64° at 9:00 am (solar time)

Tilted angle of array: Z = 36,25°

C-Si 255 W Module: length is 1,685 m, width is 0,997 m, and its efficiency is 15,18 %.

Module configuration of PV array: longitudinal 5 modules, length is L = 4,985 m; lateral 4modules, width is K = 6,74 m; total 20 modules.

Total power of PV array is 5,1 kW

a) $D_{LSD} = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) / \tan\alpha$ = 13,83 m;

b) $D_{YSN} = D_{LSD} \times \cos\beta$ = 10,17 m;

c) $D_{SD} = D_{CSN}$ = 10,91 m at hour angle is 31,77°;

d) D_{CZSN} = 12,82 m which is larger than D_{YSN}, so the final S-N distance D_{SN} is equal to D_{CZSN} = 12,82 m.

Table 9 – Distances calculation from the set time to noon time

φ °	Z °	δ °	ω °	α °	β °	L m	K m
36,25	36,25	-23,45	45	16,73	42,64	4,985	6,74
36,25	36,25	-23,45	35	19,36	38,68	4,985	6,74
36,25	36,25	-23,45	**31,77**	**23,92**	**30,12**	4,985	6,74
36,25	36,25	-23,45	25	24,32	29,21	4,985	6,74
36,25	36,25	-23,45	20	26,47	23,61	4,985	6,74
36,25	36,25	-23,45	15	28,64	15,70	4,985	6,74
36,25	36,25	-23,45	10	29,56	10,55	4,985	6,74
36,25	36,25	-23,45	5	30,11	5,30	4,985	6,74
36,25	36,25	-23,45	0	30,30	0,00	4,985	6,74
	H m	$D2$ m	$D1$ m	D_{LSD}/D_{SD} m	D_{YSN} m	D_{CSN} m	D_{CZSN} m
	2,95	9,81	4,02	13,83	10,17	7,32	9,95
	2,95	7,38	4,02	11,40		9,80	11,90
	2,95	**6,88**	**4,02**	**10,91**		**10,91**	**12,82**
	2,95	6,10	4,02	10,12		14,13	15,65
	2,95	5,69	4,02	9,71		17,84	19,07
	2,95	5,40	4,02	9,42		23,98	24,91
	2,95	5,20	4,02	9,22		36,18	36,80
	2,95	5,08	4,02	9,10		72,61	72,92
	2,95	5,04	4,02	9,06		∞	∞

15.5 Example of *E*-*W* distance calculation

For E-W distance calculation, it is based on 20° of solar altitude and the sun is in the east.

For horizontal double-axis tracking, solar azimuth is equal to array azimuth all day ($\beta = \gamma$). Distance calculations are based on array length L and array tilt Z.

The boundary conditions are as follows:

$D1 = L \times \cos Z$

$D2 = H / \tan\alpha$, $H = L \times \sin Z$

$D_{HEW} = D1 + D2 = (L \times \cos Z) + (L \times \sin Z) / \tan\alpha$

$\alpha = \arcsin(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega)$

Latitude: 36,25° N

Date: April 20, solar declination δ = 11,75°

Day length (from sunrise to sunset): 13,17 h

Sunrise at 5:24:05 (solar time)

No-shading time: 7:05:48am, solar hour angle ω = 73,70°

Solar altitude α = 20°

Solar azimuth β = 90°

E-W tilted angle: 36,25°

C-Si 255 W Module: length is 1,685 m, width is 0,997 m, and its efficiency is 15,18 %.

Module configuration of PV array: longitudinal 5 modules, length is L = 4,985 m; lateral 4 modules, width is K = 6,74 m; total 20 modules.

Total power of PV array is 5,1 kW

Calculation results:

L = 4,985 m, Z = 36,25°, H = 2,95 m

$D2 = H / \tan\alpha$ = 8,09 m

$D1 = L \times \cos Z$ = 4,02 m

The E-W distance between arrays is $D_{HEW} = D1+D2$ = 12,11 m.

a) Calculation for E-W distance at longest shading at 75 % day-length on winter solstice:

   $D_{YEW} = D_{LSD}$ x $\sin\beta$ = 13,71 m which is larger than D_{HEW} above (12,11 m), so D_{YEW} (13,71 m) should be taken as the final E-W distance (D_{EW}) for such boundary condition.

b) Calculation for E-W distance at longest shading at 9:00am on winter solstice:

   $D_{YEW} = D_{LSD}$ x $\sin\beta$ = 9,37 m which is smaller than D_{HEW} above (12,11 m), so D_{HEW} should be the final E-W distance (D_{EW}) for such boundary condition.

15.6 Land usage for horizontal azimuth tracking

Example 1: no-shading period is set within 75 % day length on winter solstice

The E-W distance between arrays is 13,71 m, and the S-N distance is 12,82 m, so the total land usage of PV array is 175,76 m^2.

The array power is 5,10 kW, the unit land usage is 34,46 m^2 /kW.

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

$$34{,}46 \times 1{,}15 = 39{,}63 \text{ m}^2 / \text{kW}$$

Example 2: no-shading period is from 9:00am to 3:00pm on winter solstice

The E-W distance between arrays is 12,11 m, and the S-N distance is 12,82 m, so the total land usage of PV array is 155,28 m^2.

The array power is 5,10 kW, the unit land usage is 30,45 m^2 /kW.

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

$30{,}45 \times 1{,}15 = 35{,}01 \text{ m}^2 / \text{kW}$

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

16 Array length and width ratio

No-shading distance for ground horizontal azimuth and double tracking will be affected by PV array length and width ratio. PV array can be configured into 3 senarios, see Figure 26:

Dimensions in metres

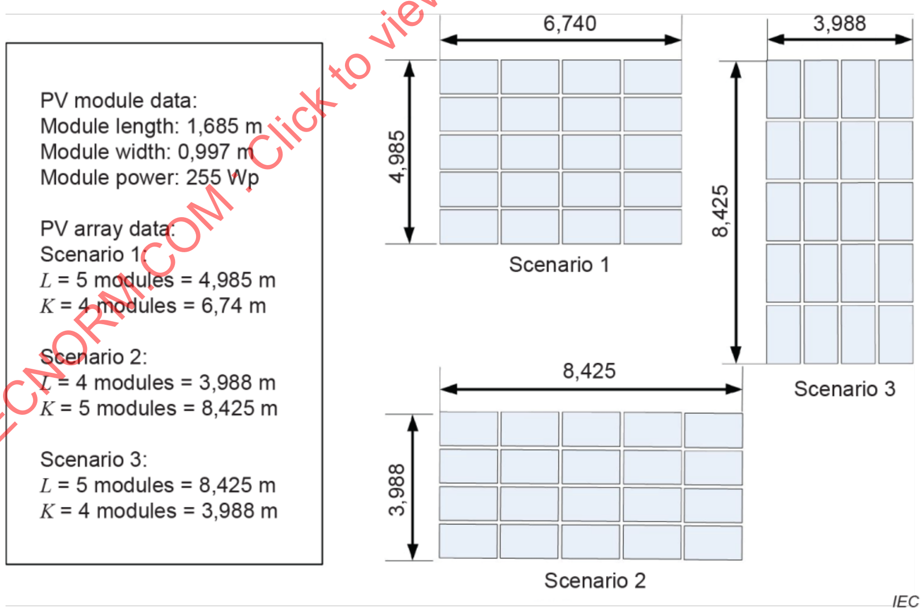


Figure 26 – Array configuration for horizontal double tracking

Land usage for 3 scenarios at different latitude were calculated and listed in Table 10 and Table 11.

Table 10 – Length and width ratio effect for 3 scenarios

Scenario 1 L = 4,985 m K = 6,740 m Power = 5,1 kW	***E-W* Distance calculation**						
	φ (°)	δ (°)	ω (°)	α (°)	β (°)	Z (°)	D_{EW} (m)
	20,00	6,75	71,125	20	90	60	14,35
	36,25	11,75	73,699	20	90	60	14,35
	40,00	12,75	74,450	20	90	60	14,35
	***S-N* Distance calculation**						
	φ (°)	δ (°)	ω (°)	α (°)	β (°)	Z (°)	D_{SN} (m)
	20,00	-23,45	45	28,26	47,43	60	10,84
	36,25	-23,45	45	16,73	42,64	60	12,82
	40,00	-23,45	45	13,95	41,95	60	14,98
Total land usage (m^2)		φ = 20°: 155,55		φ = 36,25°: 183,97		φ = 40°: 214,96	
Unit land usage (m^2/kW)		φ = 20°: 30,50		φ = 36,25°: 36,07		φ = 40°: 42,15	
Scenario 2 L = 3,988 K = 8,425 Power = 5,1 kW	***E-W* Distance calculation**						
	φ (°)	δ (°)	ω (°)	α (°)	β (°)	Z (°)	D_{EW} (m)
	20,00	6,75	71,125	20	90	60	11,48
	36,25	11,75	73,699	20	90	60	11,48
	40,00	12,75	74,450	20	90	60	11,48
	***S-N* Distance calculation**						
	φ (°)	δ (°)	ω (°)	α (°)	β (°)	Z (°)	D_{SN} (m)
	20,00	-23,45	45	28,26	47,43	60	11,68
	36,25	-23,45	45	16,73	42,64	60	14,07
	40,00	-23,45	45	13,95	41,95	60	14,97
Total land usage (m^2)		φ = 20°: 134,09		φ = 36,25°: 161,52		φ = 40°: 171,86	
Unit land usage (m^2/kW)		φ = 20°: 26,29		φ = 36,25°: 31,67		φ = 40°: 33,70	
Scenario 3 L = 8,425 K = 3,988 Power = 5,1 kW	***E-W* Distance calculation**						
	φ (°)	δ (°)	ω (°)	α (°)	β (°)	Z (°)	D_{EW} (m)
	20,00	6,75	71,125	20	90	60	24,26
	36,25	11,75	73,699	20	90	60	24,26
	40,00	12,75	74,450	20	90	60	24,26
	***S-N* Distance calculation**						
	φ (°)	δ (°)	ω (°)	α (°)	β (°)	Z (°)	D_{SN} (m)
	20,00	-23,45	45	28,26	47,43	60	12,36
	36,25	-23,45	45	16,73	42,64	60	20,96
	40,00	-23,45	45	13,95	41,95	60	24,97
Total land usage (m^2)		φ = 20°: 299,85		φ = 36,25°: 508,49		φ = 40°: 605,77	
Unit land usage (m^2/kW)		φ = 20°: 58,79		φ = 36,25°: 99,70		φ = 40°: 118,78	