14 WINDPRO SOLAR-PV

14.1 Solar-PV – introduction

14.1.1 Introduction to Solar-PV

The windPRO Solar-PV module allows users to design and perform energy yield calculations for a Solar Photovoltaic (PV) plant.

A PV plant can be designed in multiple areas with individual properties (panel type, tilt, row distance etc.) making it easy to handle also complex plant designs.

The designed plant can be visualized using the windPRO PHOTOMONTAGE module.

The Solar-PV module can handle any size of PV-plant, from just one panel to millions of panels. The calculation time can although limit what is realistic to calculate. This is solved by a reference panel calculation when plants get very large. When enabled, just one panel (table) is calculated and scaled up to the full area. The tool will give a warning if a calculation is started with more than 300.000 panels (~200 MW), which will take 10-15 hours to calculate with a 20-year time series on a standard PC. With the reference panel calculation method, calculation time is less than 1 minute. It is possible to calculate some areas with reference panels, other as individual panel calculation and thereby get correct shading calculation where obstacles are near panels, while still working with a reasonable calculation time. We are constantly working on improving the calculation time.

windPRO handles both bifacial (panels utilizing irradiance at the rear side of the panel) and tracking plants. Tracking can be set to manual (seasonal tilt adjustment for panels facing Equator) or as continuous (for e.g., East-West facing panels, becoming more and more common due to higher electricity prices morning and afternoon). Not all tracking variants are included at present, only the most common.

The module can optimize tilt angles for fixed tilt plants or season tracking plants based on an optimizing algorithm. This algorithm uses the time series irradiance data and all losses to find the tilt angles giving the highest annual energy production after loss deduction. For continuous tracking systems backtracking is included in the tilt angle calculations, so panel shading is prevented when the solar angle is low.

Starting from windPRO 4.0 a more advanced optimization tool is available, where multiple parameters of the layout can be optimized: tilt, row spacing, azimuth, number of vertical panels and AC/DC ratio of the plant. The objective of the optimization can be maximizing annual energy production (AEP), minimizing levelized cost of electricity (LCOE) or maximizing net present value (NPV).

The basic philosophy of the module is it to make it quick and easy to design PV-plants and to calculate the expected energy production accurately. The module enables handling and analysing the meteorological input data for the calculation, because poor data quality can lead to significant bias and high uncertainty in any calculation. Calibration of long-term model data with local short-term local measurements is an option. The comprehensive METEO ANALYSER tool in windPRO handles solar data just as flexibly and comprehensively as it does for wind data.

The calculation of the shading reductions is of high importance when designing a plant. This is where the plant developer can make a difference. Panel shading by many rows in a field or on a flat rooftop, is the major loss component for modern PV plants, and this is handled quickly and easily in the module by testing different alternatives. In addition, as a windPRO speciality; how much shading loss will wind turbines cause, when the PV-plant is placed within a wind farm? The 3D shading calculation model utilizes windPRO's advanced elevation data handling, in which detailed elevation data are available for download in high quality for many countries. Topographic shading loss can be calculated as well, which is relevant for sites located close to hills or mountains. Another feature included in the solar-PV module is the handling of by-pass diodes for reducing shading losses. This enables windPRO to calculate all shading losses very accurately.

The module only handles the basics in electrical losses to make for a smooth workflow, emphasising other more important losses.

The energy calculation is always performed in the time domain and the average lifetime degradation loss is calculated using specified annual degradation loss from panel specifications.

A very efficient design decision support is the xyz result to file output, with calculated shading reductions per panel. This helps to avoid including panels where shading losses are so high, that they won't be feasible to include, see Figure 144.

AEP Calculation flow overview:

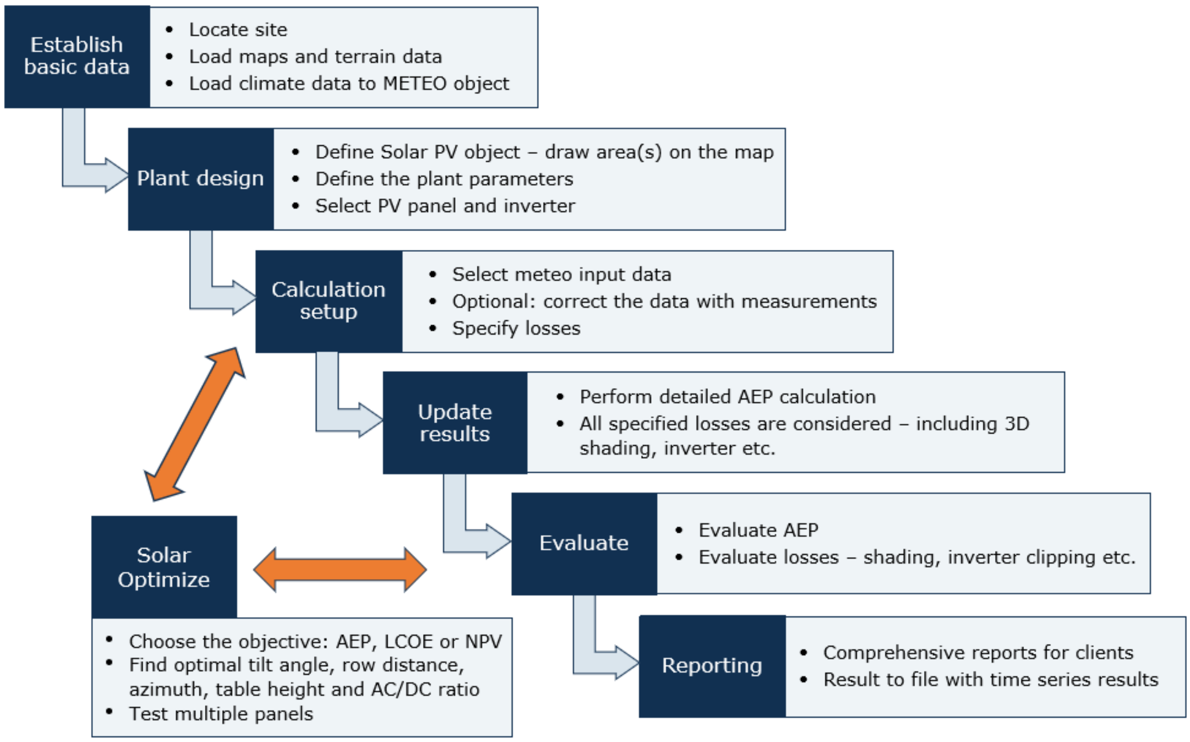


Figure 1 The calculation flow.

14.1.2 Workflow of the module

What follows is a short walk through on how the calculations are created, saved and reopened. The PV calculation module is different from other windPRO modules, as the calculation results are shown interactively. For other windPRO modules calculation results are only available after a report has been created. This makes the workflow slightly different.

When designing one or more PV areas within the Solar-PV object by drawing on the map, a status window will appear, from where the calculation setup (selection of solar data etc.) is handled. When the calculation setup is established, the calculation can be performed, and results seen in status window. A report can be generated for printing. The results seen in status window can be copied to clipboard and several calculation variants are easy to compare.

It is also possible to start a Solar PV calculation by selecting the module in the *Solar* tab. Assuming a solar PV area has already been created, a calculation can be started by choosing *SOLAR PV* in the *Solar tab*:

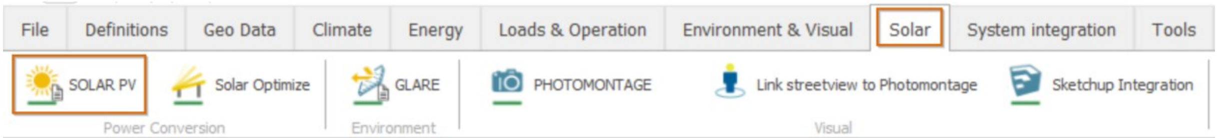


Figure 2 Location of the SOLAR PV module in the Solar tab.

Clicking on the *SOLAR PV* icon will open a calculation setup window.

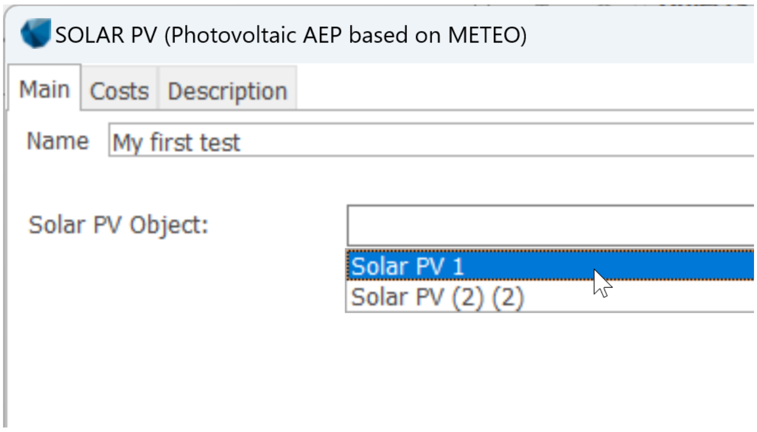


Figure 3 Main window of the Calculation setup.

In the *Main* tab calculation name should be entered, and a Solar PV object selected (assuming at least one Solar PV object has been created). Then the other tabs are activated, and calculation setup can be entered:

Figure 4 Tabs in the Solar PV Calculation setup.

When entered and saved, the interactive PV-status window will open:

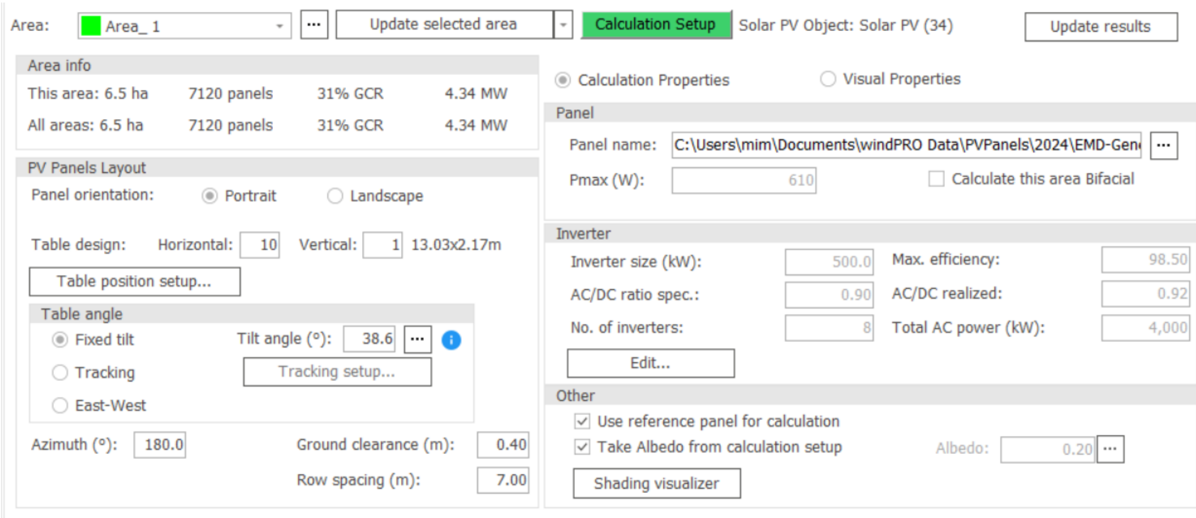


Figure 5 PV status window - data input form.

The status window shows the properties of an Area in the Solar PV object selected for the calculation. The window is divided into setting groups. The *Area info* holds information about the plant size, of both the active area and the sum of all areas defined in the object. The power, shown in last column, is the nominal front side DC power. The *PV Panels Layout* holds information about the placement of the PV panels in the Area – tilt, azimuth, row spacing and more. The right side of the status window is divided into *Calculation Properties* and *Visual Properties*. In the *Calculation properties* the *Panel* and *Inverter* can be selected. In *Other* settings it is possible to select *Reference Panel calculation* and specify albedo if other than in the *Calculation setup*. If the view is switched to *Visual Properties*, the settings needed for visualization are available.

Note that the definition of a calculation for Solar PV is slightly different from other windPRO calculations as it consists of one Solar PV object and a calculation setup. Other calculation modules handle multiple objects.

The calculation is started by clicking *Update results*. Once the results are ready the calculation results appear in the right part of the status window:

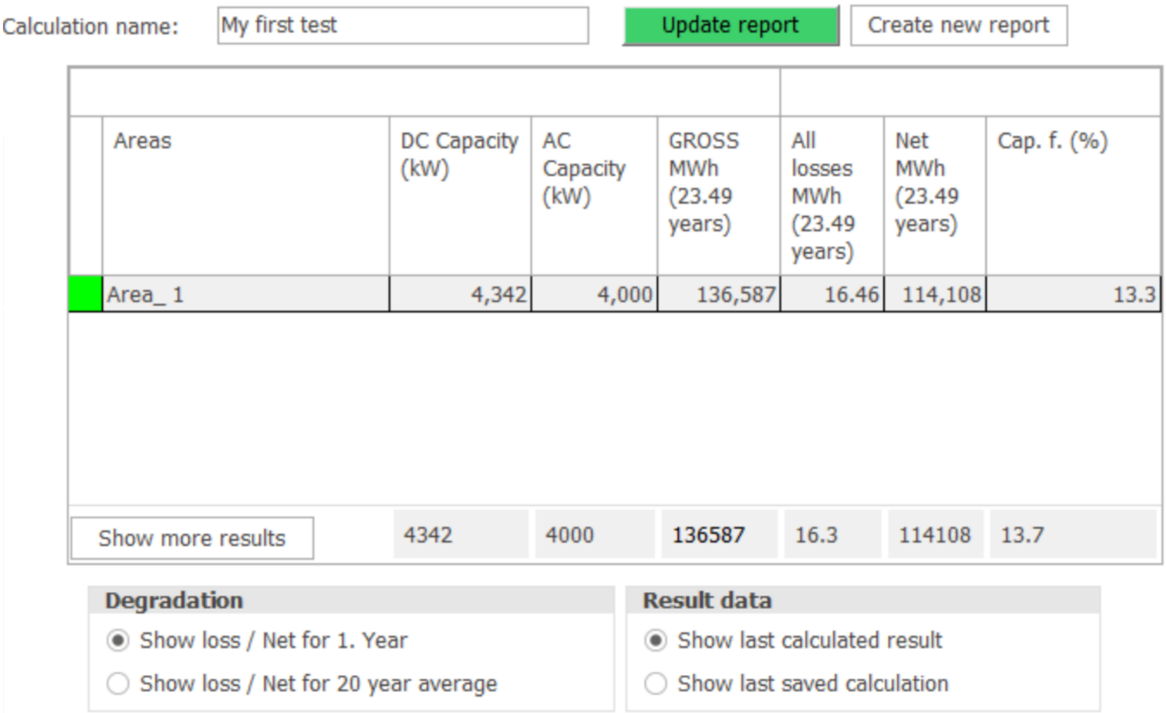


Figure 6 PV status window – calculation results.

The table can be expanded to show more results by clicking on *Show more results*:

Figure 7 PV status window – calculation results, expanded table.

Clicking *Create new report* creates the calculation in the calculation tree:

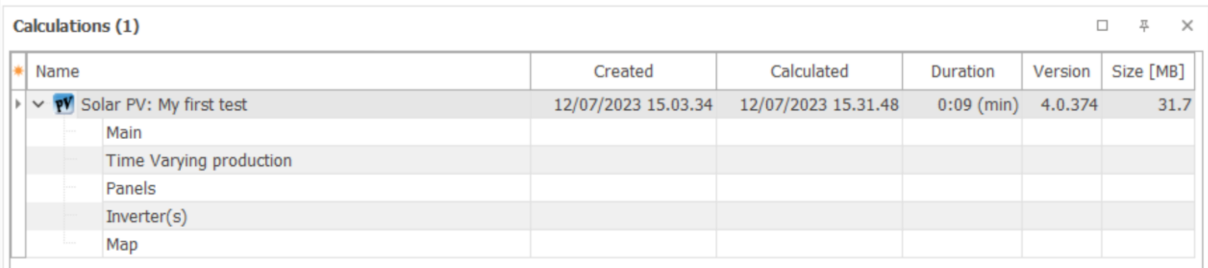


Figure 8 Calculation report.

The *Create new report*, will establish a new saved calculation in the calculation tree, whereas the Update report will overwrite the previously established report (saved calculation).

When a previously saved calculation is revisited (updated or used as template for a new calculation) it is done by right clicking on the existing calculation:

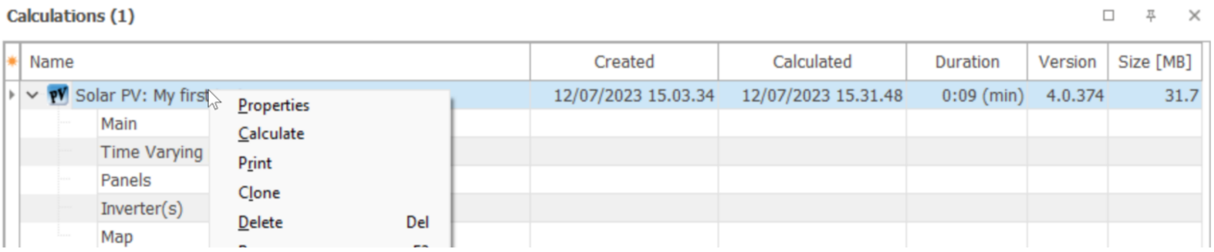


Figure 9 Reopen a previous calculation.

Right click and chose *Properties*, then the PV status window opens with the saved calculation setup AND the Solar PV object used in the calculation. Keep in mind, the Solar PV object may have been edited since the calculation was performed, so a re-calculation might be different to the previous results. To keep the old calculation, *clone* it before opening it with *Properties*.

14.2 Establish basic data

The following data should be established prior to designing the solar plant:

- Background maps (to be able to design the panels at the right place)
- Elevation data (Height contour lines or elevation grid data to calculate shading correctly and make visualisations)
- Meteo data (solar irradiance and temperature in Meteo objects, optional: humidity to have the "basics" for solar AEP calculations). Meteo data (Heliosat (Sarah) and ERA5) can be downloaded directly from the Calculation setup, see 14.3 Meteorological data.

14.2.1 Background maps

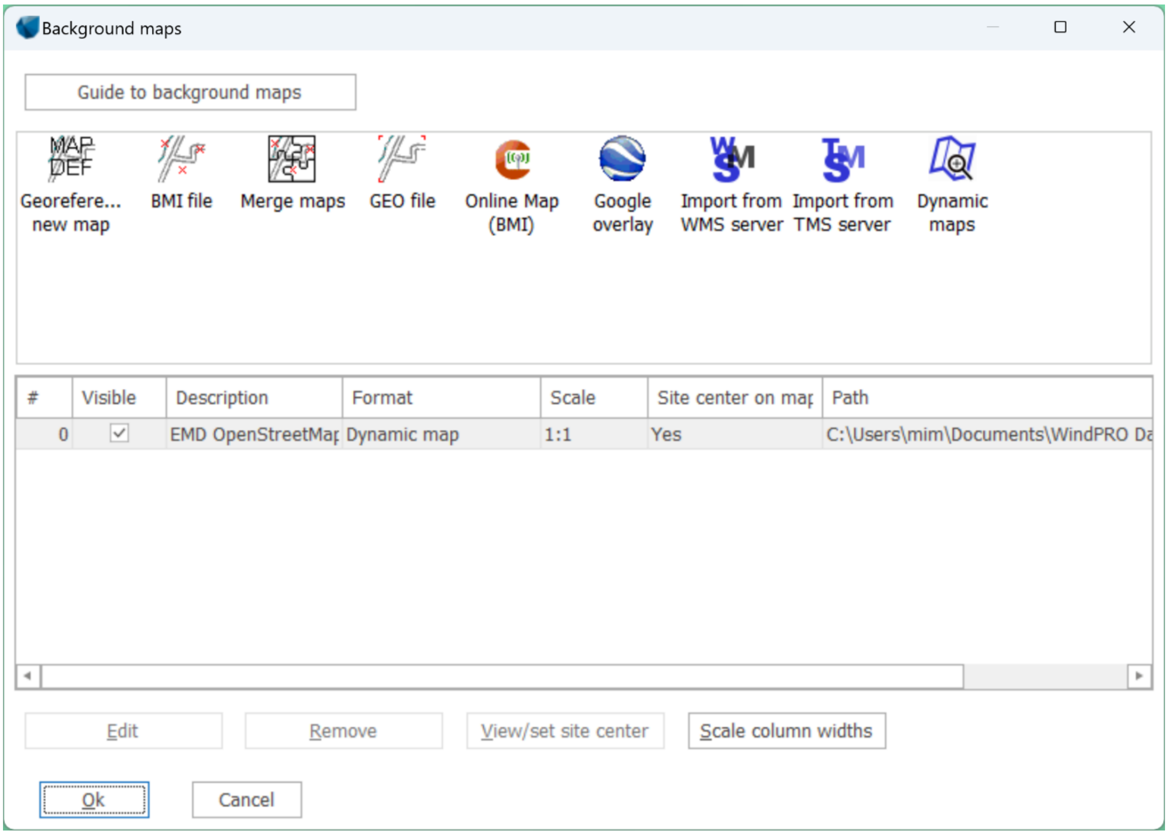


Figure 10 windPRO offers a number of different background map formats.

If you are new windPRO user, you should go through BASIS chapter to get familiar with the map handling. Background maps are attached using the menu seen in Figure 10.

14.2.2 Elevation data

For the elevation data, there are two different objects:

Click on the *Elevation Grid Data Object* button, then on the map to establish the data (likely to be more accurate in areas where contour lines are well-separated).

Similarly, the *Line Object* if you prefer height contours (easier to modify by yourself or the choice if you want to digitize your own data).

There are numerous on-line datasets available for download from EMD-Server. In most cases they will fulfil your demands. See BASIS chapter section 2.8 and 2.10 for details.

The elevation data creates a TIN (Triangular Irregular Network), which means that any point on your map has a z-value. It can be decided which object the TIN is calculated from if you have multiple elevation objects. The TIN decides how the individual panels are elevated, and how the shading elements are elevated. Therefore, the TIN is essential for the calculations.

IMPORTANT: Elevation data can be terrain (DTM – digital terrain model) as well as surface data (DSM – digital surface model). The type and how those are handled has a large impact on solar calculations.

Solar panels are placed based on TIN, where the x,y position of the two lower corners of a panel is used to find the corresponding z-values. An important issue when designing PV-plants is having very detailed elevation data. If there are many small bumps in the elevation data, this can lead to non-realistic placements of the panels. When constructing a project, the ground will be levelled by dig and fill before construction, or the substructures will be adjusted to absorb the elevation differences. Thereby, the user either must manipulate the elevation data to reflect this or use less detailed elevation data to compensate for this. This is one of the user challenges. Setting panels together in tables helps, as the tables will link the panels together. This is further described below.

Obstacles are placed in a way that the four corners of the obstacle decide the elevation from TIN. It is possible to uncheck the TIN use, and Obstacles are therefore assumed horizontal (like a house). See more details in section 14.7.2.2 .

If surface data is used for TIN, these might already hold the obstacle top elevation, and in this case, it might be needed to set the obstacle's z-value manually. Do not rely on Topographic shading for handling obstacles near panels, this is a far too coarse calculation, designed for handling hill/mountain shading at larger distances.

Four ways to handle elevation and its pros and cons:

Table 1 Ways to handle elevation data - overview.

<table>
<tr><th></th><th>NO TIN</th><th>TIN as terrain (DTM)</th><th>TIN as surface (DSM)</th><th>TIN as surface for panel area (e.g., a roof manually digitized) plus TIN based on terrain for surroundings</th></tr>
<tr><td>Advantage:</td><td>Full manual control.</td><td>The intuitive way of seeing elevation.</td><td>Simple to handle roof top panels.</td><td>Simple to handle both roof top panels and obstacles, just entered by height.</td></tr>
<tr><td rowspan="2">Disadvantage:</td><td rowspan="2">Only for fully flat panel areas (although sloped roof top panels can be handled).

If not fully flat, panel designs and calculated shading will be wrong.</td><td>Requires manual calculation of ground offset for panels. Some intensive labour if many roofs with different heights.</td><td>Obstacles must be disabled from TIN and elevation manually set.</td><td>Requires "advanced" pre-processing of elevation data.</td></tr>
<tr><td colspan="3">Be aware that variation in TIN can distort the panel orientations if high resolution elevation data used. The terrain would usually be levelled out before construction and the same can be done in windPRO.</td></tr>
</table>

Special attention:	It can still have a high value for measuring purposes, to have access to surface data when designing the plant/ finding the obstacle heights.	Design of the PV plant MUST be related to the elevation data, NOT the background map. Often, these two sources can be shifted several meters relative to each other.

For sites with access to detailed surface data, e.g., 1 m resolution or better, surface is a great help for setting up a project on e.g., a roof. Below an example illustrates some features.

In the following example, the elevation dataset has a resolution of 0.4 meter. This can be very useful, yet it requires attention to the dataset's horizontal uncertainty, as there can easily be an offset between the location of a rooftop on the background map compared to the surface data.

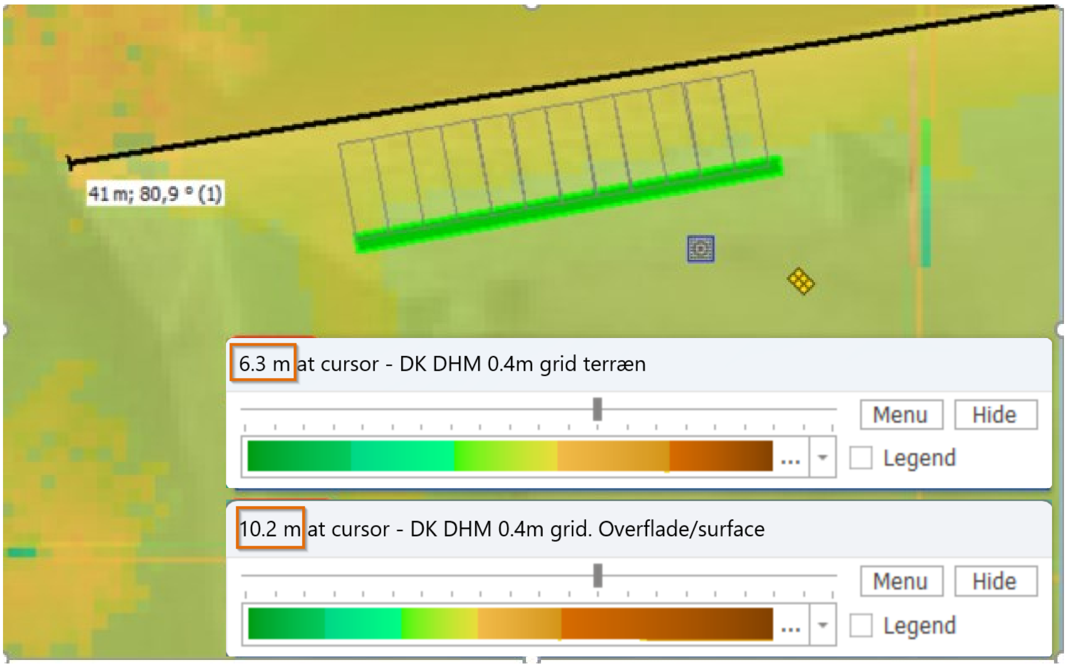


Figure 11 Terrain and surface data in two elevation grid objects.

In the above picture, the terrain and surface elevation are shown at one position.

Using terrain as TIN, the ground offset for the solar panel must be set to 10.2-6.3 m = 3.9 m.

Figure 12 Placing obstacle on background map for checking surface data.

The offset between orthophoto and surface data is seen by placing an obstacle on the highest roof points on the orthophoto.

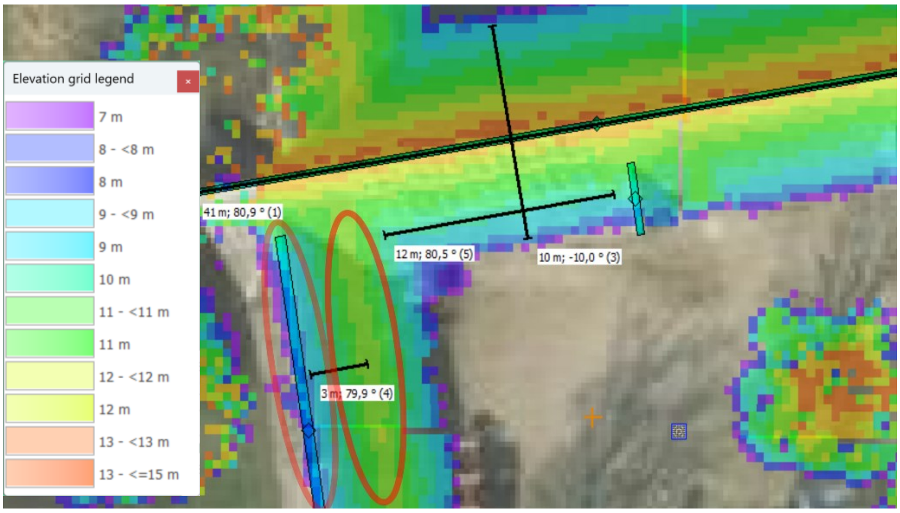


Figure 13 High resolution surface grid data show "elevation roof top".

A surface model with 0.4 m grid resolution is shown in Figure 13. The surface elevation data is 3 m off relative to Orthophoto in east direction. This can be seen by comparing the location of highest elevation (yellow colour) on the roof marked with red with the obstacle location. The difference between obstacle location and roof top from the elevation data is 3 m. This is important knowledge when designing PV plant based on surface data. The surface data decides where to place the PV panels, not the background map/photo.

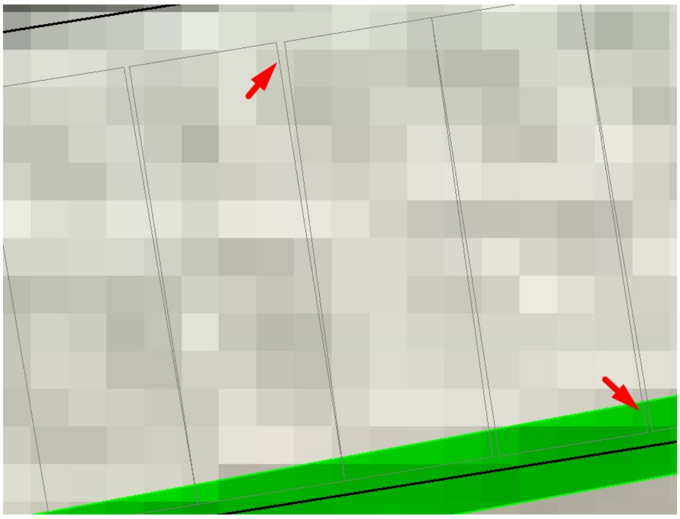


Figure 14 High resolution elevation data can violate design.

Here TIN from terrain. Due to smaller irregularities in the high-resolution terrain data, the panel arrangement is skewed. The solution is to modify the terrain elevation data:

Enter properties of the Elevation Grid object, select Edit layer and select an area to modify:

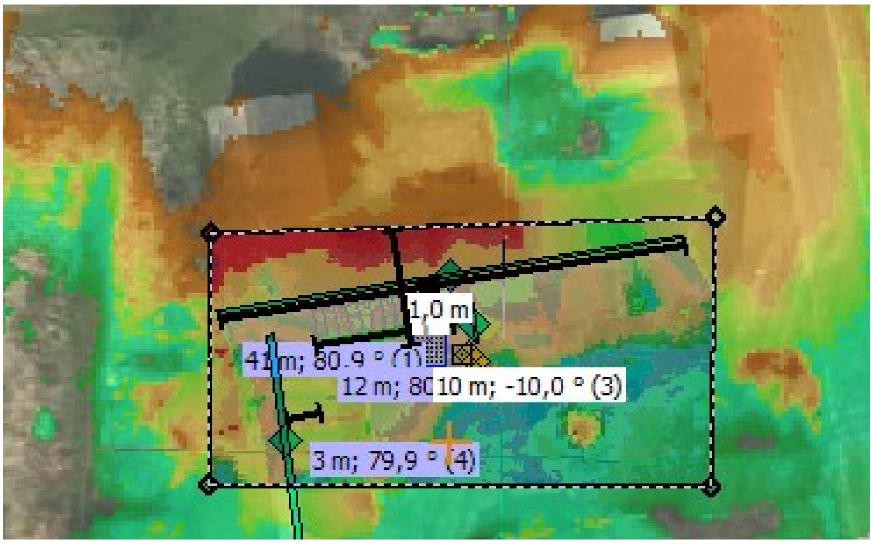


Figure 15 Select area for elevation grid modifications.

Within the selected polygon, the elevation should be 6.3 m, to get a fully flat basis for the solar panel arrangement:

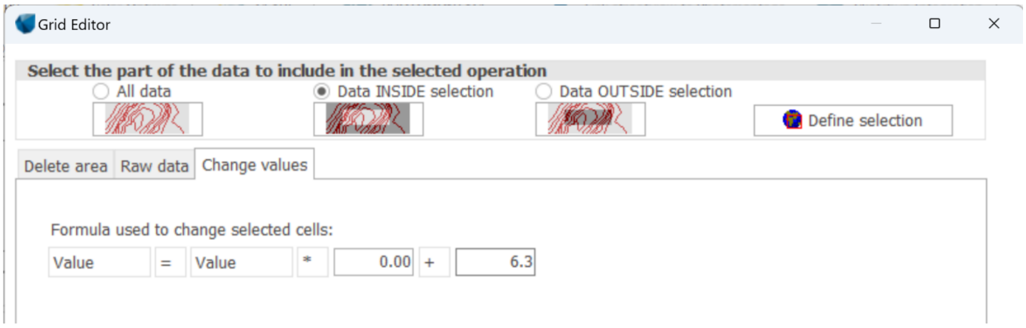


Figure 16 elevation data grid editor.

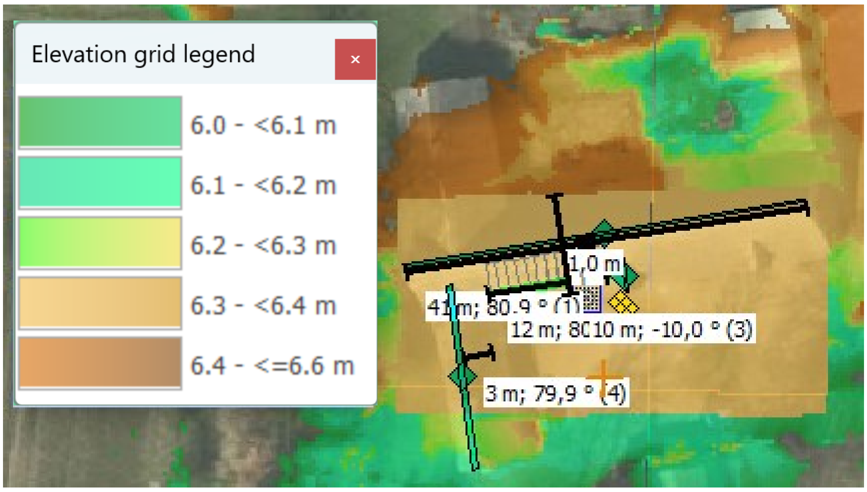


Figure 17 Modified (dozed) terrain data.

As seen in the above picture, there is now a fully flat terrain area where the solar panels are going to be designed. This is needed, while the panels are placed at a roof with homogenous elevation.

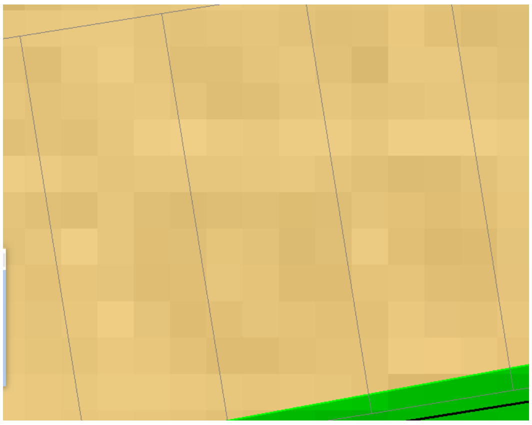


Figure 18 The terrain modified positioning of panels.

After *Update selected area* in the Solar PV status window is clicked, the PV area layout is updated and the panels are fully parallel, as they will be in a real installation.

Working with contour lines can be the faster and easier way to go, especially if the terrain or surface data must be established from scratch. Often, for solar plants on roof tops, sufficiently accurate elevation data will not be available.

14.3 Meteorological data

The easiest way to establish the meteorological data is by clicking on *Download data* in the *Meteo Solar Data* tab in Calculation setup. The Heliosat (SARAH) (if available for the site) plus ERA5-T data will be downloaded for the nearest data point to the site. Solar irradiance, temperature and humidity are downloaded.

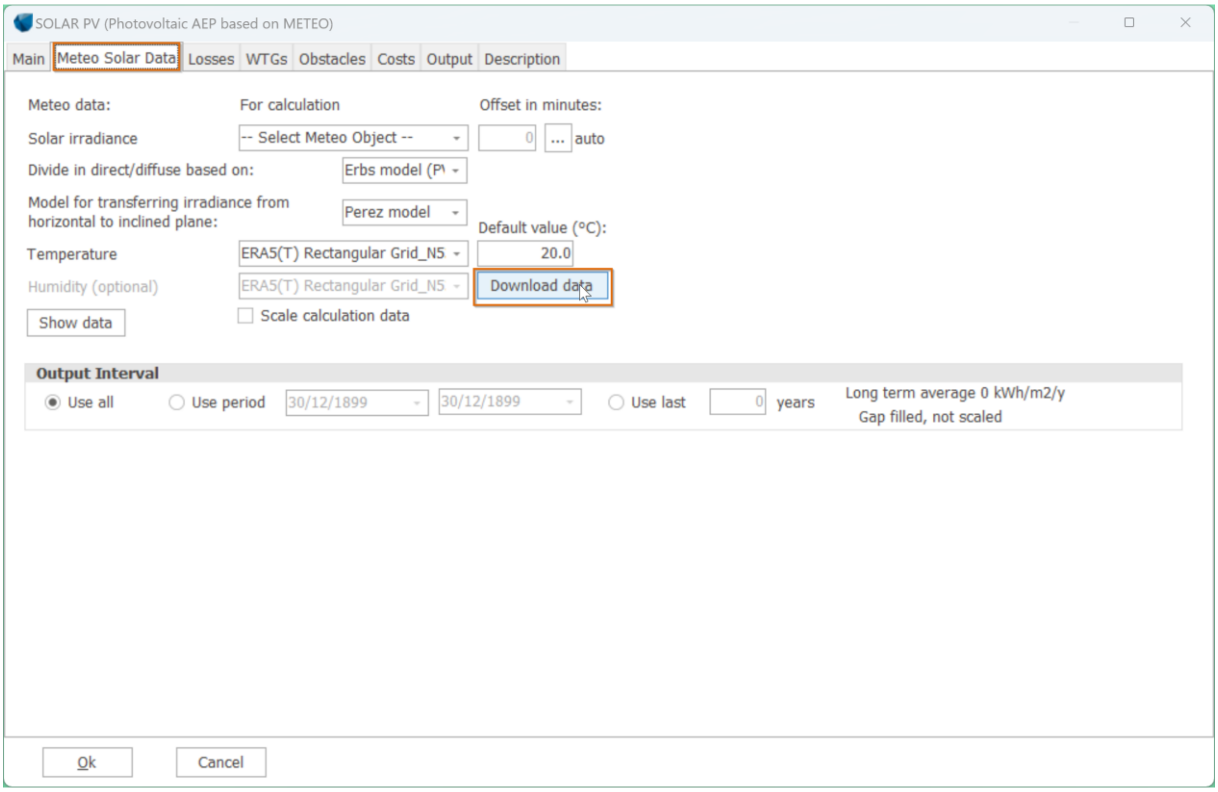


Figure 19 Downloading irradiance, temperature and humidity data from SOLAR PV Calculations setup.

The two data sets, Heliosat (SARAH) and ERA5-T are chosen by default when downloading the data. Tests have shown that these are the most precise data sets. Heliosat (SARAH) outperforms ERA5-T but does not provide global coverage (see coverage in Figure 21 and Figure 22). ERA5-T is the second-best dataset available in windPRO and provides global coverage. Both datasets are updated monthly, within 1-2 weeks after month end, offering historically full, actual data. These downloads do not require license to the METEO module.

For users looking for more flexibility while working with the data, for example, use local measurements or make more comprehensive analyses or modifications of the data, the METEO license is recommended. METEO object along with the Meteo Analyzer tool offer a comprehensive solution for data handling. The workflow is described below.

Start by inserting a  Meteo object in the map window:

Click at the object symbol, then click at the map (anywhere, the exact geographic location of this object is not used in Solar calculations). The Meteo form open with this window:

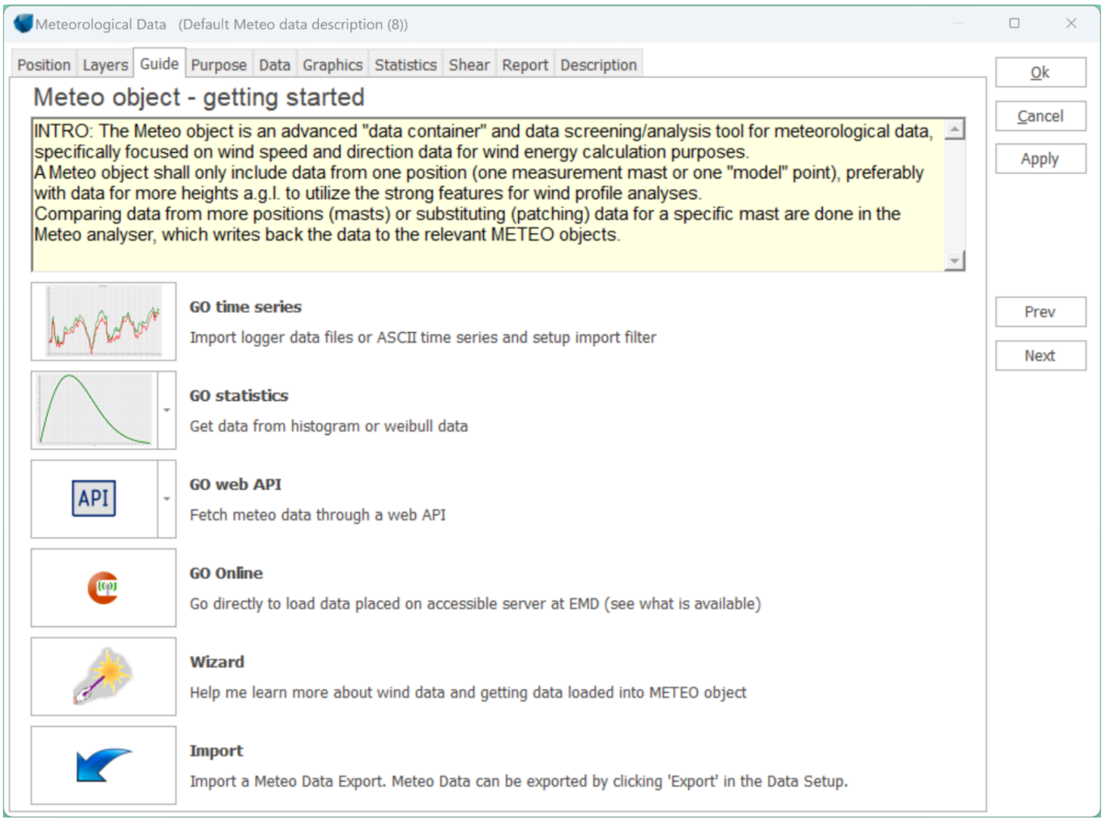
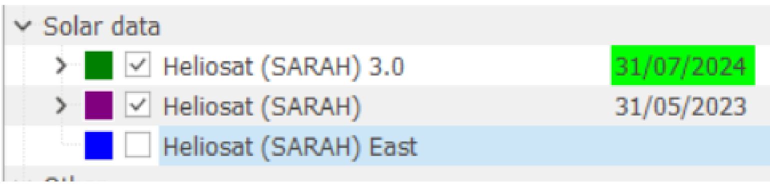


Figure 20 Meteo object start window.

Depending on which data you have available/want to use, different option needs to be selected:

Local measurements as time series in text files – use GO time series, see Meteo manual for details.

Downloading online data – use GO Online. Here it will be possible to select from multiple data sets. It is highly recommended to use these Solar-PV license data:



Tests show, that this model dataset represents local measurements very accurately, as it is based on satellite measured cloud coverage, which makes the cloud representation much more accurate than in other model data. For reference, see:

https://www.cmsaf.eu/SharedDocs/Literatur/document/2016/saf_cm_dwd_val_meteosat_hel_2_1_pdf.pdf?__blob=publicationFile.

Starting from windPRO 4.1, Heliosat (SARAH) 3.0 is available in windPRO. It is the newest version of the dataset, which is being updated monthly by the provider. The EMD databases will hold data back to 1999. As part of the integration of the dataset in windPRO, the EMD team prepared a validation note. It can be found here:

https://help.emd.dk/mediawiki/images/c/cf/20240222_SARAH3_Evaluation.pdf

The Heliosat (SARAH) dataset is available for a quite large area, see coverage in Figure 21. Heliosat (SARAH) data are composed by utilization of satellite images of cloud coverage with 30 min. resolution in time and ~5 km spatial resolution. There are two data sets - West and East (lower resolution).

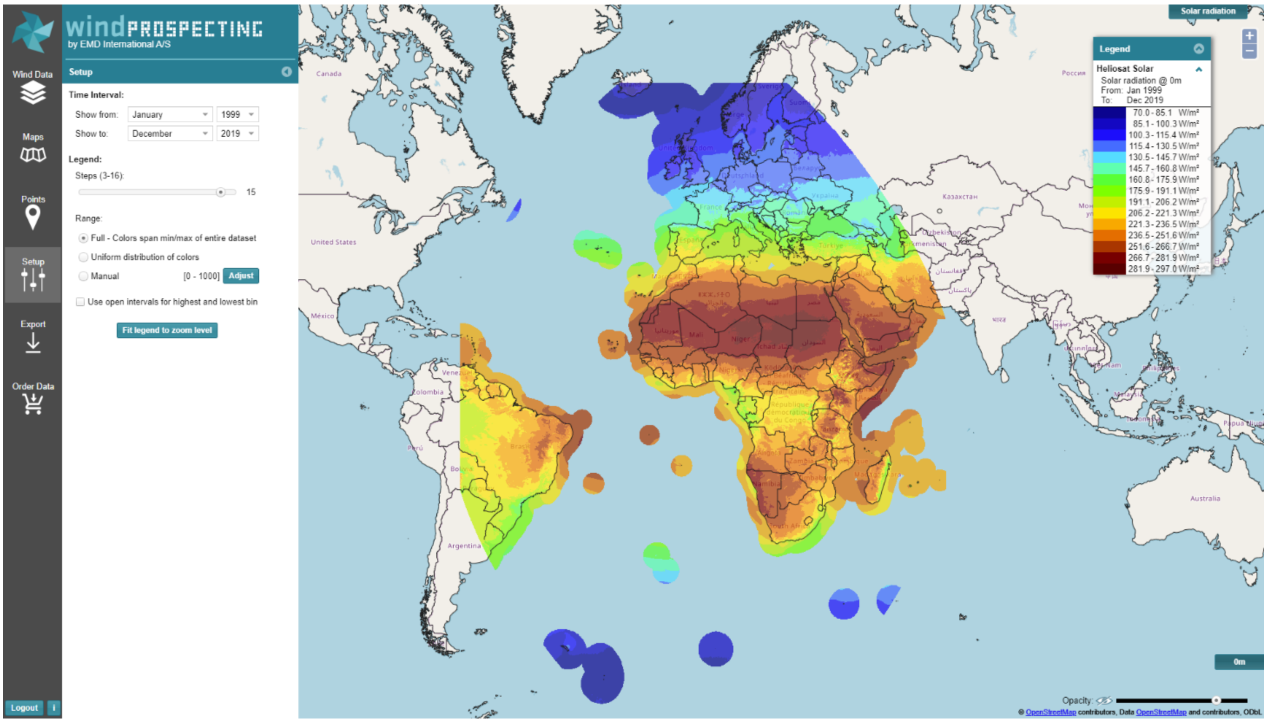


Figure 21 Heliosat West data coverage – Europe, Africa and part of South America.

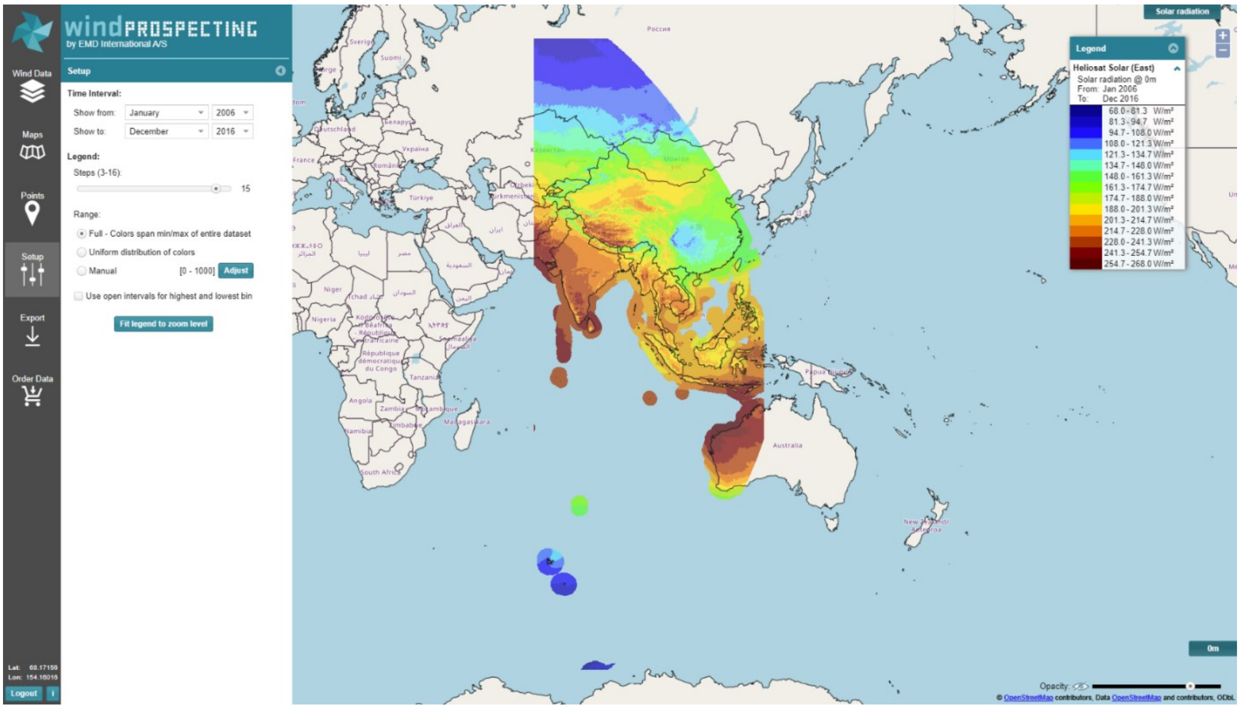


Figure 22 Heliosat East data coverage - part of Asia and Australia.

The Heliosat (SARAH) data are updated monthly and are available in the Online Data service with a Solar-PV license for windPRO.

If the project is outside the regions covered by Heliosat (SARAH) data, it is recommended to use ERA5-T data.

After downloading Heliosat (SARAH) or ERA5-T data, you now have a solar radiation data set. In addition, a Meteo Object with Temperature is necessary, optionally also Humidity. Here ERA5 or ERA5-T (updated within a week after end of the month), will be sources accurate enough and available worldwide. If you have subscription to EMD-WRF data sets (mesoscale data), use these to get a more accurate temperature and humidity data set, mainly due to the higher spatial resolution.

14.3.1 *Meteo analyser* for advanced data analysis and substitution

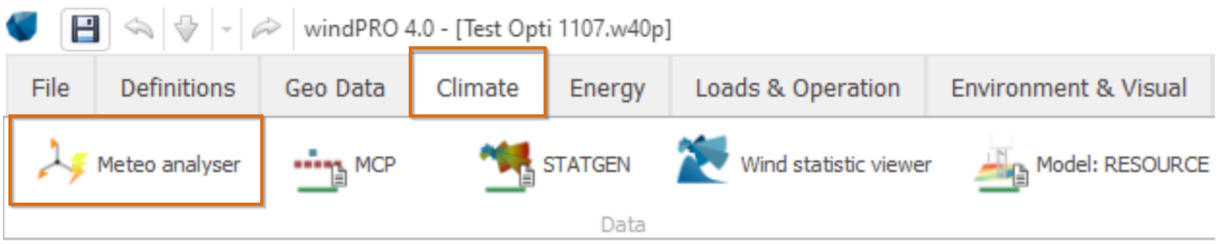


Figure 23 How to start the Meteo analyser.

The *Meteo analyser* is a comprehensive tool for comparing different time series, loaded in different *Meteo objects* (see Meteo manual for a more comprehensive guide). The tool can:

- View time series from many different sources together
- Extract concurrent data for comparison 1:1
- View aggregated time series by year, month, diurnal or view running averages

- Disable bad data for selected periods (graphically)
- Substitute data from one time series into another

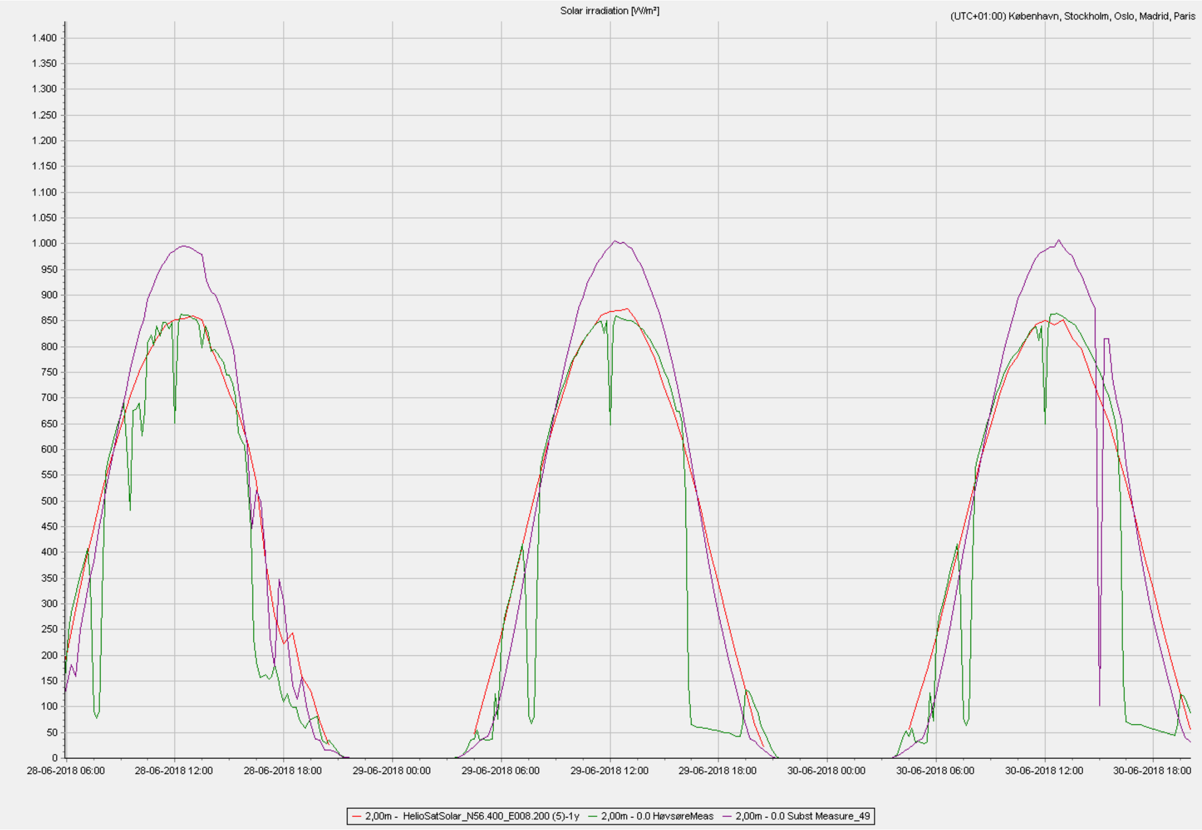


Figure 24 Data inspection by meteo analyser tool.

The graph shows 28-30th of June 2018. Purple is local measurements, green Høvsøre (nearby "official" measurement mast), red Heliosat (SARAH) on-line model data.

A couple of interesting observations can be made comparing these three data sets:

There are systematic down spikes in the Høvsøre data, probably related to shading from the mast on which the radiation measurement equipment is mounted. Especially in afternoon, a longer down period is seen. On the afternoon of the 28th (left peak), some clouds are passing, this is seen as well in the local measurements as in Heliosat (SARAH) data. This is what makes the Heliosat (SARAH) data set very strong compared to other model data, because clouds are included quite accurately. It is also seen that the local measurements are too high at the middle of the day. Which based on later information received, was later found to be due to tilted measurement equipment, not radiation on horizontal, as assumed. Høvsøre and Heliosat (SARAH) fully agree on the middle of day irradiance level. This shows the importance of knowing how the data are measured. Currently, the module does not yet include the capability to use tilted measurements, only measurements on horizontal plane.

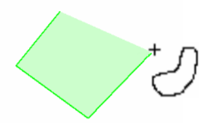
14.4 PV-plant/panel design

Start by inserting a *Solar PV object* in the map window:

Figure 25 How to insert a Solar PV object.

Place the *Solar PV object* near the area you want to establish solar panels (here we will design a solar plant at the light grey area NE of the WTG). The exact position is not important, but the map will automatically zoom into the area where the object is placed. The object must be close to the project location though because the Top of atmosphere radiation is calculated for the location.

Once placed, the cursor changes to a drawing cursor, so you can draw an area by left-clicking on the map. The selected points will be the corners of the area. If Caps Lock is activated the area will be digitized by simply moving the cursor over the map.



To stop digitizing the area, right-click and select *Stop*.

The area will automatically be filled with solar PV panels:

Figure 26 Creation of PV area.

14.4.1 Panel tables design options

From windPRO version 3.5 it is possible to select how the panels/tables shall be arranged within the area.

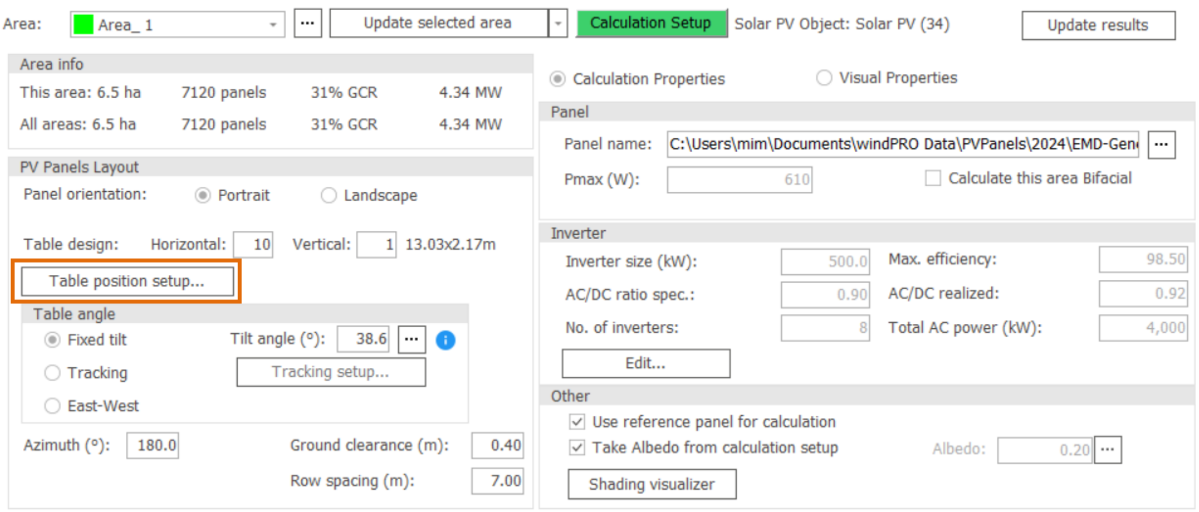


Figure 27 Table position setup button placement.

Press the *Table position setup…* button to get the options:

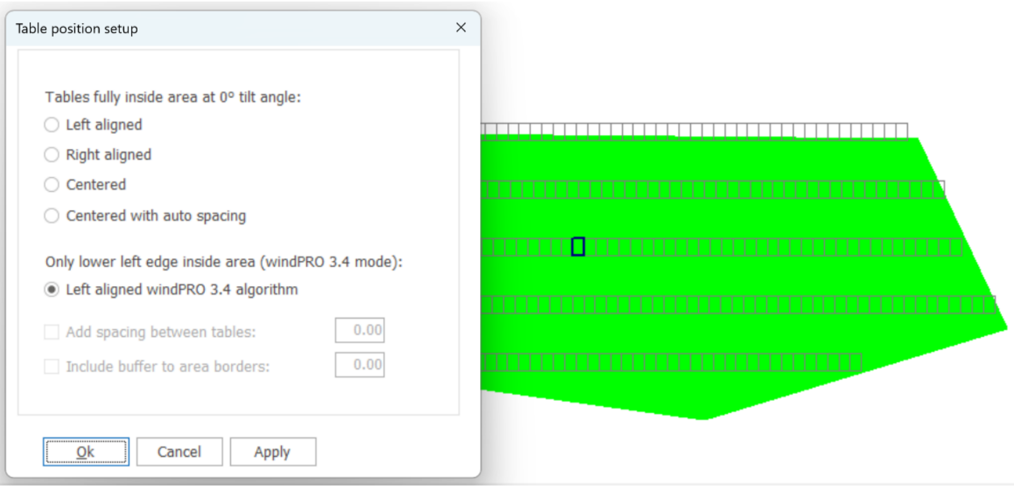


Figure 28 Panels arranged in windPRO 3.4 mode.

In previous windPRO versions, panels were aligned left, with only the lower part of panel/table inside the area.

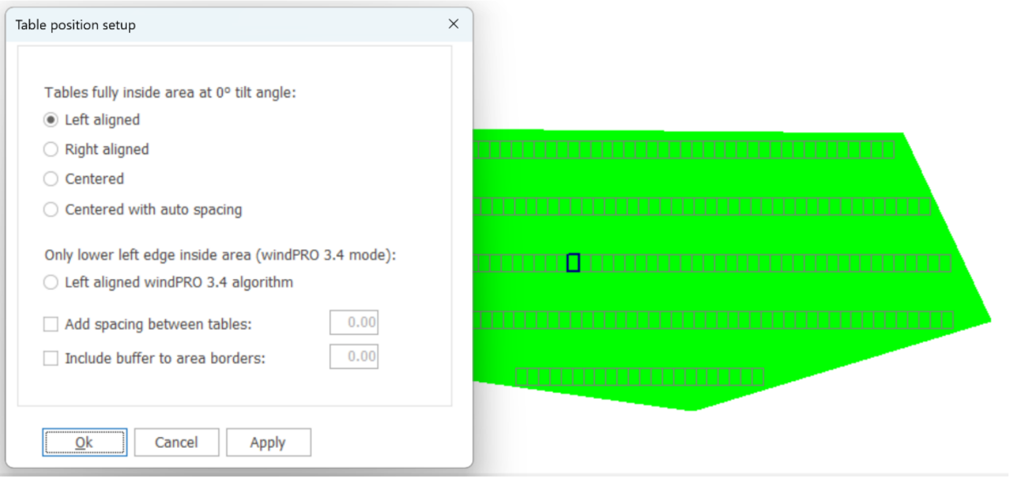


Figure 29 Panels left aligned fully inside area.

Starting from windPRO 3.5 the panels are left aligned and all panels/tables are fully inside the area with a tilt of 0 degree. 0-degree tilt is used to keep consistent layout regardless of the tilt selected tilt angle and if tracking is chosen. As many panels/tables as possible will be fit into the selected area and the number will not change depending on the tilt angle setting.

Note: The options in the *Table position setup* window are dynamic based on the azimuth angle. The above shows options available for 180 degrees +/- 45 degrees on northern Hemisphere. For 90 degrees +/- 45, options will change from *Left* to *Bottom* and *Right* to *Top* etc. For 270 degrees +/- 45 degrees, *Bottom* and *Top* will switch position.

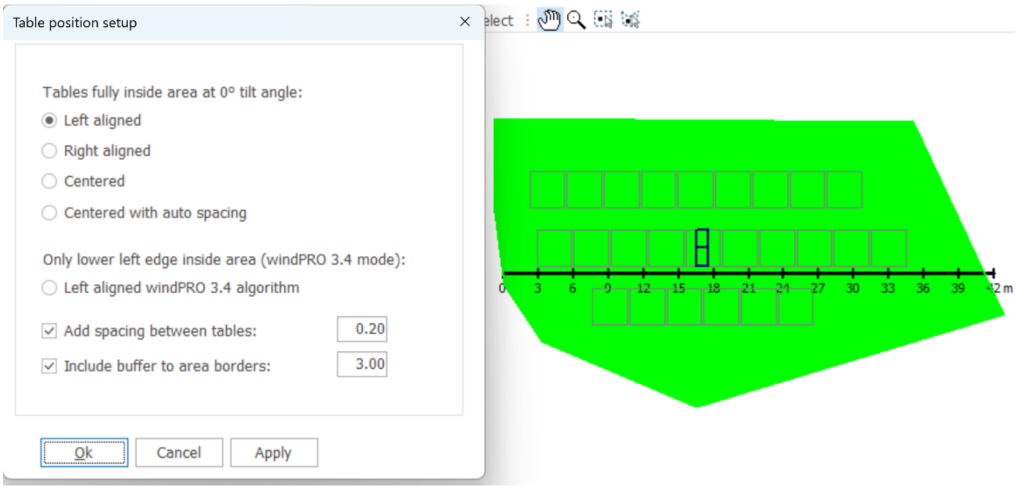


Figure 30 Panel design, illustration of flexibility.

As shown in Figure 30 a buffer to area borders and spacing between panels can be added. This leaves a high degree of flexibility.

Note: To update the layout on the map use the *Update selected area* button or *Update ALL areas* button. The design properties are individual per area. With the dropdown list in the Solar PV status window, it is possible to select how the changes should be applied:

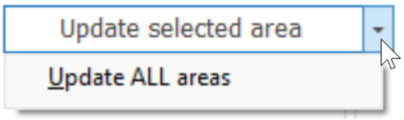


Figure 31 Dropdown list for updating area settings.

By clicking on *Update ALL areas*, the design properties are written to all areas along with all other settings.

14.4.2 Exclusion areas

It is possible to define exclusion areas, where no panels are to be installed. This can be used to remove panels and create some open space for substations, access roads, buildings etc.:

While in edit mode, right-click on the map where you want to start digitizing the exclusion area and select *Create new Solar PV Area*:

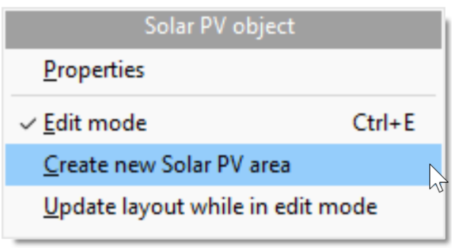


Figure 32 Create new Solar PV area.

Then define the area as an *Exclusion area*:

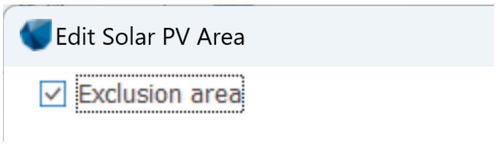


Figure 33 Create Exclusion area.

Click Ok, and start digitizing the exclusion area:

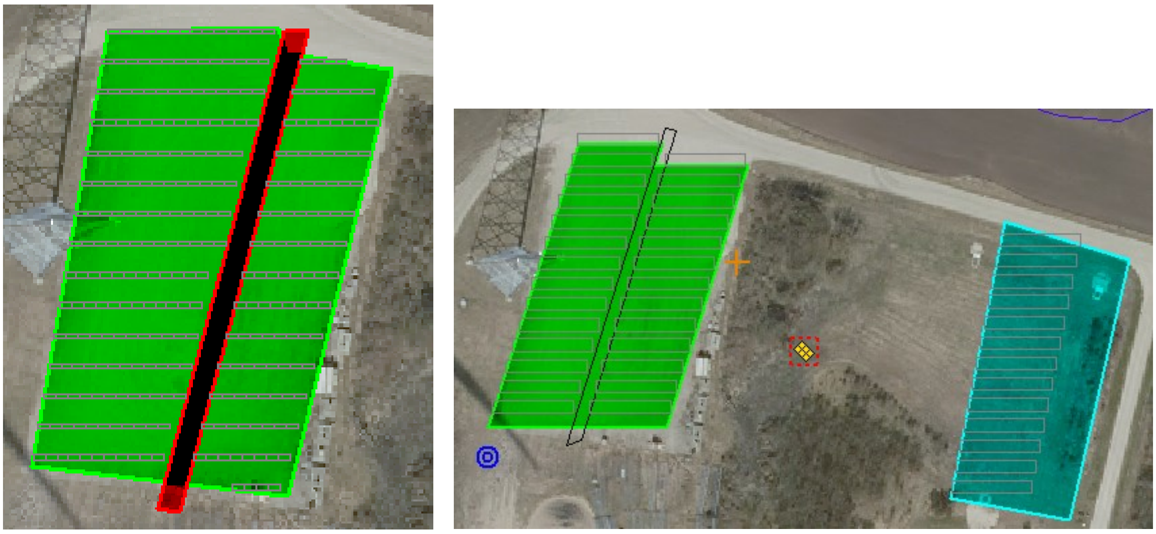


Figure 34 Exclusion area on map. Right with extra area added.

Multiple PV areas and Exclusion areas can be created within the same Solar PV object. The list of created areas (except the Exclusion Areas) can be seen in the PV status window in a dropdown list:

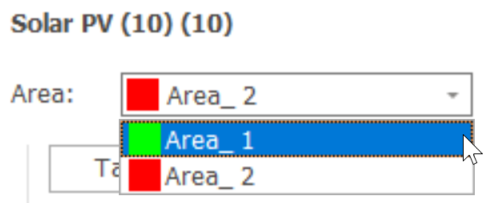


Figure 35 List of Areas in the Solar PV object status window.

14.4.3 Plant design explanations one-by-one

Each area can have different characteristics to the panel layout, panel type, visual design etc. This section describes the settings one by one. The status window is divided into groups of settings. The left part of the window is static, whereas in the right part of the window it is possible to select between *Calculation properties* and *Visual properties*.

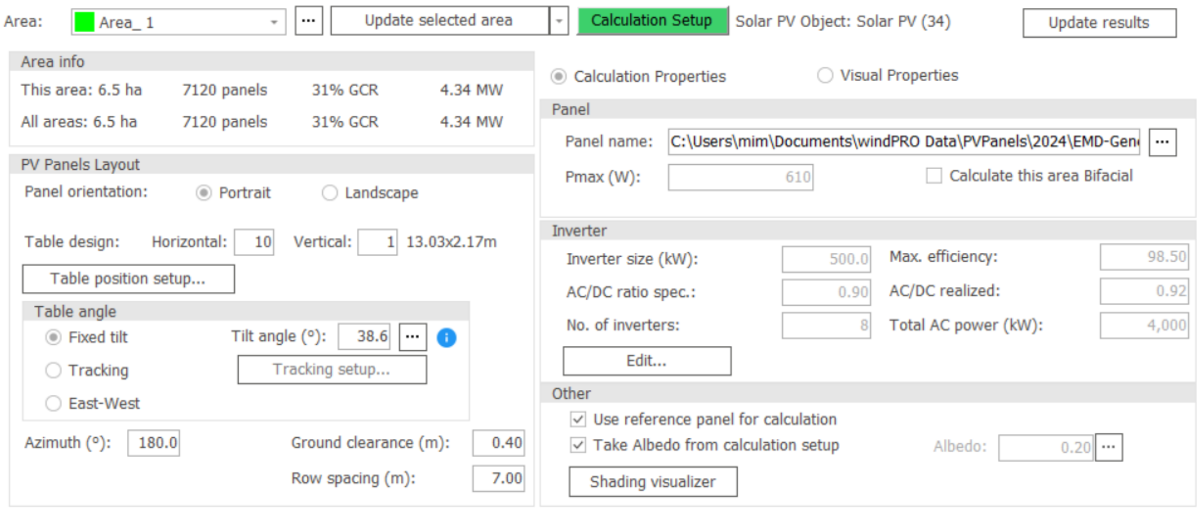


Figure 36 Solar PV object status window, where parameters of the plant can be specified.

Area selection drop down list

Allows you to choose the area for which properties are displayed in the window. All areas can have individual settings. By clicking on the three dots, the name and color of the selected area can be changed, the area can be deleted or centred on the map by selecting Focus on map.

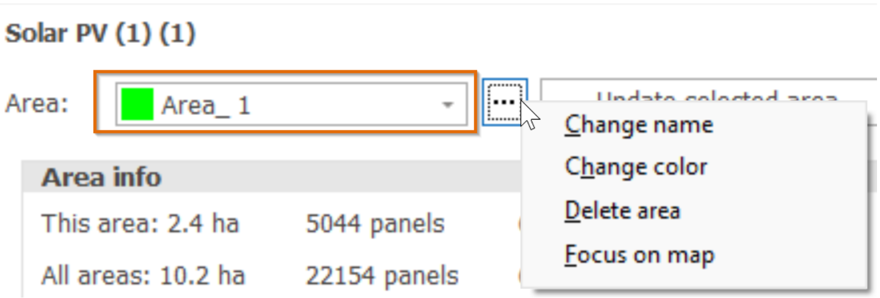


Figure 37 Area's dropdown list.

Area info

This section shows the size of the area in m2 or ha, number of panels, Ground Coverage Ratio (GCR) and installed DC power in kW or MW. The second line shows the same properties but for all areas combined.

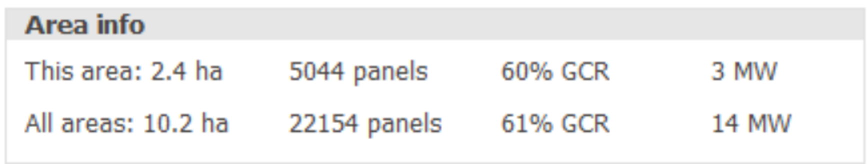


Figure 38 Area info section in the Solar PV status window.

PV Panels layout

In this section it is possible to specify the details about the *PV Panels layout* in the Area.

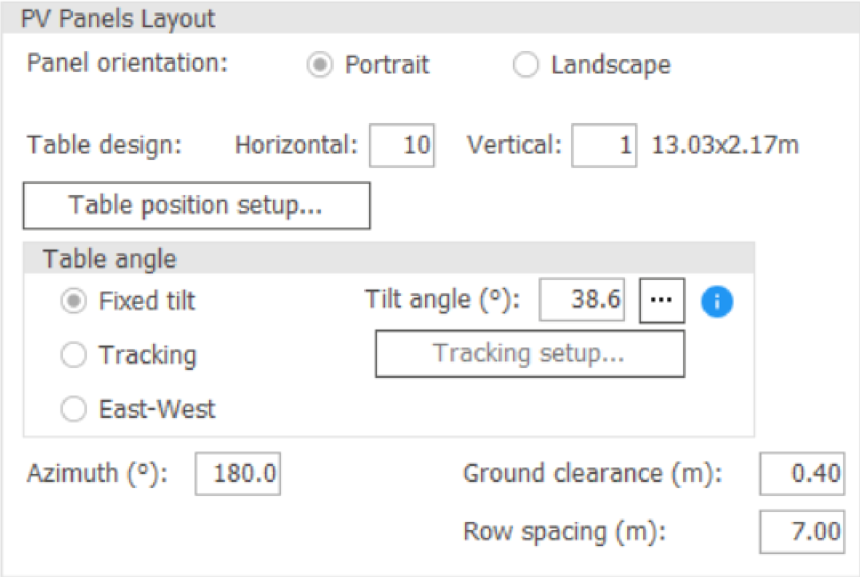


Figure 39 PV Panels Layout section in the Solar PV status window.

The following settings are available here:

- Panel orientation – defines how the panels are installed, bypass diode placement should be considered here. If mismatch between the orientation and bypass diode placement is detected a warning will be shown.
- Table design – defines the size of the table, a table defines the number of panels installed as one building block of the array. If more panels are to be installed in vertical direction it should be specified in Vertical. If there is a minimum requirement for length of one row, this can be specified in Horizontal. This is a useful setting when considering an inverter/string for a minimum number of panels in one row. The table will have locked Z-coordinate for the full table.
- Table position setup – possibility to change placement of panels/tables inside the Area, distance to the border and spacing between panels/tables can be added. See more details in Section 14.4.1
- Table angle – here it is possible to select between Fixed tilt system – where the tilt should be specified in the field Tilt angle, Tracking system – where one axis, horizontal tracking can be selected and East-West – where the panels are placed facing two opposite directions. If Tracking system is selected, the setup window is available by clicking on *Tracking setup…* button. Tracking is described separately in section 14.4.4 . East-West configuration is described in more details in 14.4.5 .

  The Tilt angle (in fixed tilt systems) is by default the optimal for the location, giving highest production for a panel free of shading. Often a lower tilt than the default will be used. As an example, for a Danish site where the optimal angle is around 40 degrees, a 20-degree angle will be used as optimal when array shading is accounted for (more panel rows, not mounted at a sloping roof). Wind loads and substructure costs will also be positively affected by the lower tilt angle. The three dots button to the right of tilt angle optimizes the tilt angle. This is a nice feature that makes a net AEP optimization including all losses by simulating the data period specified in calculation setup, where an optimization algorithm seeks towards the highest value by modifying the tilt angle.

- Azimuth - follows the general conventions in windPRO, 0° is north, 90° is east, 180° south, etc. In the northern hemisphere this means, that 180° will make the panels face towards Equator and on the southern hemisphere, 0° will make panels face Equator. These are the defaults when creating a new project.
- Ground clearance – is the distance from the ground to the lower edge of the panel. If tracking is selected, the field name changes to *Axis above ground level* and it is the distance to the centre of panel/table, where the tracking device is assumed mounted.
- Row spacing – in fixed tilt and East-West systems: distance between the lower front edge of the panel in one row to the lower front edge of the panel in the next row. In tracking systems: distance between the centre of the panel in one row to the centre of the panel in next row.

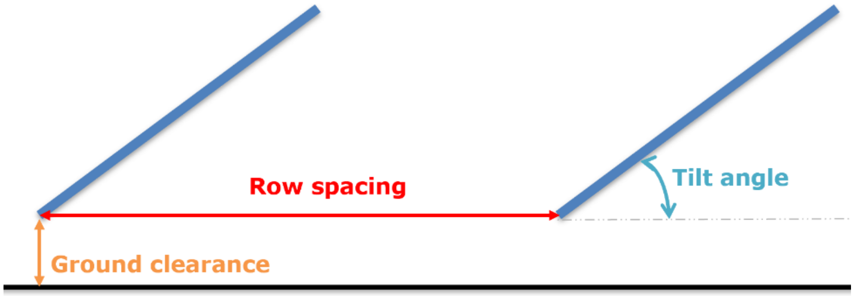


Figure 40 Definition of parameters to be specified in PV Panels layout (fixed tilt system).

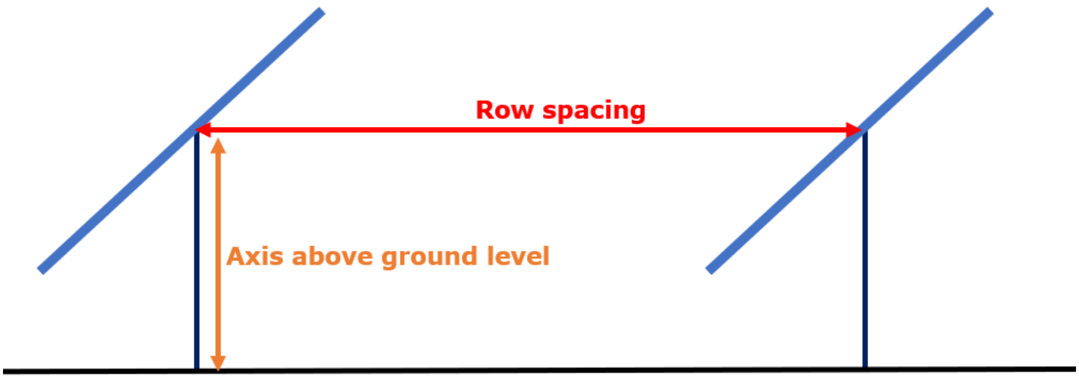


Figure 41 Definition of parameters to be specified in PV Panels layout (Tracking system).

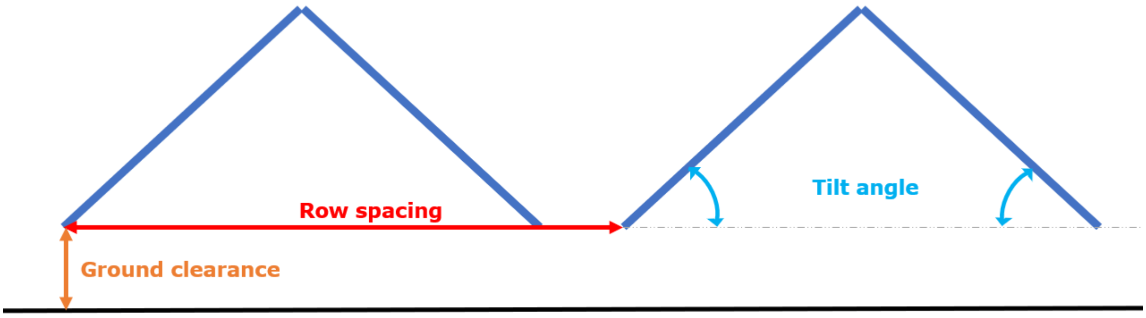


Figure 42 Definition of parameters to be specified in PV Panels layout (East-West system).

Panel

Here a quick view of which PV panel is selected for the calculation.

If the *Calculation Properties* is selected the panels power is shown and it is possible to specify if the Area should be calculated as a bifacial – if the selected panel is not bifacial, a red warning message will be displayed but the calculation will still be possible and done using the default value of Bifaciality Factor specified in the Calculation Setup.

If *Visual properties* is selected the .dae file used for visualization is shown.

By clicking on the three dots next to the panel name it is possible to Select another panel, Edit the existing or create a New one. See more details in section 14.5 Panel specifications.

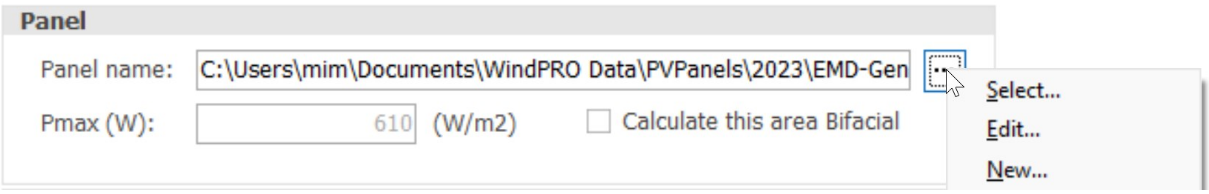


Figure 43 Panel section in the Solar PV status window.

Inverter

This setting section is only shown if *Calculation Properties* is selected. The main parameters of the inverter (Inverter Size and Maximum Efficiency) are shown in the top. The remaining values indicate what is the AC/DC ratio, both specified and realized, the number of inverters and resulting AC power. The properties of the inverter can be changed by clicking *Edit…*

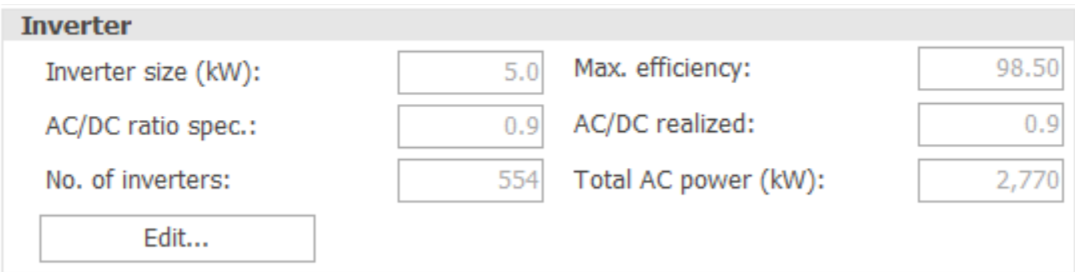


Figure 44 Inverter section in the Solar PV status window.

Other

This section is only shown if *Calculation Properties* is selected. In the Other section of the window, two settings are available: *Use reference panel for calculation* and *Take albedo from calculation setup*.

Use reference panel for calculation is a very important feature for large plants. It is simply not possible to calculate plants > ~50 MW within a reasonable timeframe. A 50 MW plant takes around 1 hour to calculate, depending on the shading calculation settings and computer specs. With the reference panel calculation, it takes less than 1 minute, and huge plants can be calculated within minutes. The approach when designing a large plant for using reference panel is to design the areas based on similarities. The Solar-PV areas should be created, so that all panels within the areas have reasonably similar conditions regarding shading elements and/or terrain slopes. If it is a hilly site, make an area for the east-west slope and another for the north-south sloped terrain etc. If there are critical shading elements, like obstacles or WTGs make a separate area around these, and possibly do not use representative panel for these areas, but only for the larger areas without special shading elements. On the map it is possible to select the panel stack to be the representative one. By stack is meant that if multiple vertical panels are on top of each other a reference panel is the full stack, while the bottom panel has more panel shade than the top panel. Therefore, it is needed to calculate for the full stack to get a reference panel (stack). It is also advised to use this setting in preliminary calculations.

Take Albedo from calculation setup can be checked or the Albedo can be entered. The Albedo is of high importance for bifacial gain as it describes how much the ground reflects. A white surface will reflect much, a black surface little. Default is 0.2, grass.

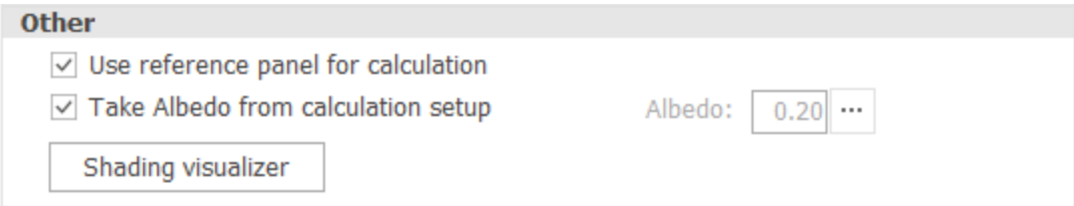


Figure 45 Other section in the Solar PV status window.

Photomontage

This section is only shown if *Visual Properties* is selected.

Here it is possible to view the PV table by clicking on *Preview table*.

The substructure to be used in PHOTOMONTAGE can be defined here – see more in the PHOTOMONTAGE manual.

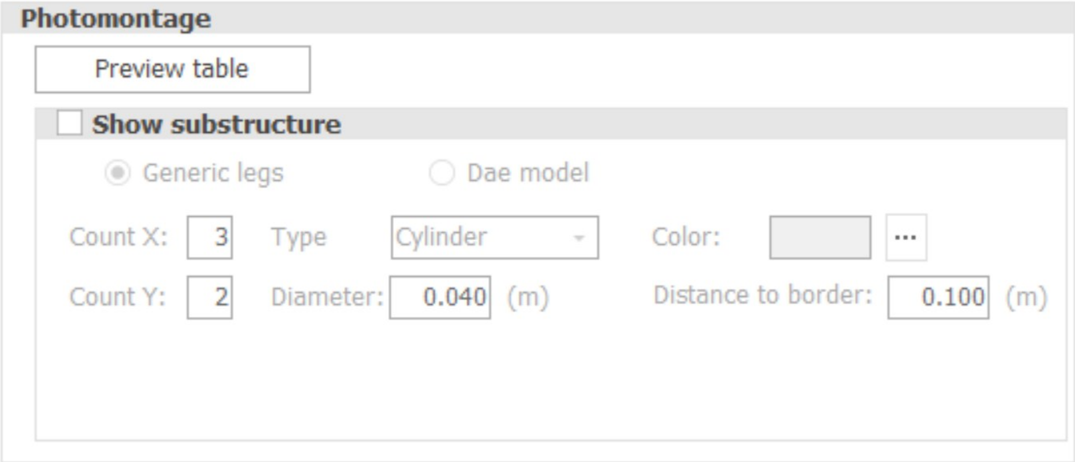
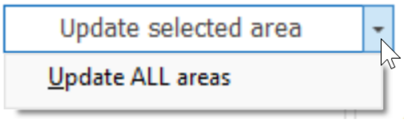


Figure 46 Photomontage section in the Solar PV status window.

Note: To update the layout on the map use the *Update selected area* button or *Update ALL areas* button. The design properties are individual per area. With the dropdown in the Solar PV status window, it is possible to select how the changes should be applied:



If all design parameters are used for all areas, use the button *Update ALL areas*. Then ALL the present settings will be written to all areas, so be careful with this if individual properties per area regarding part of the parameters is a wish.

14.4.4 Tracking settings

When activating tracking the following window opens:

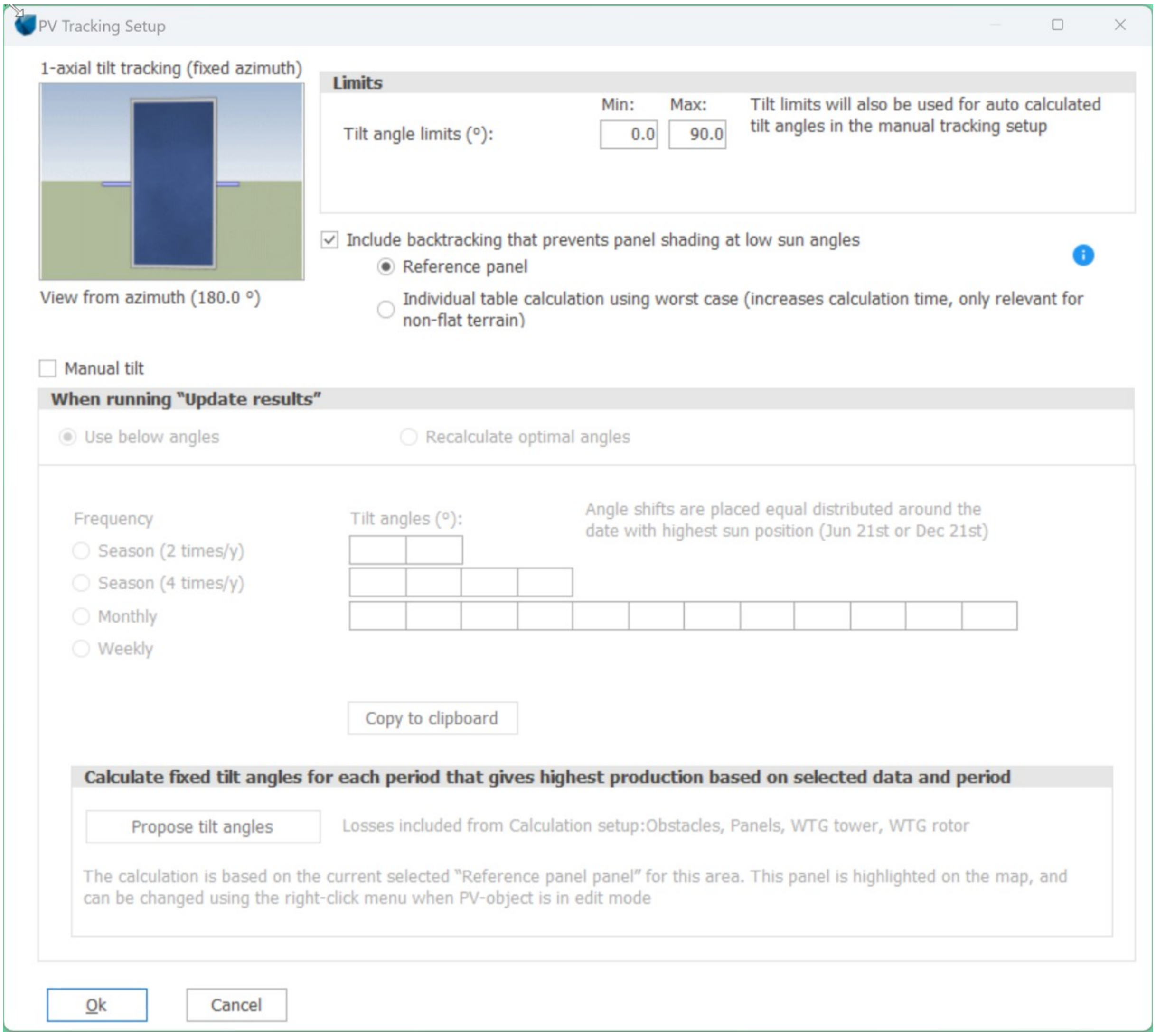


Figure 47 Tracking settings.

So far, only 1-axial tilt tracking is available, but these settings are well-suited for panels facing the Equator as well as East-West facing panels.

The two main options are manual and continuous tracking. For both of the options backtracking can be included – see the description below.

Manual tracking

The panel tilt is set by season, and typically only used for panels facing the Equator. The optimal angle giving highest net AEP is calculated by an optimizer component.

Backtracking (lower tilt at low sun angles to prevent more panel shading loss than gain by tilt perpendicular to sun angle) can be included in the calculation, but only if panel shading is included in calculation setup. To save calculation time when updating the calculations, it is possible to lock the calculated tracking angles – this can speed up the calculation when changes to the area are made. If changes are made to the table/panel size or row spacing, the recalculate option should be chosen as the optimal angles can change.

Continuous tracking

For continuous tracking, the angles are calculated automatically for each timestep. It is possible to specify limits on the tracking angles, which are used during the calculation to not allow the tracker to change the position below the minimum and above maximum specified angle. These limits can also be used for manual tracking angles calculation.

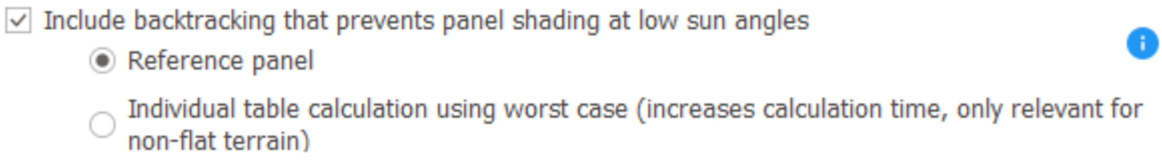


Figure 48 Options for backtracking.

Backtracking option can be selected to prevent panel shading – this is recommended for all calculations. A reference panel can be used, or the user can calculate for all panels and use worst case tracking. In terrain with elevation differences, the panel shading free tracking angles highly depend on if a table is lower or higher elevated than its neighbour tables. Which one of the two options to use depends on how the tracking will be set up in the real project. There could be many possibilities. Some projects even work with group tracking - meaning that the trackers work together to minimize the overall panel shading.

14.4.5 East-West facing panels

It is more and more common to establish panels facing east and west, due to better electricity prices morning and afternoon than midday.

Starting from windPRO 4.1, it is possible to easily perform calculations and visualization for East-West facing panels by selecting this kind of system in the PV panels layout section in the status window – see Figure 49.

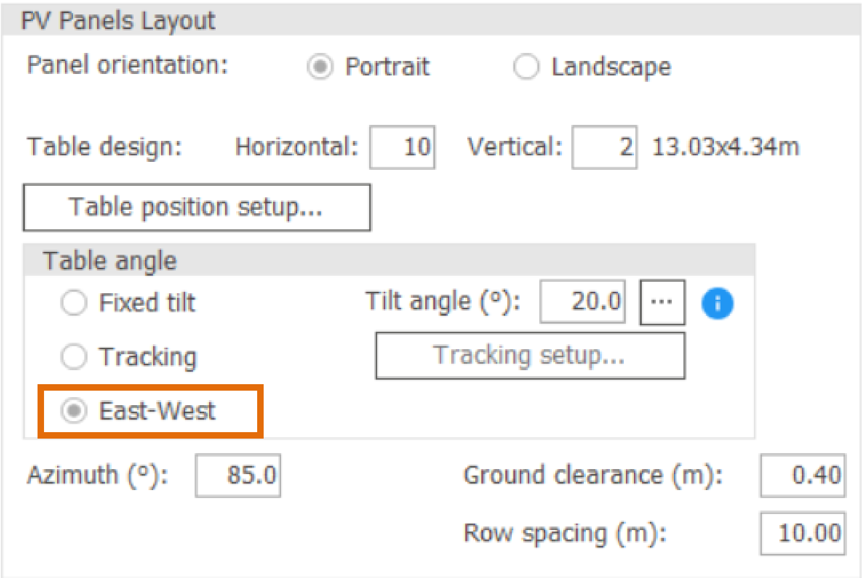


Figure 49 East-West PV plant selection in the Solar PV status window

When East-West PV plant is selected, a twin area is automatically created in the Solar PV object. The two areas have the same name and color, each of them is marked with the orientation of the PV panels in the area. All changes, made in either of them, are automatically applied in the other one. The difference between the orientation of the modules is always 180 degrees and is not only limited to panels facing exactly East and West – if the available are or other conditions make other orientations more favourable they can also be modelled in windPRO. The installed capacity and number of panels is always the same in the twin areas.

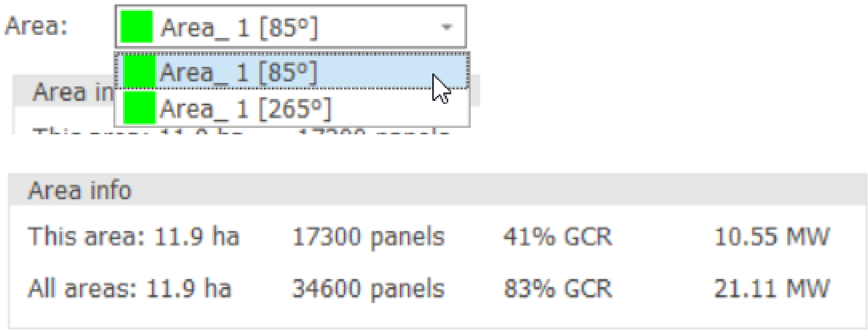


Figure 50 East-West PV plant setup in windPRO. The top figure shows the representation of the twin areas, the bottom is a summary of the details of the plant.

The PV plant is represented as one area on the windPRO background map – see Figure 51.

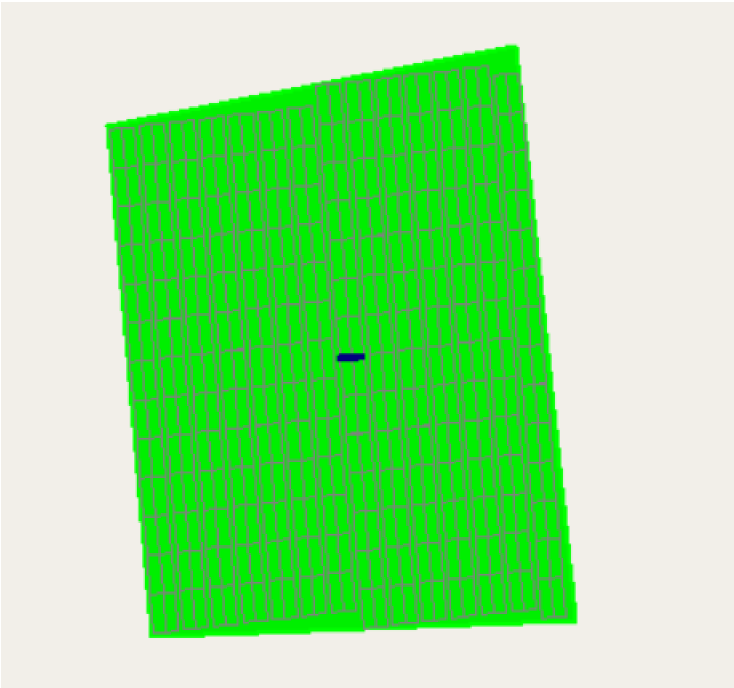


Figure 51 East-West PV plant presentation on the background map in WindPRO

The East-West facing PV panels can also be easily visualized using the PHOTOMONTAGE module as shown in Figure 52.

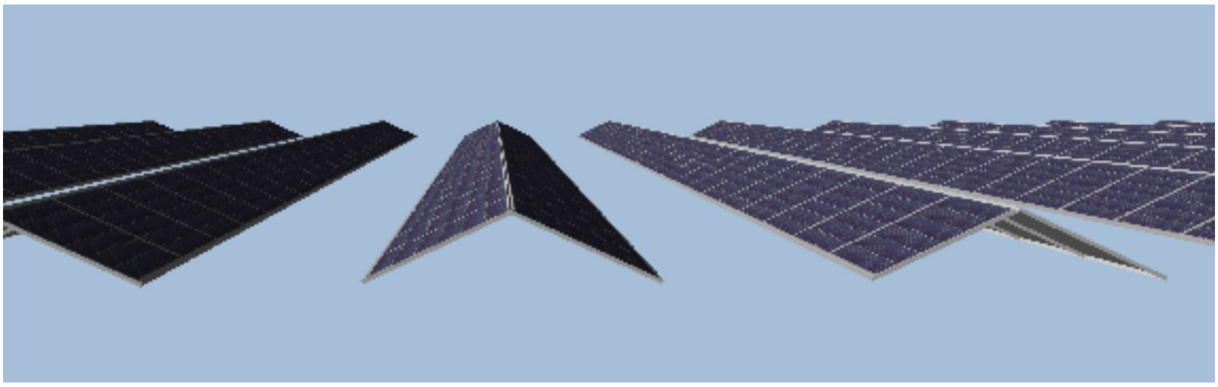


Figure 52 Visualization of East-West facing panels.

14.5 Panel specifications

The panel data describes the panel size and power output and how this is affected by temperature. In addition, by-pass diodes for reduction of shading loss can be described. Finally, data for visualisation can be added for visualisation in PHOTOMONTAGE.

Panels can be oriented either in portrait or landscape arrangements in the layout. This, in combination with the by-pass diodes, is important for the shading loss.

14.5.1 Database structure

Panel data are saved in files. This makes it easy to share and move files between users.

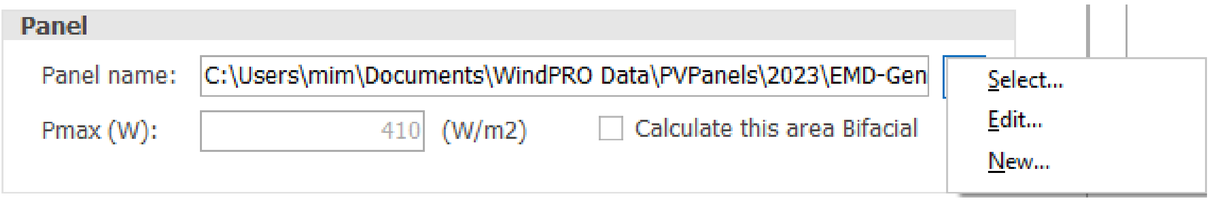


Figure 53 Access to panel data editing by the […] button.

The user can create a new panel data by clicking the […] button next to the panel name selection list and selecting "New…", edit the existing file by selecting "Edit…" or a select another from the saved panels by clicking "Select…"

If "Select…" is chosen, the database of PV panels will be opened. It is divided into year. Inside each of the years folders, a list of generic panel files available with windPRO installation can be found. The panels have properties based on the values seen on the market in each year. This is a good starting point of the analysis, when the specific panel was not yet selected. The panel file holds information about the panel specifications used in energy calculations as well as the visual properties used for photomontage. Hence, starting from 2023, separate files are prepared to represent different visual properties of the panels. This makes it easier to use the PV panel files in visualization. The properties are included in the name of the panel file, where the available options are:

- Bifacial or not – this determines if the module is bifacial or not, the .dae file for visualization is different and the Bifacial is enabled in the Bifacial panels together with a generic Bifaciality factor
- Light Edge or Dark Edge – this determines the color of PV panel frame

- Portrait or Landscape – this determines the orientation of the panel, correct .dae file must be chosen for correct visualization – see more in section 14.12.1

Other properties of the panels with the same power in the database are kept the same. More details about the panel settings can be found in the following sections.

› Documents › WindPRO Data › PVPanels › 2023

Name	Date modified	Type	Size
EMD-Generic_2023_410W_1.134x1.722_HC_Bifacial_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_410W_1.134x1.722_HC_Bifacial_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_410W_1.134x1.722_HC_Bifacial_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_410W_1.134x1.722_HC_Bifacial_LightEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_410W_1.134x1.722_HC_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	17 KB
EMD-Generic_2023_410W_1.134x1.722_HC_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	17 KB
EMD-Generic_2023_410W_1.134x1.722_HC_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_410W_1.134x1.722_HC_LightEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_460W_1.134x1.903_HC_Bifacial_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_460W_1.134x1.903_HC_Bifacial_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_460W_1.134x1.903_HC_Bifacial_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_460W_1.134x1.903_HC_Bifacial_LightEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_460W_1.134x1.903_HC_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	17 KB
EMD-Generic_2023_460W_1.134x1.903_HC_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	17 KB
EMD-Generic_2023_460W_1.134x1.903_HC_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_460W_1.134x1.903_HC_LightEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_550W_1.134x2.274_HC_Bifacial_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_550W_1.134x2.274_HC_Bifacial_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_550W_1.134x2.274_HC_Bifacial_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_550W_1.134x2.274_HC_Bifacial_LightEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_550W_1.134x2.274_HC_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	17 KB
EMD-Generic_2023_550W_1.134x2.274_HC_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	17 KB
EMD-Generic_2023_550W_1.134x2.274_HC_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_550W_1.134x2.274_HC_LightEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB
EMD-Generic_2023_610W_1.303x2.172_HC_Bifacial_DarkEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_610W_1.303x2.172_HC_Bifacial_DarkEdge_Portrait.PVPanel	10/08/2023 21.07	PVPANEL File	18 KB
EMD-Generic_2023_610W_1.303x2.172_HC_Bifacial_LightEdge_Landscape.PVPanel	10/08/2023 21.07	PVPANEL File	19 KB

Figure 54 Part of the generic panels in the 2023 folder available with windPRO installation.

The user can create new or modify the existing PV panels and save them in the desired folder for later use in the calculations.

14.5.2 Panel data

Each panel data set contains information about the cell type, width, height, 3D model, Pmax, temperature specifications and by-pass diodes of the individual panel. Additionally, if the PV panel is bifacial, the bifaciality factor of the panel can be specified:

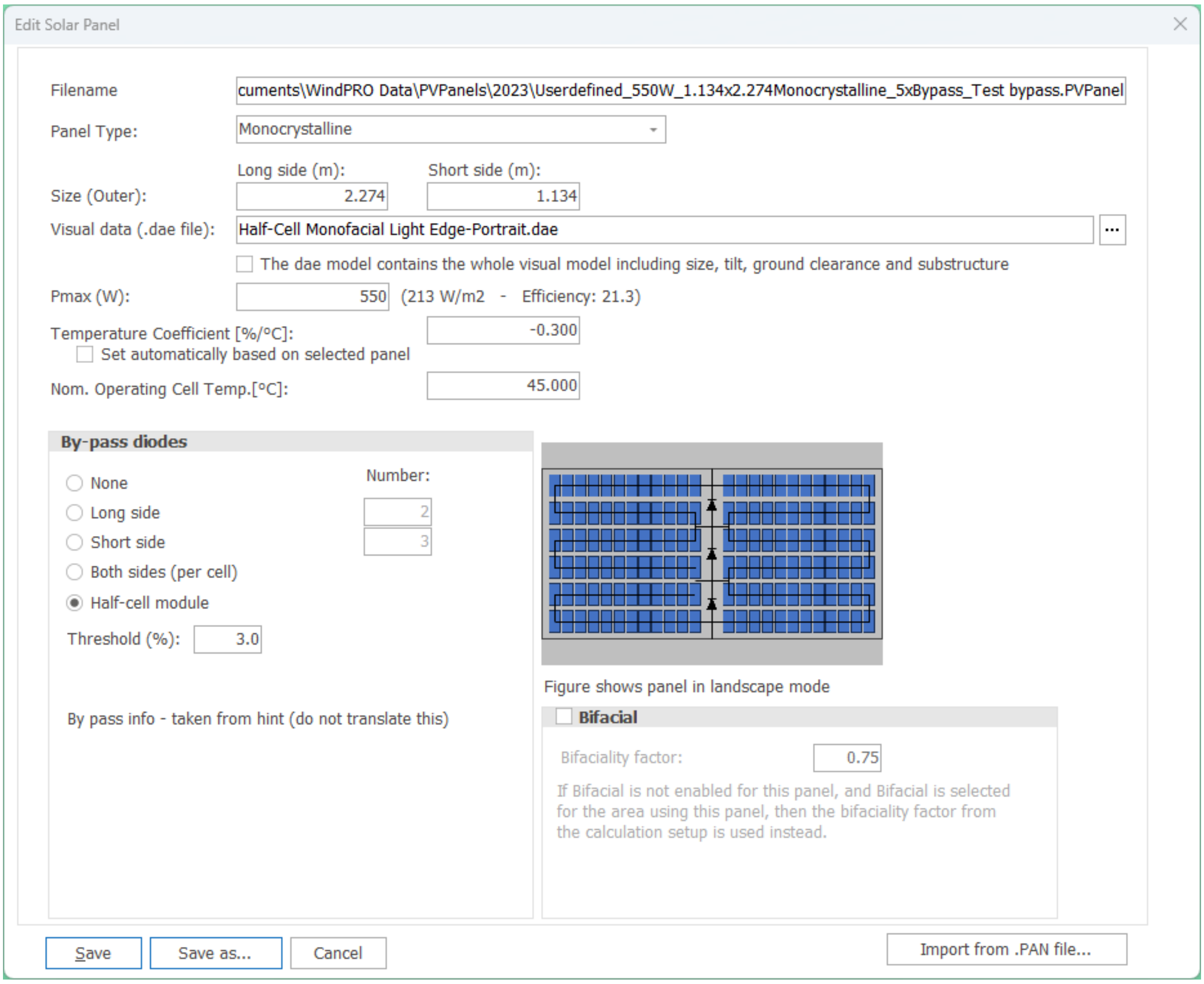


Figure 55 PV panel data.

Panel type is used to validate if P_{max} is within reasonable limits for the panel type. This is done by calculating the efficiency based on the specified dimensions and P_{max} and comparing it to the expected efficiency. The following panel types can be chosen:

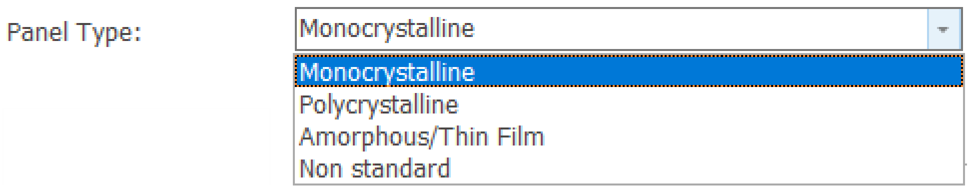


Figure 56 List of available panel types in windPRO.

The sizes are the outer dimensions of the panel. These are used for checking the panel efficiency and to scale the specified Visual data file.

The Visual data must be a .dae file, which contains a 3D model of the PV panel. It contains dimensions of the panel, however if these are not the same as specified in the size fields, the model will be scaled to match the specified dimensions. If the model should not be scaled with the specified size, the following checkbox should be selected:

With this checked, the photomontage tool will know that all is included and handle the rendering based on this. Important: Before using this, read 14.12.1 Panels in photomontage!

A set of predefined panel files available together with windPRO installation – see Figure 54. This includes bifacial and non-bifacial panels, dark and light panel frame as well as separate file for portrait and landscape orientation of the PV panel. For realistic photomontages it is important to make sure that the .dae file is selected correctly for the selected orientation of the panel. If portrait orientation is selected, the .dae file should also represent a panel in portrait orientation. In future versions of windPRO, the aim it to handle it automatically.

The size, P_{max} and temperature specifications are used for the calculation of the power in each time step. The P_{max}, is the maximum power output of the front side of the panel under Standard Test Conditions (STC): irradiance of 1000 W/m^2, cell temperature of 25°C and air mass equal to 1.5. As previously mentioned, when entering the panel power there is a check that it is within a reasonable range for the panel type and size:

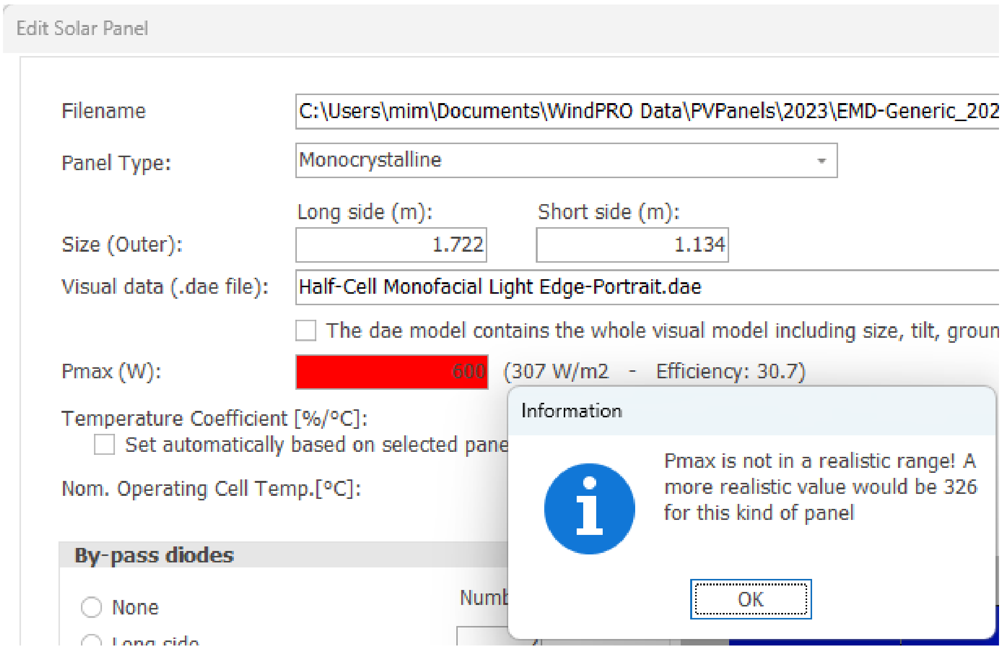


Figure 57 Panel power is validated based on panel type.

The by-pass diodes affect the shading reduction calculation. Panel shading, which normally would prevent the entire panel from producing electricity, is limited by bypass diodes. It is of high importance that the by-pass diodes are defined correctly in the panel data. On a sloped roof, where no array shading will occur, the optimal orientation depends on which other shading elements may be present. Shading can come from the sides as well as the from the bottom, depending on the specific environments. The module calculates the vertical and horizontal shading cover of the panel and from this the by-pass diodes make the decision on how much the direct radiation shall be reduced. Starting from windPRO 4.0, half-cell PV modules can be defined as an option for bypass diode configuration. These have the solar cells split in half and hence the current flowing through them is also half. This results in reduced losses, boosting efficiency. The panel is split into two sections connected in parallel, with both sections having half of the nominal current flowing through them. This means that if no shading is present the total current flowing through the panel is the same as it would be in a panel with full cells. The three bypass diodes are installed in the middle of the panel, as illustrated in the preview in windPRO – see Figure 58.

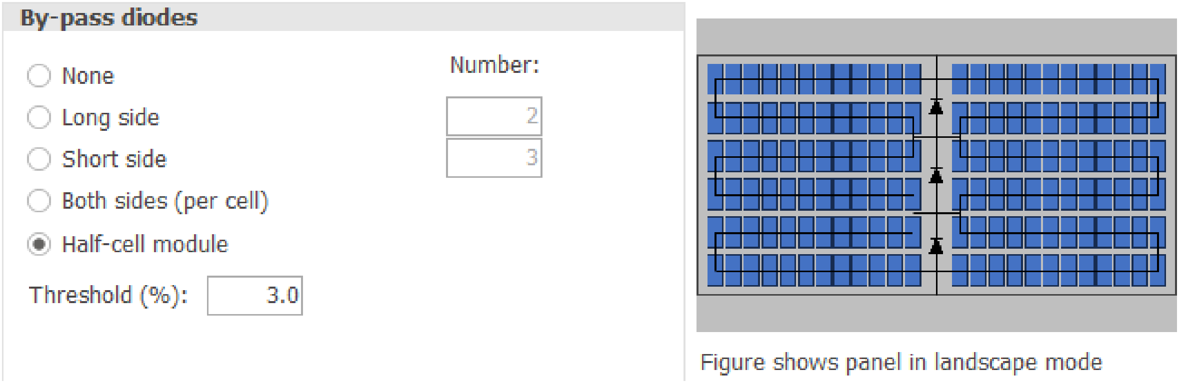


Figure 58 Half-cell modules in windPRO.

14.5.3 Bifacial panels

When using bifacial panels, the $\mathbf{P_{max}}$ **shall not be increased** by the added power from the rear side of the panel. This would give a wrong calculation.

Bifacial panels utilise the solar radiation on both sides of the panel. This can be specified by the lower right checkbox at the panel settings. The Bifaciality factor compensates for less efficiency at the rear panel side. A default value of 0.75 is recommended in the literature, but can be attributed on an individual basis by panel manufacturer and construction arrangements (shading from substructures). In windPRO any additional losses on the rear side of the panel should be included in the Bifaciality factor. Hence, it is advised to further reduce it to account for shading due to substructure and cabling, and increased mismatch losses on the back side etc.

Note: the Bifacial checkbox on Area settings overrules the panel settings.

14.5.4 Importing .PAN files

Staring from windPRO 4.0 it is possible to import .PAN files when creating a new PV panel or editing the selected one. To import a panel from .PAN file, the user should click on *Import from .PAN file* button in the right bottom corner of the Edit Solar Panel window – see Figure 59.

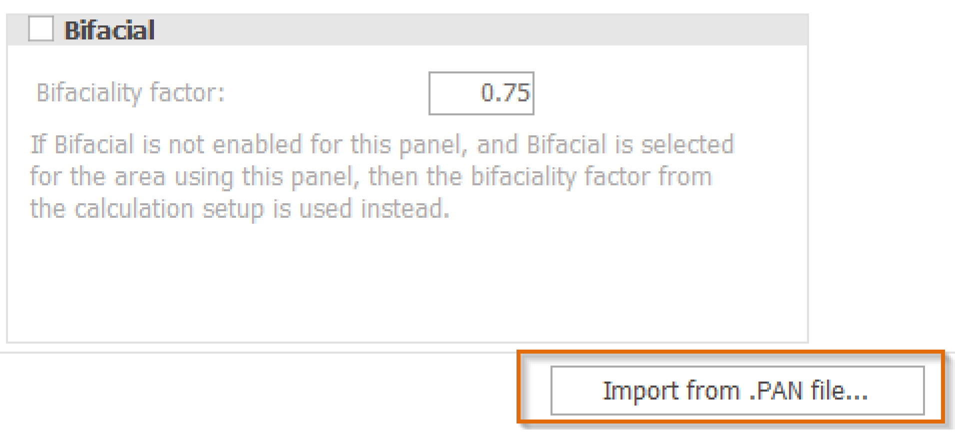


Figure 59 Importing information about a PV panel from a .PAN file.

This will open a window where the .PAN file to import can be selected. Once the desired file is chosen, import window will open, where the user can see the parameters, which can be imported into windPRO:

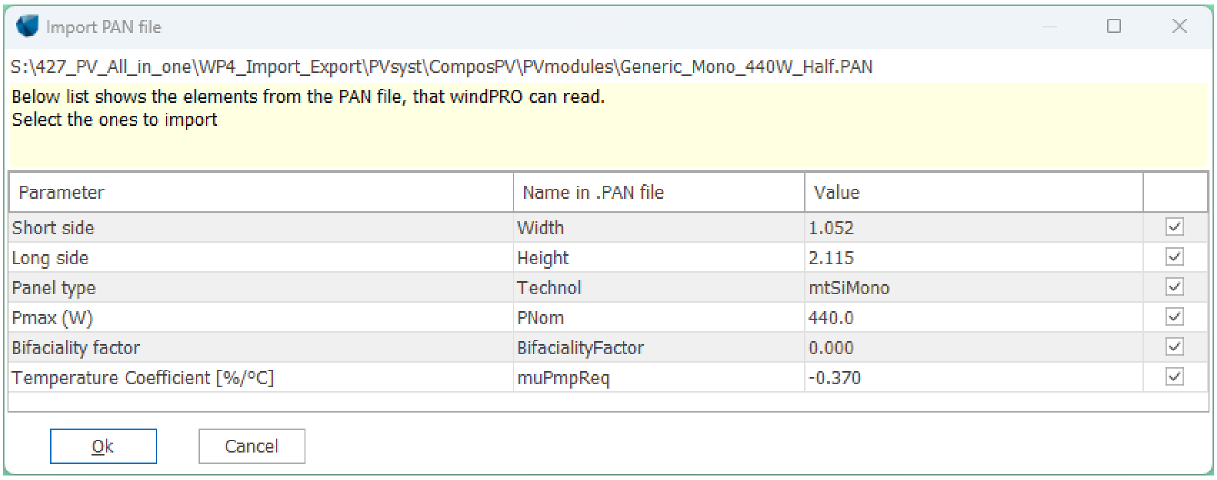


Figure 60 Import of parameters from .PAN file - window with parameters found in the .PAN file which can be imported to windPRO.

By using the checkbox in the last column of the table, the user can decide which parameters should be imported. Parameters, which will not be imported from .PAN file will remain unchanged. It is advised to check the values of parameters, which were not imported from the .PAN file.

Once the parameters are imported from .PAN file, the values can be seen in the Edit Solar Panel window and the changes should be saved by clicking Save or Save as. This will update the existing windPRO panel file or create a new one, with the parameters imported from the selected .PAN file. The updated/created file can be later used in all Solar PV calculations.

14.5.5 Reading data from PV panel datasheets

When creating a new Panel based on values specified in the datasheet it may be challenging to extract the correct values to use. This section shows, based on examples, which values should be used in the solar panel specification in windPRO.

The Maximum Power used in windPRO must be the power under the Standard Test Conditions (STC). Often, the datasheets provide additional information e.g., about maximum power output under Nominal Module Operating Temperature (see Figure 61) or combined maximum power of front and back side of bifacial module under certain assumption for the back side of the module. These should not be used as input in the P_{max} field in windPRO.

The Nominal Operating Cell Temperature (NOCT) is directly available in datasheets, together with an uncertainty. The average should be used in windPRO, however, sensitivity study with higher and/or lower value can also be performed.

The temperature coefficient in windPRO is the Temperature coefficient of P_{max}, sometimes also referred as temperature coefficient of power. The unit should be [%/ºC]. It is a negative value, meaning that the power output of the PV panel will decrease with increase of efficiency. The lower the absolute value, the better the panel perform in high temperatures.

If the module is bifacial, the bifaciality factor is specified in the datasheet. It can be referred to as Bifaciality, Bifaciality factor, Bifacial factor etc. It is usually around 75 to 80%. It accounts for worse optical properties of the back side of the panel compared to the front side. This value should be further reduced to account for losses due to substructure mounting, cabling mounting etc. See an example of Bifaciality factor value of 80% in Figure 62. Similarly, to NOCT, the Bifaciality factor is often specified together with uncertainty. This can be used for sensitivity studies, and in the future, it will be used as an input to uncertainty calculations in the Solar PV module in windPRO.

ELECTRICAL DATA | STC* ← Max Power mustbe at STC conditions

CS7N	645MS	650MS	655MS	660MS	665MS	670MS	675MS
Nominal Max. Power (Pmax)	645 W	650 W	655 W	660 W	665 W	670 W	675 W
Opt. Operating Voltage (Vmp)	37.7 V	37.9 V	38.1 V	38.3 V	38.5 V	38.7 V	38.9 V
Opt. Operating Current (Imp)	17.11 A	17.16 A	17.20 A	17.24 A	17.28 A	17.32 A	17.36 A
Open Circuit Voltage (Voc)	44.8 V	45.0 V	45.2 V	45.4 V	45.6 V	45.8 V	46.0 V
Short Circuit Current (Isc)	18.35 A	18.39 A	18.43 A	18.47 A	18.51 A	18.55 A	18.59 A
Module Efficiency	20.8%	20.9%	21.1%	21.2%	21.4%	21.6%	21.7%
Operating Temperature	-40°C ~ +85°C						
Max. System Voltage	1500V (IEC/UL)) or 1000V (IEC/UL))						
Module Fire Performance	TYPE 1 (UL 61730 1500V) or TYPE 2 (UL 61730 1000V) or CLASS C (IEC 61730)						
Max. Series Fuse Rating	30 A						
Application Classification	Class A						
Power Tolerance	0 ~ + 10 W						

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

ELECTRICAL DATA | NMOT*

CS7N	645MS	650MS	655MS	660MS	665MS	670MS	675MS
Nominal Max. Power (Pmax)	484 W	487 W	491 W	495 W	499 W	502 W	506 W
Opt. Operating Voltage (Vmp)	35.3 V	35.5 V	35.7 V	35.9 V	36.1 V	36.3 V	36.5 V
Opt. Operating Current (Imp)	13.72 A	13.74 A	13.76 A	13.79 A	13.83 A	13.85 A	13.88 A
Open Circuit Voltage (Voc)	42.3 V	42.5 V	42.7 V	42.9 V	43.1 V	43.3 V	43.5 V
Short Circuit Current (Isc)	14.80 A	14.83 A	14.86 A	14.89 A	14.93 A	14.96 A	14.99 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m² spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline
Cell Arrangement	132 [2 x (11 x 6)]
Dimensions	2384 × 1303 × 35 mm (93.9 × 51.3 × 1.38 in)
Weight	34.4 kg (75.8 lbs)
Front Cover	3.2 mm tempered glass with anti-reflective coating
Frame	Anodized aluminium alloy, crossbar enhanced
J-Box	IP68, 3 bypass diodes
Cable	4 mm² (IEC), 12 AWG (UL)
Cable Length (Including Connector)	410 mm (16.1 in) (+) / 250 mm (9.8 in) (-) or customized length*
Connector	T6 or T4 or MC4-EVO2 or MC4-EVO2A
Per Pallet	31 pieces
Per Container (40' HQ)	558 pieces

* For detailed information, please contact your local Canadian Solar sales and technical representatives.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.34 % / °C
Temperature Coefficient (Voc)	-0.26 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	41 ± 3°C

Figure 61 Example of a Canadian PV panel datasheet (selected part), with parameters to be used in windPRO marked in green.

Electrical Characteristics (STC*)

MSMDxxxG12-HJT132DS	680	685	690	695	700
Maximum Power (Pmax)	680W	685W	690W	695W	700W
Module Efficiency (%)	21.89%	22.05%	22.21%	22.37%	22.53%
Optimum Operating Voltage (Vmp)	41.49V	41.65V	41.80V	41.95V	42.10V
Optimum Operating Current (Imp)	16.39A	16.45A	16.51A	16.57A	16.63A
Open Circuit Voltage (Voc)	49.50V	49.66V	49.82V	49.98V	50.13V
Short Circuit Current (Isc)	17.19A	17.25A	17.31A	17.37A	17.43A
Operating Module Temperature	-40 to +85°C				
Maximum System Voltage	DC1500V (IEC)				
Maximum Series Fuse	30A				
Power Tolerance	0~+5W				
Bifaciality	80%±5%				

*STC: Irradiance 1000 W/m², cell temperature 25°C, AM=1.5, Tolerance of Pmax is within +/- 3%.

Temperature Characteristics

Nominal Operating Cell Temp. (NOCT)	44°C±2°C
Temperature Coefficiency of Pmax	-0.26%/°C
Temperature Coefficiency of Voc	-0.24%/°C
Temperature Coefficiency of Isc	0.04%/°C

Safety & Warranty

Safety Class	Class Ⅱ
Product Warranty	15 yrs Workmanship
Performance Warranty	30 yrs Linear Warranty*

* 1st year 99%, after 2nd year 0.375% annual degradation to year 30.

Figure 62 Example of a Munchen Energieprodukte PV panel datasheet (selected part), with parameters to be used in windPRO marked in green.

14.6 Inverter specifications

Inverters convert the solar panel Direct Current (DC) output to Alternating Current (AC). Normally, the installed capacity of the inverters (AC power) is lower than the installed capacity of the panels (DC power). This is done because the energy generation from the panels will be lower than the rated power for most of the time. Reduction of the inverter(s) AC power can also be used to limit the plant maximum power output and hence reduce grid connection cost – this saving can outweigh the loss due to inverter clipping at peak production. Regarding Bifacial, see also section 14.6.3 .

The main parameters of the inverter setup are shown in the Solar PV status window. The properties can be modified by clicking in *Edit…*, this will open the table shown in Figure 63.

SolarInverterList

Areas	AC/DC spec.	DC-power (kW)	Inv. Size (kW)	No. Of inverters	AC power (kW)	AC/DC realized	
Edit all	**0.900**		**5.0**				**Edit inv.**
Area_ 1	0.900	2,052	5.0	370	1,850	0.90	Edit inv.
Area_ 2	0.900	10,437	5.0	1,879	9,395	0.90	Edit inv.
Sum or average	**0.900**	**12,489**	**5.0**	**2,249**	**11,245**	**0.90**	**Edit inv.**

Ok   Cancel

Figure 63 the inverter specification is input as AC/DC ratio.

For each panel design area, the AC/DC ratio as well as inverter size can be set, and the number of inverters is calculated.

The changes can be applied to all areas by changing the values in the first row of the table – *Edit all*. If different inverter or AC/DC ratio is to be used in the Areas, these should be changed in the corresponding row. In the table it is possible to see how many inverters will be installed in each Area. The required number of inverters per area is calculated so the realized AC/DC ratio is as close as possible to the specified AC/DC ratio but never smaller. The inverter size, efficiency and losses can be modified by clicking on *Edit inv.* in the last column of the table. This will open a new window.

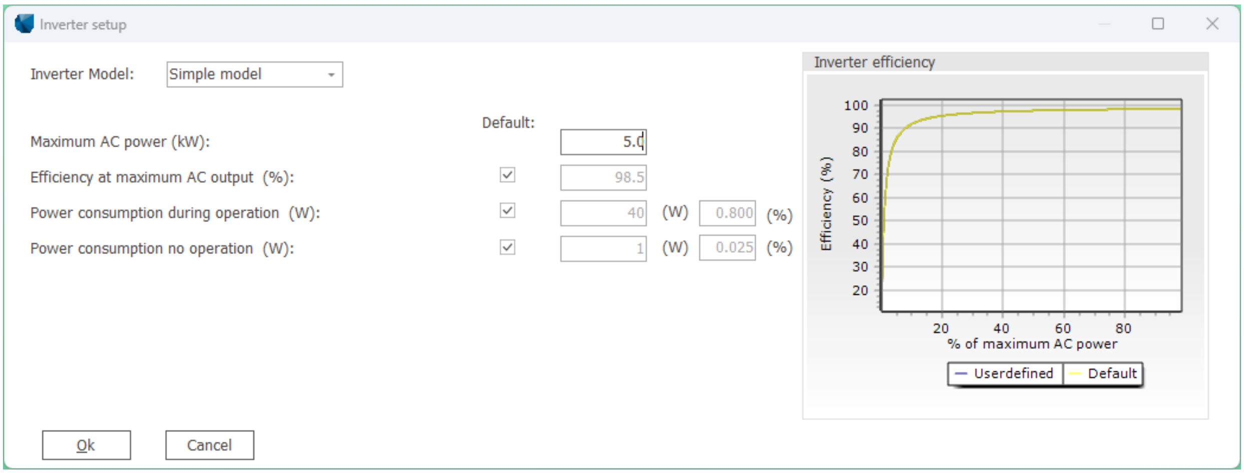


Figure 64 Specification of inverter size and efficiency.

Starting from windPRO 4.1, the inverter can be specified with use of the previously available Simple model or as Efficiency curve. The choice is made by selecting the model in the dropdown menu in the top of the Inverter setup window. In the following sections, both approaches are described in detail.

14.6.1 Inverter – simple model

The inverter size and efficiency are specified as seen in Figure 64. The default efficiencies/losses might be conservative, see the data sheets of the inverter to be used for more precise data. The graph compares the default values to the entered values. If the power consumption during operation is not defined the inverter data sheet, it will be possible to access by comparing the efficiency graph most often seen in the inverter data sheets. Then adjust power consumption until a reasonable match is seen. An example is shown in Figure 65:

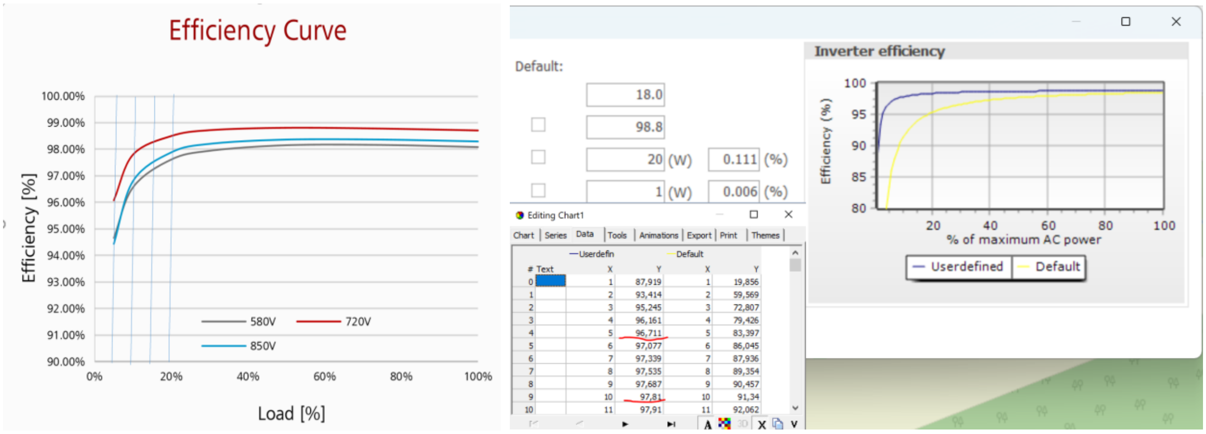


Figure 65 Inverter efficiency curve from inverter data sheet and the "calibration".

In Figure 65, the power consumption during operation is trimmed to reproduce the efficiency curve from the data sheet as well as possible. By double-clicking on the graph, the data can be shown. An attempt is made to try and hit 96% at 5% load and 98% efficiency at 10% load, as seen in data sheet graph. Due to the formulas behind the inverter efficiency calculations, it will not necessarily be possible to get an exact match, but it can be close.

Here it is assumed that the inverter will operate in 720 V (curve below). Based on one-year measurements this is tested in the Meteo analyser:

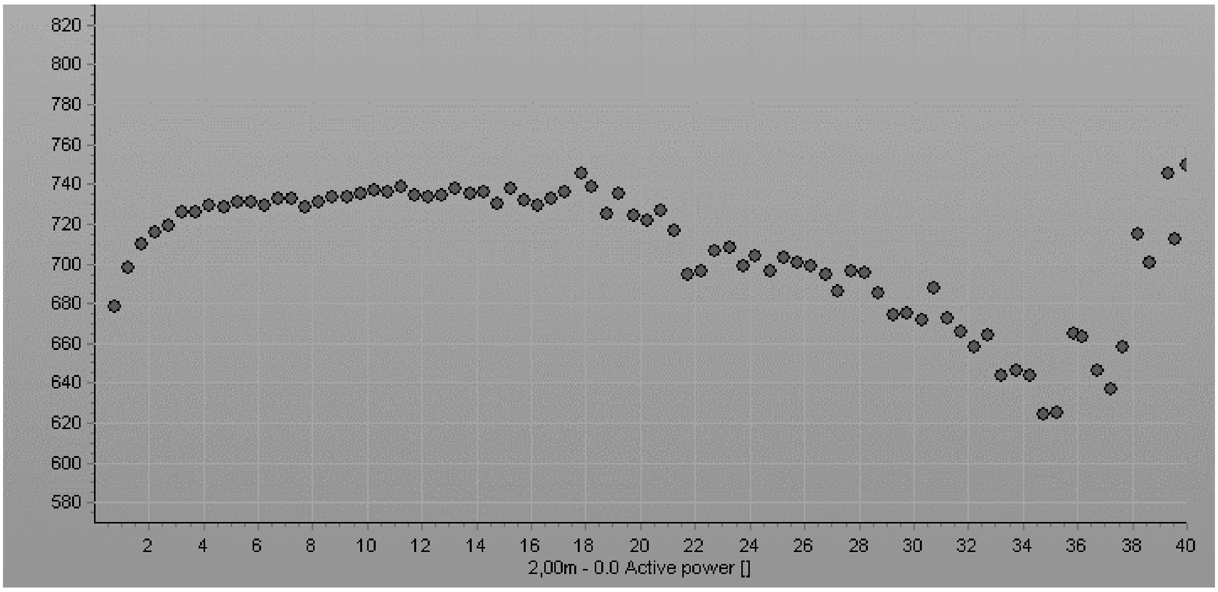


Figure 66 Measured Voltage versus Active power.

Figure 66 shows that the voltage drops a little at high active power, related to the inverter clipping, where the power limiter by the inverter reduces the voltage. However, for most of the operational range, measured voltage is close to 720 V.

The inverter handling in the simple model and formulas behind are based on The Sandia inverter model used by programs like SAM (NREL, https://www.nrel.gov/docs/fy15osti/64102.pdf).

TIP: If the real project has inverters crossing more design areas, a workaround will be to lower the size of inverter to e.g., 25%. Then more inverters will be established, but with efficiencies scaled the inverter losses will be as when the full-size inverters handle more areas. (Remember to reduce the power consumption for inverter similarly to the inverter size if defaults are not used).

14.6.2 Inverter defined with efficiency curve

The inverter can be defined as an efficiency. If Efficiency curve is selected as the inverter model, the inverter setup window will look as shown in Figure 67.

The characteristic of the inverter is specified in the Efficiency Curve table. The values can be added manually or copied from a spreadsheet in the Efficiency Curve table by right-clicking on the table – see Figure 68. The data should be copied without headers, the AC power specified in kW and efficiency in % (as number).

The Maximum AC power (kW), Maximum efficiency (%) and EURO efficiency (%) fields are automatically field in based on the specified efficiency curve.

EURO efficiency is calculated according to standard CSN EN 50530:

$$\eta_{EURO} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.1 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.2 \cdot \eta_{100\%}.$$

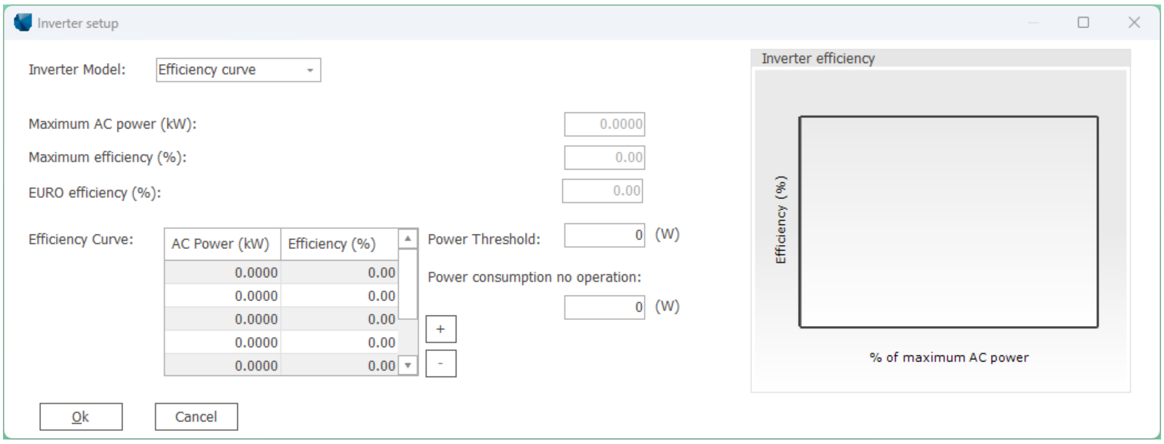


Figure 67 Inverter model window when Efficiency curve selected as Inverter Model

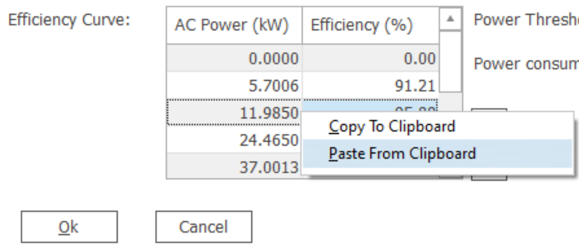


Figure 68 Pasting Efficiency curve from a spreadsheet.

The Power threshold field determines what needs to be the input DC power (measured in Watts) for the inverter to start working. DC power below the specified threshold will be lost.

The Power consumption no operation field allows to specify the consumption of electricity of the inverter when it is not in operation – specified in Watts.

The graph in the right site of the window is automatically created based on points specified in the Efficiency curve. This characteristic will be used in the energy yield calculations. The Inverter setup window with all inputs specified is shown in Figure 69.

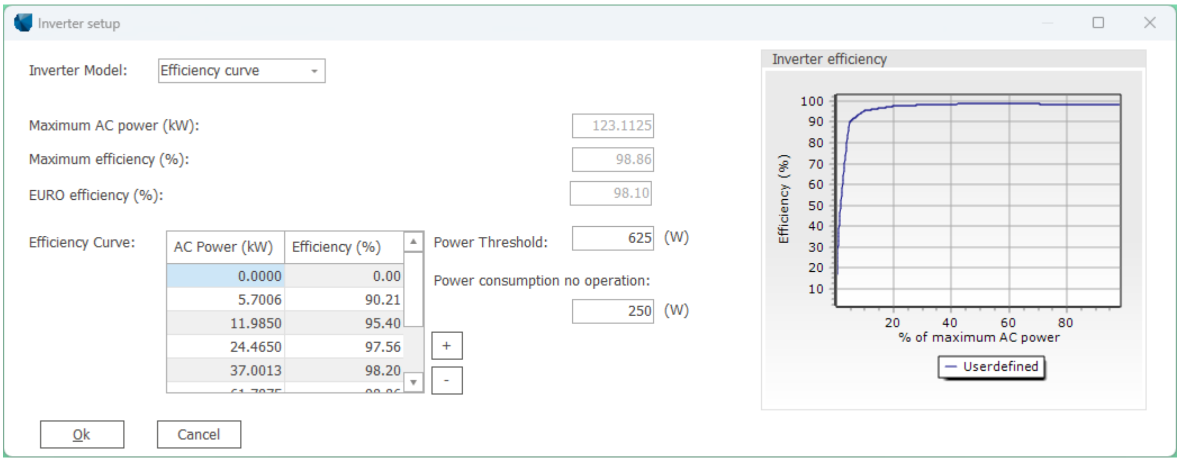


Figure 69 Inverter model window with all specified inputs

14.6.3 Inverter design when using bifacial PV panels

Utilizing bifacial panels, the power output can go above the specified power given in the panel data. Therefore, it might be necessary to increase the size or number of inverters when using bifacial panels. The way this is handled is by increasing the AC/DC ratio in the inverter specification. This is by default 0.9. If this is used, there should be no need for increasing. For typical large plants, the ratio will be set to round 0.7 for optimizing the inverter costs. When using bifacial, this should be increased to e.g., 0.8. To get the optimal sizing, the cost of inverters should be compared to the calculated inverter clipping loss.

14.7 Calculation Setup

The choice of input data, losses setup etc. is done in the *Calculation Setup*. It is accessible from the Solar PV status window and directly from the Solar tab – see marked in orange in the below figure.

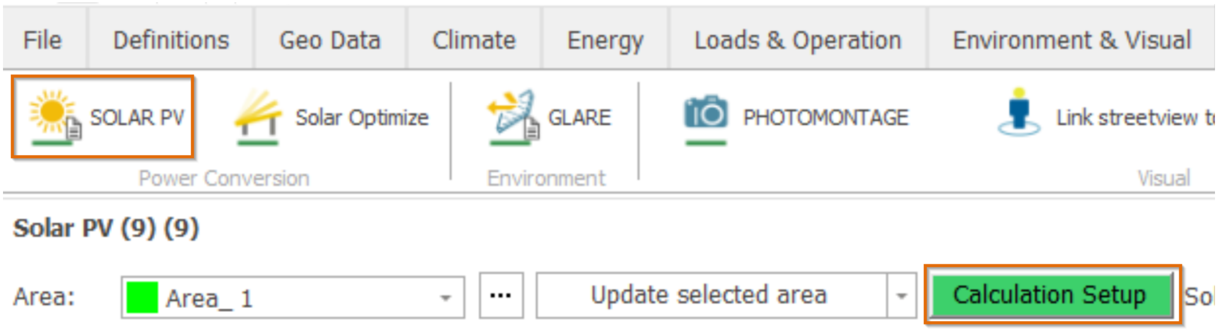


Figure 70 Accessing the Calculation Setup.

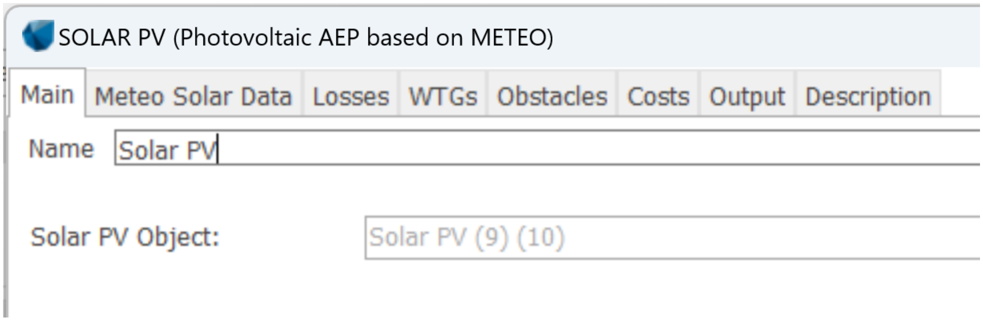


Figure 71 The calculation setup form.

14.7.1 Meteo solar data

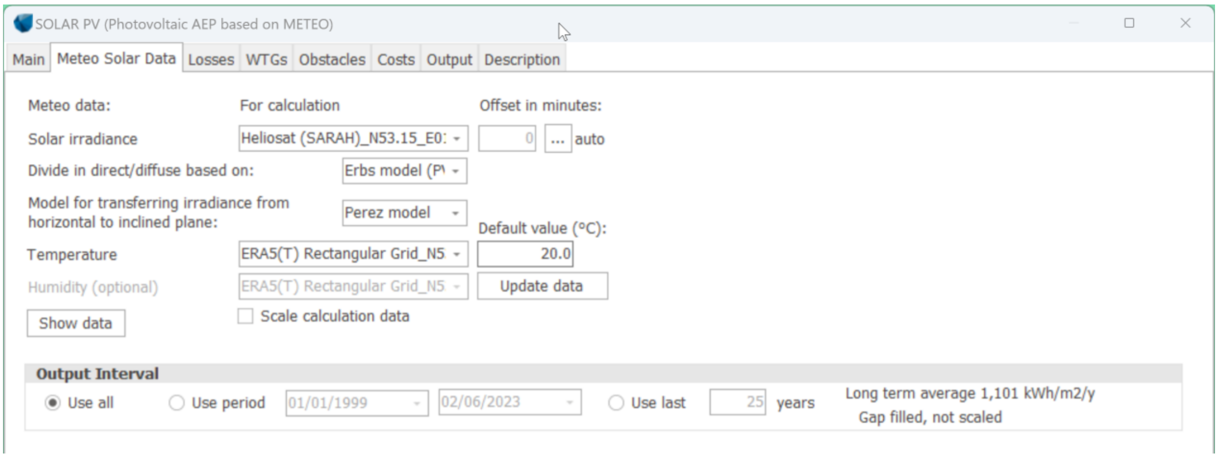


Figure 72 Selection of data and period for calculation.

From the dropdown buttons the METEO object time series are selected.

The Global Horizontal Irradiation (GHI) for the selected period is shown in Figure above as 1.101 kWh/m2/y. This is an important figure as this indicates whether your data are in a reasonable order of magnitude.

A recommended practice is to go to www.globalsolaratlas.info and point out the location. If the value: Global horizontal irradiation GHI **1066.3** kWh/m^2 differs more than 10% from the value shown in the form, there is a high risk that your data is wrong and possibly additional check is required. One potential mistake could be that your measurements are not on horizontal but tilted.
If no temperature data is available, a default value can be used. Humidity data is only used for subdividing global irradiance into direct and diffuse when Reindl model is used. For the default method humidity is not required as an input. Humidity is available in many EMD data sets, including the EMD-WRF EU+.

The calculation period can be specified freely by the user. But there will always be a minimum ONE-year time series generated based on an advanced gap filler/data series extender if less than one year of data is selected. This establishes the ratios between TOA (Top of Atmosphere) and data for nearest time period and uses this for filling missing data. At the later explained Output tab setup, it can be decided to not use gap-filled/extended data.

It is recommended only to use one year for the initial design phase, as this reduces the calculation time, roughly by a factor 10 when using 1 year instead of 20 years.

14.7.1.1 Time offset for calculation

A very important feature is the time offset. While the Top of Atmosphere (TOA) radiation is used when subdividing global irradiance into direct and diffuse, it is extremely important that TOA is aligned in time with the used data. Therefore, a tool that makes this adjustment is available in windPRO. It can be accessed through the […] button in the Meteo Solar Data tab.

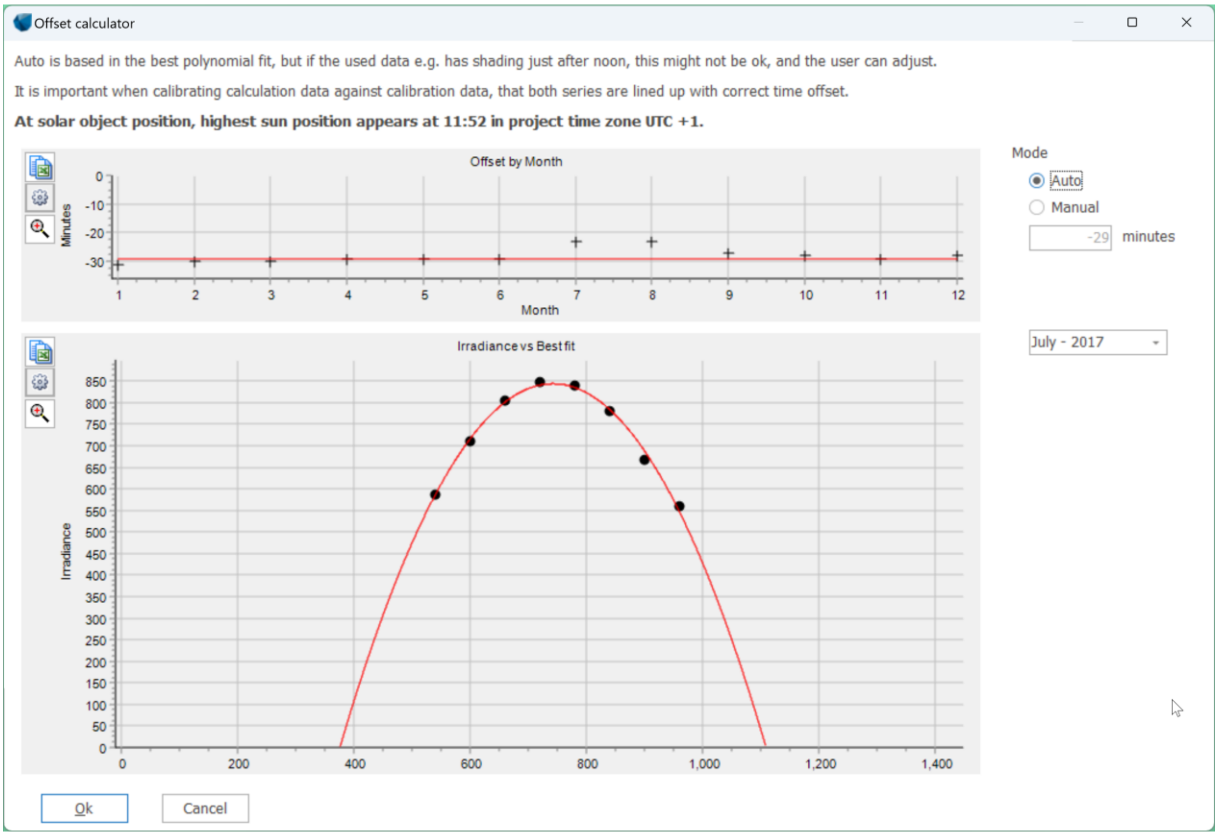


Figure 73 Tool for adjusting time to TOA irradiance.

For each month, the day with GHI closest to the TOA irradiance is found. The upper half of the irradiance data is fitted to a 2nd degree polynomial, and the top point identified as highest sun position. This is then compared with the time where theoretical maximum is at the specific site, and the time shift between measurements and the site is automatically found for each month. The monthly offsets are shown in the top graph and fit of the data for each month can be viewed in the graph below. The median of the found monthly offsets is used as the suggested offset for the data set. This can be overruled by the user by selecting Manual and specifying a custom value. Normally, this should not be used. If needed, e.g., due to shading that makes the fit poor, the data quality is probably also too poor to be used in an energy yield calculation. In that case it is advised to use one of the global model datasets.

The offset is used for correcting the timestamp of the data – to align with the calculation approach in windPRO and the location of the plant. In windPRO it is assumed that the timestamp of the data is representing the middle of the measurement interval. Hence, if timestep of the data is 9:00 the assumption in windPRO is that it represents average irradiance measured from 8:30 to 9:30. If this does not hold, the offset will account for it. E.g., the time stamp of ERA5T data is the accumulated irradiance for the past hour, time stamp of 9:00 is used for average irradiance measurement from 8:00 to 9:00. This will be reflected in the offset if this data set is used – it will be around -30 min. Additional differences can be caused by a difference in the location of the measurement and the Solar PV plant.

14.7.1.2 Treating irradiance data in the Meteo solar data window

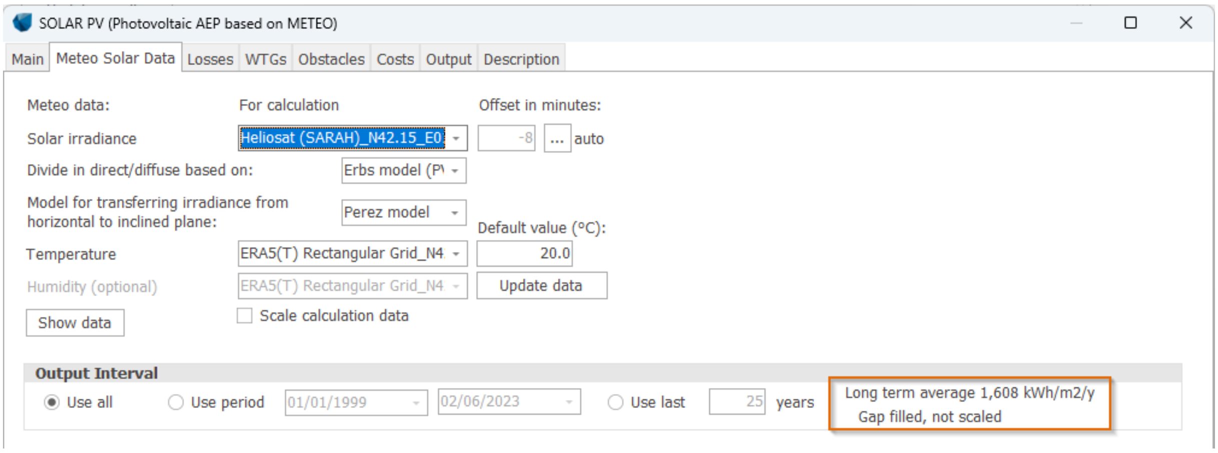


Figure 74 Meteo Solar Data tab of calculation setup - marked in orange the irradiation based on the selected irradiance data.

The irradiation shown in the *Meteo Solar Data* tab (see the above figure) and in the report is calculated as described below. Note there is an interaction between the irradiation value shown, and the choice made on the *Output* tab.

For each month-hour, e.g., January at 11:00, all 31 values (i.e., one for each day of the month) are averaged.

If no gap filling is performed, and there is one gap, 30 values are averaged for that specific time.

If gap filling is enabled, and there is one gap, this gap is filled with the average of the 30 values from this time stamp, and 31 values are averaged. (This is done ONLY for calculation of the shown kWh/m2/y – during the energy calculation, the gap is filled based on the neighbour samples).

It is possible that non-gap-filled irradiation is higher than gap-filled.

The reasoning behind this is that if Scaling is to be used, there must be reasonable values for each month-hour. If the missing samples (gaps) were set to 0 and these were used for calculation of the average and then used in the scaling, fully unrealistic scaling factors could appear if one of the time series e.g., had most days missing in a month. To have a consistent calculation method this is used also if no scaling is chosen.

14.7.1.3 Scaling data

The solar irradiance data can be scaled. The most obvious use is when having local site measurements for a shorter period (should at least be 1 year), which then can be used for scaling model data that has a longer data period. Another reason for scaling could be the use of model data, which is known to have a bias, e.g., mesoscale model data. Due to mesoscale models not being able to model the clouds with sufficient accuracy, this data will typically show too high solar irradiance, up to around 25%. If no better data are available for a calculation, a scaling of these can be used.

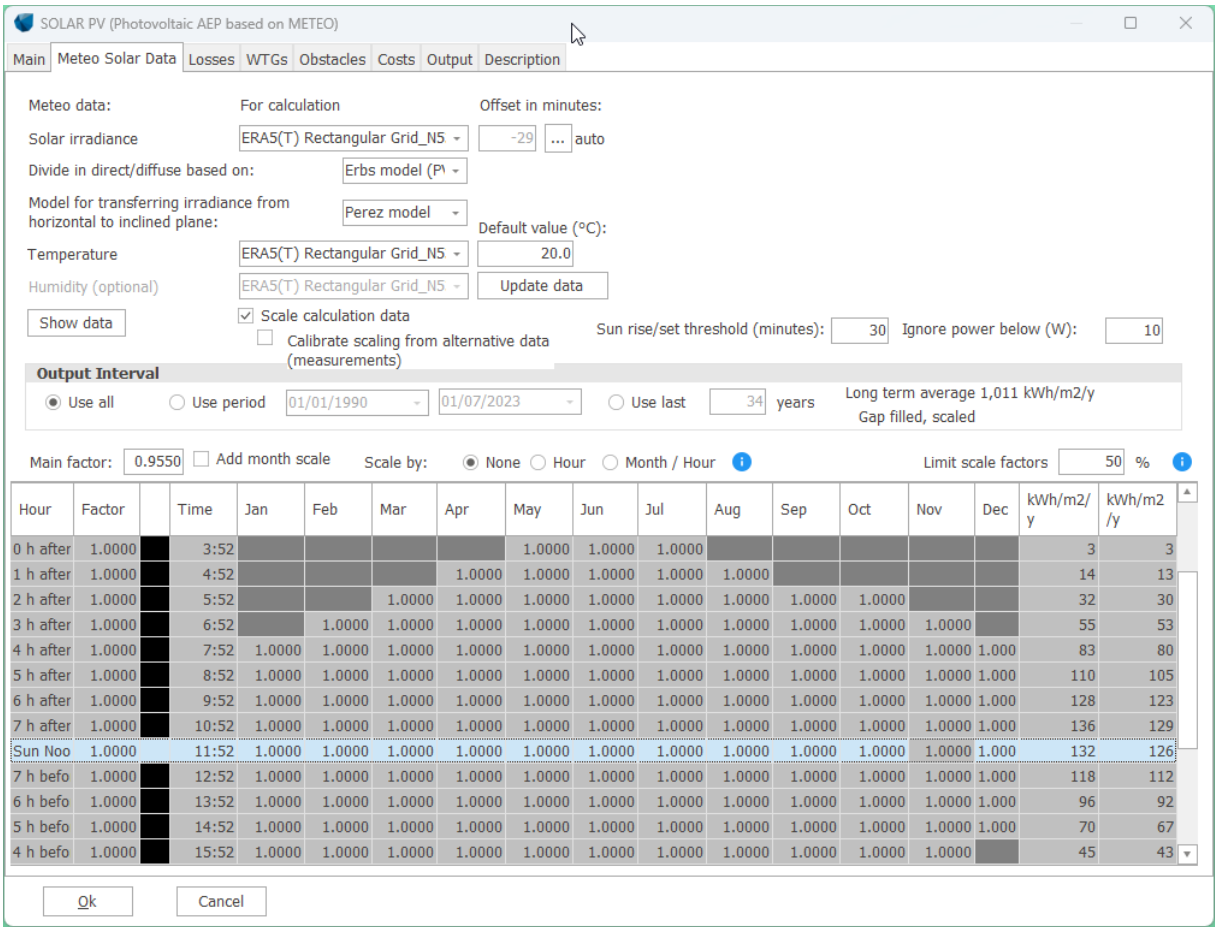


Figure 75 Scaling Mesoscale irradiance data to unbiased.

In Figure 75, we know that the irradiation level shall be around 1010 kWh/m2/y. In the data, it is 1058 kWh/m2/y. A scaling of 0.955 brings the level down to the assumed correct level. This should be specified in the field Main factor. When running a calculation, the scaling factor is applied on each time stamp to the calculation data series.

More refined scaling can be performed if the bias is better understood. Two more options are available: Hour and Month/Hour.

When Hour is chosen, the factor should be specified in the Factor column. The factors can be specified for certain number of hours after sunrise and before sunset. The reason for this is that analyses of model data versus measurements show that the nature of the bias is related to the time relative to sun rise/set, not the time of the day. Therefore, a more precise unbiasing can be established. The 0 hour after sunrise means 0-1 hour after, 1 hour after mean 1-2 hour after etc.

If Month/Hour is chosen as an option, one scaling factor can be specified for each hour in each month in the dataset.

For better understanding of the Hour and Month/Hour scaling factors, see the example in Figure 76. If the user specifies a factor of 1.2 for 1h after the sunrise it is equivalent to specifying a factor of 1.2 for the hours marked in orange in the Month/Hour setup.

Main factor: 1.0000 ☐ Add month scale Scale by: ○ None ○ Hour ● Month / Hour

Hour	Factor		Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
			1:52								
			2:52								
0 h after sunrise	1.0000		3:52					1.0000	1.0000	1.0000	
1 h after sunrise	1.2000		4:52				1.0000	1.2000	1.2000	1.2000	1.0000
2 h after sunrise	1.0000		5:52			1.0000	1.2000	1.0000	1.0000	1.0000	1.2000
3 h after sunrise	1.0000		6:52		1.0000	1.2000	1.0000	1.0000	1.0000	1.0000	1.0000
4 h after sunrise	1.0000		7:52	1.0000	1.2000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5 h after sunrise	1.0000		8:52	1.2000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
6 h after sunrise	1.0000		9:52	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
7 h after sunrise	1.0000		10:52	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Sun Noon	1.0000		11:52	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Figure 76 Entering calibration factors by hour relates to sun rise/set.

14.7.1.4 Calibrating data

With a licence to the Meteo module, local measurements can be loaded into the Meteo object. Local measurements for a shorter period (should be at least a year), can then be long term corrected with model data that are available for a long time period. The time alignment is used to establish best possible conditions for the calibration.

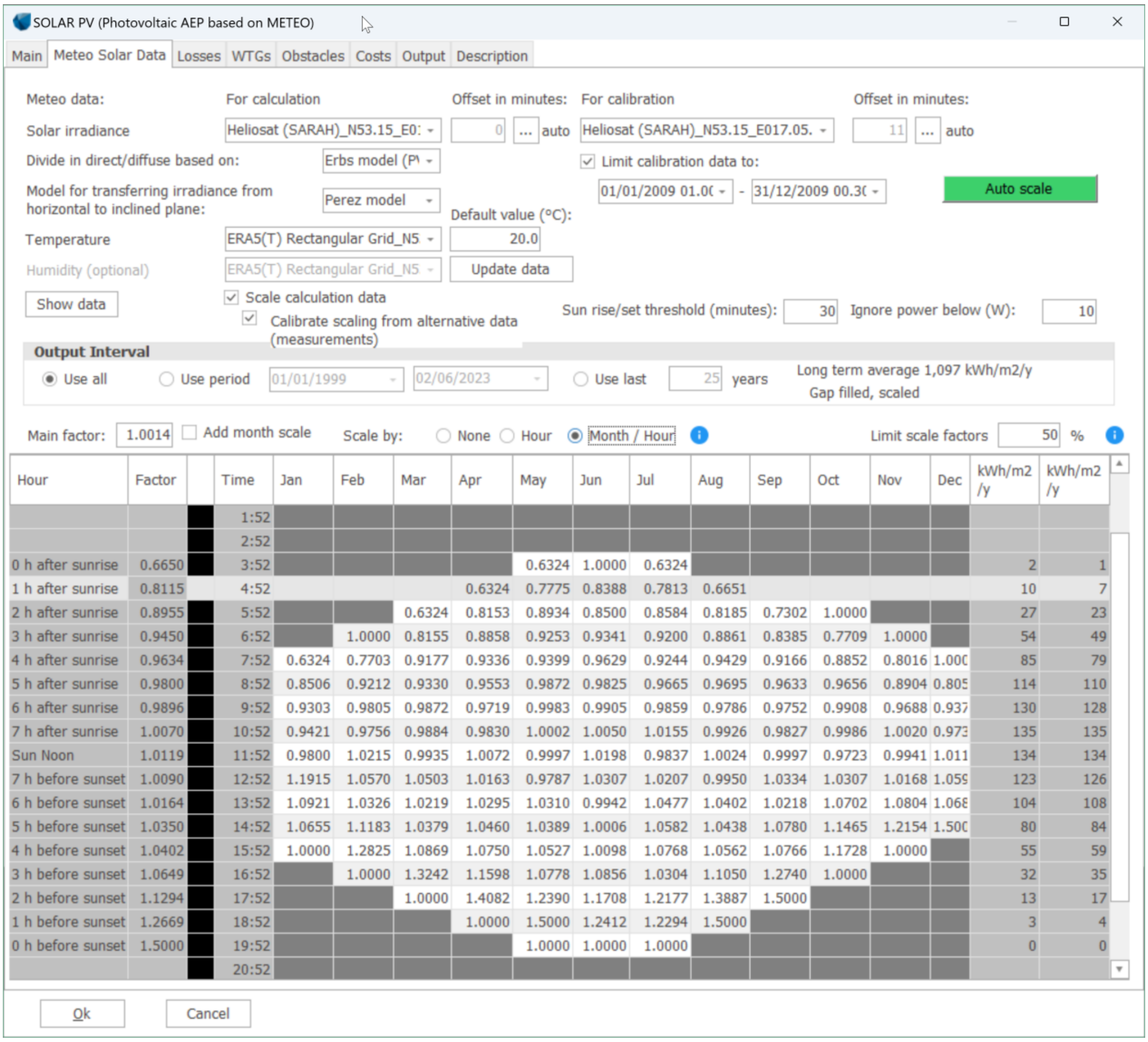


Figure 77 Calibrating long-term data with local measurements.

Based on concurrent data, the calibrator finds the required scaling factors that makes the best match between long-term data and local data. It can be decided just to scale with one factor, or in addition to scale by hour or by hour each month.

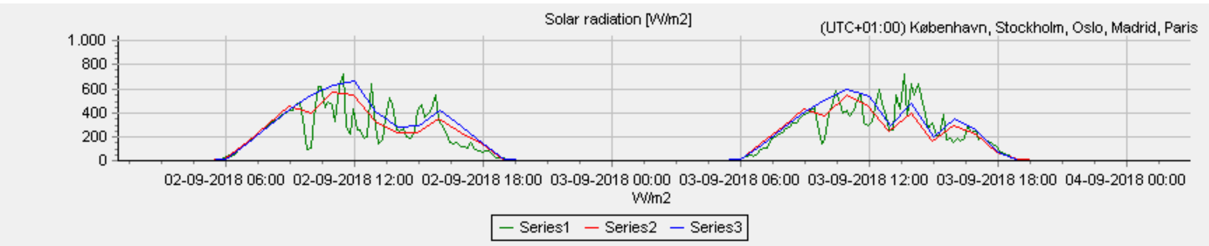


Figure 78 Example on calibrated data.

As seen in Figure 78 the calibrated data (red) does not have the full dynamic behaviour as seen in the measurements (green), but on average the level will be correct.

Some important notes about the calibration:

The data for **calculation** must be the long-term data, typically model data, while the data for **calibration** are the local measurements.

The concurrent data used for calibration are limited by the Output Interval set, and possible limit set for calibration data (to be used if it is known that data quality is poor in part of the period).

It is advised to avoid calibrating with less than one-year of calibration data. If one year is not available, it will probably be better to directly use the model data.

Remember to press the Auto Scale button if the period or number of scaling factors are changed.

Always inspect the data and check that the annual irradiance sum after scaling matches the value that can be found as Global horizontal irradiation at https://globalsolaratlas.info/map :

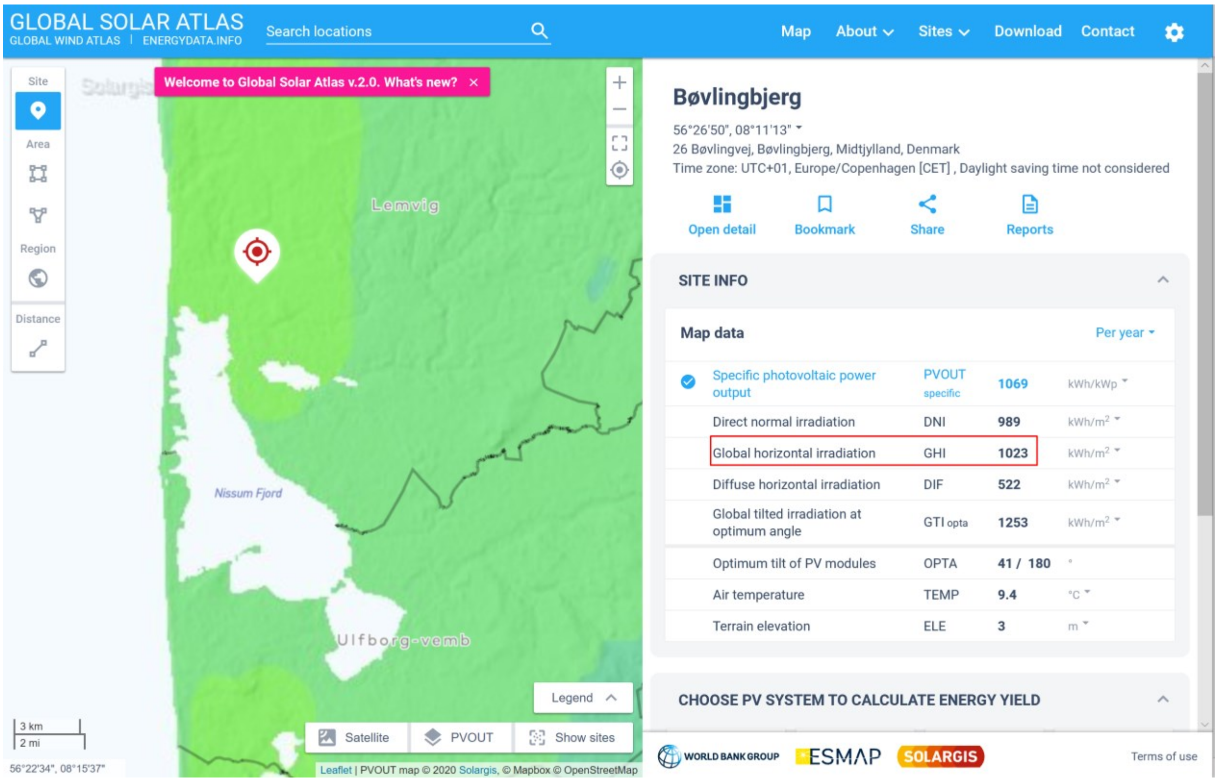


Figure 79 Global solar atlas is a good tool to crosscheck the data used for calculations.

14.7.1.5 Viewing and analysing data

The data used in the calculation can be viewed in the Meteo Solar Data tab of the Calculation Setup by clicking on Show data .

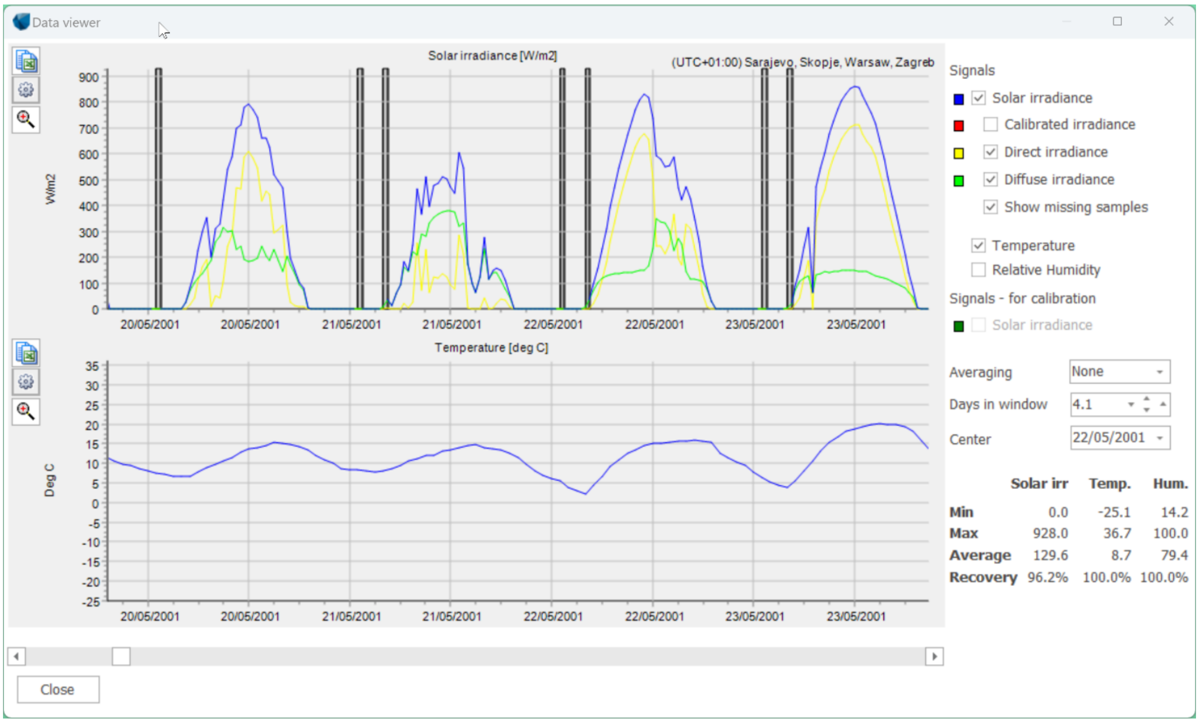


Figure 80 Data viewer in Meteo setup.

The relevant data can be displayed as time series. Data gaps are highlighted as grey bars. These will be gap-filled, but later it can be decided to use the gap-filled data or not. The table in the lower right corner show min, max and average of the main signals in units as shown on graphs y-axis.

A more comprehensive viewer is available in the Meteo analyser tool, which also has aggregated views, x/y graphs etc. However, Figure 80 shows exactly what will go into the Solar PV calculation and how the data are subdivided into direct and diffuse, as illustrated in Figure 81 for one day:

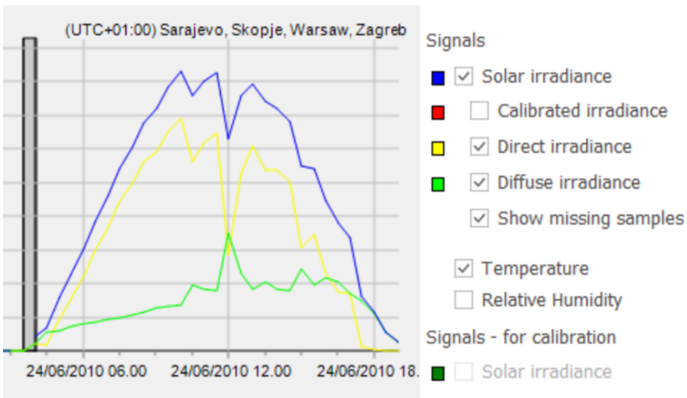


Figure 81 Graphic view of subdivision in direct and diffuse.

14.7.2 Losses Setup

Loss calculation is an important part of the energy calculation. The losses are defined in the Losses tab in the Calculation Setup – see Figure 82. The corresponding losses are described in the following sections.

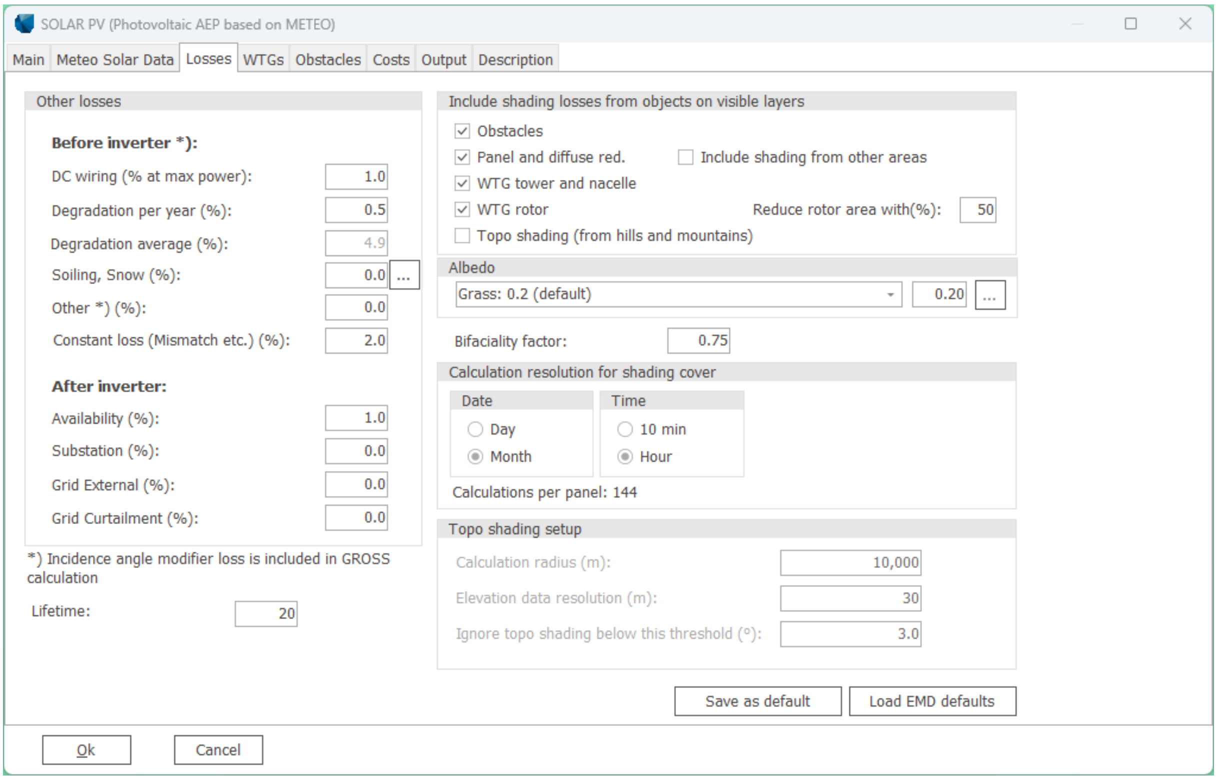


Figure 82 Loss specifications.

14.7.2.1 Shading calculation

Shading losses are based on an advanced 3D model of the solar plant and shading elements, where shading losses are calculated for each time step during a year.

Important: Shading elements (Obstacles, WTGs) appear as separate tabs in the calculation setup, where objects of the type are present. When the calculation setup is entered first time, by default, the visible layers will all be chosen (checked) as the layers with objects to be included. The selected layers and objects in the layers can be edited from the calculation setup, and will stay fixed, so a recalculation will reuse the last selected objects.

When adding new objects, these rules apply:

If a new object is added to a layer where Use all from selected layers is selected, this will be included in a calculation update.

If a new object is added to a layer where individual objects are selected, the new object will NOT be used in a calculation update. The calculation setup must be manually adjusted to include this object.

If a new object is added to a layer not selected, the new object will NOT be used in a calculation update. The calculation setup must be manually adjusted to include this object.

See the two first variants illustrated in next two figures:

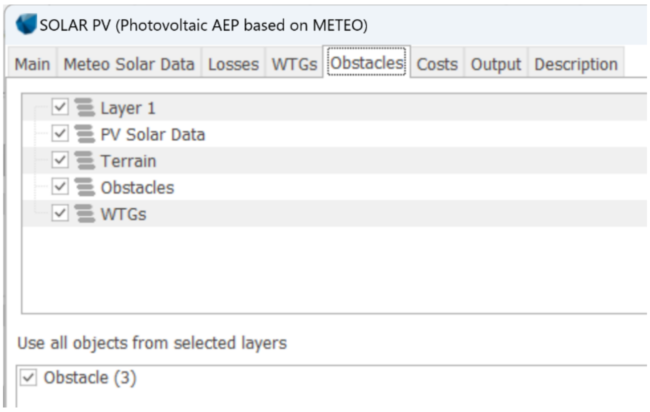


Figure 83 All objects in a layer selected.

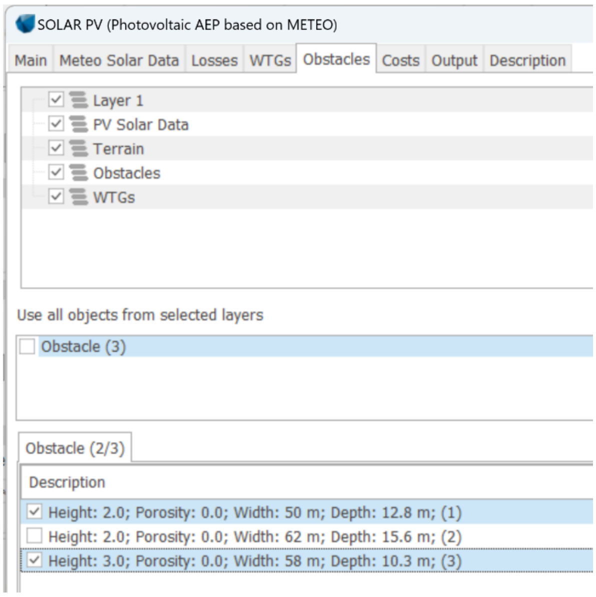


Figure 84 Individual objects within a layer selected.

For the Solar PV objects, those selected in the PV calculation form will always be used, even if the layer is not visible.

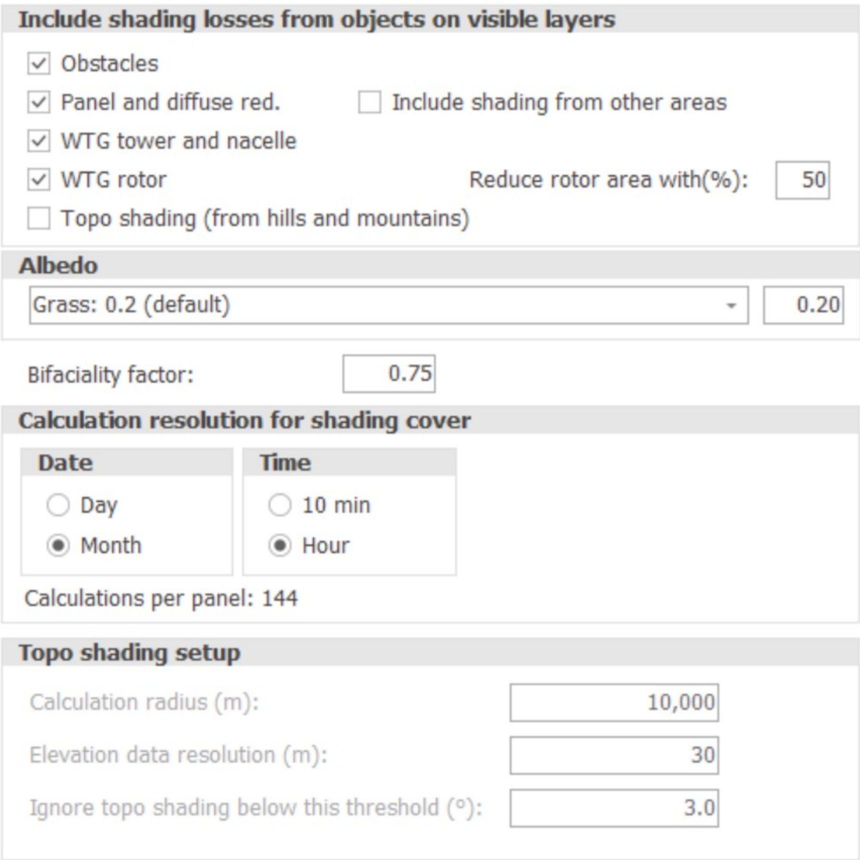


Figure 85 Shading loss calculation setup.

For shading losses each type can be deselected, which in an initial design phase can decrease calculation time significantly but will of course need to be checked for the final calculation and might be needed in a layout optimization process. The panel shading and diffuse shading from other areas might not be needed (if there are no shading interactions), which can further reduce the calculation time significantly.

To explain this a little better:

Case 1: Two PV-areas are created while two different panel types are used, but it is one plant. In this case the shading from other areas shall be included, while panels from one area affect panels in the other area.

Case 2: Two PV areas are established on each side of a road. The distance between the areas will then be so large that there will be no shading from panels in one area on panels of the other area. Then calculation time is saved by unchecking the inclusion of shading from the other PV-area.

For the WTG rotor, the rotor area can be reduced in the calculation to compensate for the rotor disc not being a solid structure and not always facing south, as assumed in the calculation. Experimentally, a reduction of about 50% (default) seems to reproduce the rotor shading well. See Validation in Section 14.13 .

The shading loss calculation is very time consuming for large PV plants. Therefore, some options are provided for reducing the calculation time. Calculating the shading for one day per month each hour will normally have sufficient accuracy and saves much calculation time. However, for special purposes, the resolution can be increased.

Topo(graphic) shading will often not be needed, as PV-plants most often are placed in relative flat terrain or on roofs. See more details on Topo shading in 14.11.2 , which has some very interesting visualization options.

TIP: If the PV-plant is large (+10 MW), it can be time consuming to calculate shading losses. In the calculation setup, the shading calculations can be deselected:

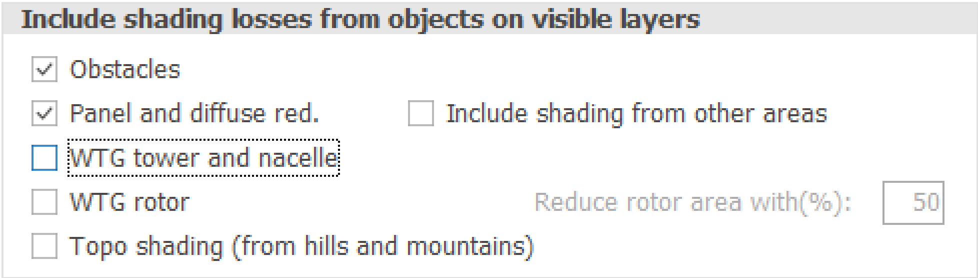


Figure 86 Deselection of shading calculation at initial setup improves calculation speed.

This can be convenient to get a first fast calculation, which later can be updated with full shadow calculation.

14.7.2.2 Handling of Obstacle shading

The obstacle object in windPRO can be used for obstacle shading calculation. Draw on the map and specify height. The porosity is not used, the obstacle is assumed solid block. Some important issues on handling obstacles:

When selecting the obstacle tool, and clicking on map, the first click is the corner of the obstacle defining the coordinates AND the elevation (z-value) if taken from TIN. If z-value is taken from TIN, the obstacle follows the terrain, meaning the corner coordinates take the z-value from the actual location. By manual input of the z-value, the obstacle is treated horizontal, e.g., a building, with the vertical position specified by the z-value for all corners. An example is shown in Figure 87:

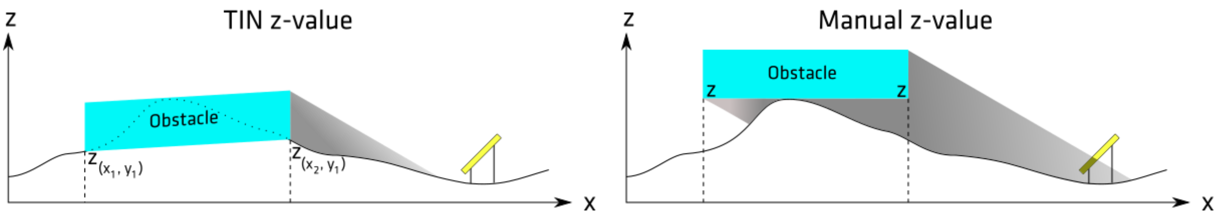


Figure 87 Illustration of the difference between taking the z-value from TIN versus manually entering a z-value.

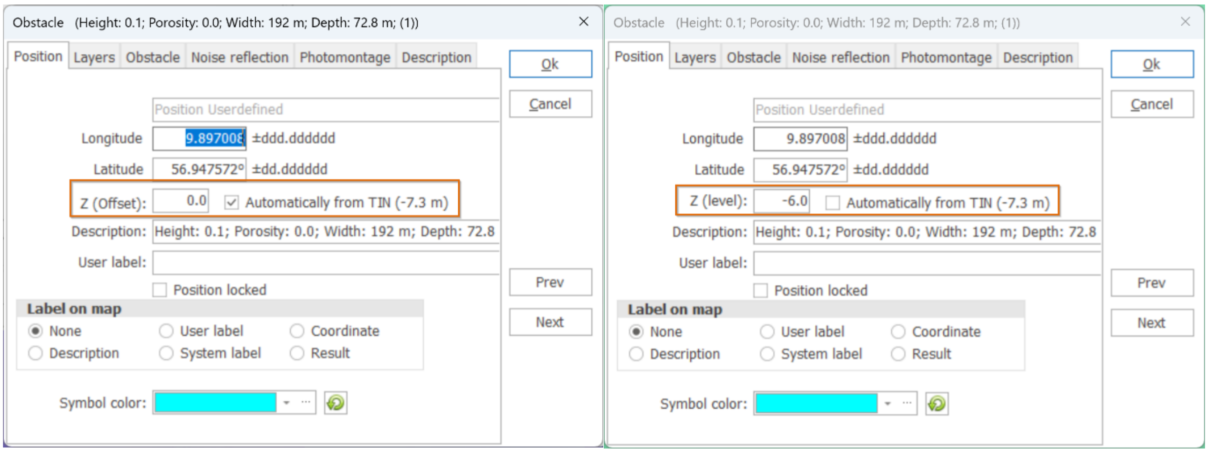


Figure 88 Obstacles will by default take Z-value from TIN, here -7.8 m.

As seen, the z-level for the first corner is -7.3 m (taken from TIN). To the right, it is manually given the value -6 m. To illustrate the impact of these different setups for the obstacle, an example is presented below. Figure 89 illustrates how the solar panels affected are located in approximately 7-8 m different elevation, with the middle part of the panel rows in the sloped terrain varying from +2 to -8 m, constructed by two contour lines.

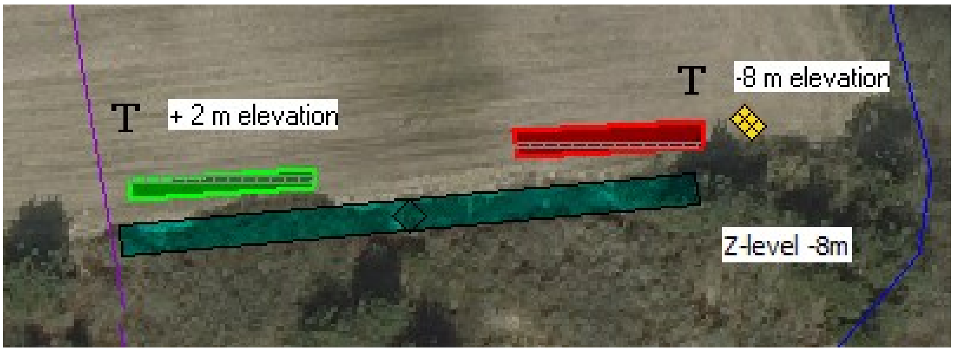


Figure 89 Test example setup with elevation difference. Obstacle is 5 m high.

				Shading losses (%)				
Areas	DC Capacity (kW)	AC Capacity (kW)	GROSS (MWh/y)	Panel and diffuse red.	Obstacles	WTG Towers	WTG Rotors	Topo
Area_ 1	3,90	5,00	4,837	3,4	32,77	0,00	NA	NA
Area_ 2	3,90	5,00	4,837	3,4	32,14	0,00	NA	NA

				Shading losses (%)				
Areas	DC Capacity (kW)	AC Capacity (kW)	GROSS (MWh/y)	Panel and diffuse red.	Obstacles	WTG Towers	WTG Rotors	Topo
Area_ 1	3,90	5,00	4,837	3,4	0,00	0,00	NA	NA
Area_ 2	3,90	5,00	4,837	3,4	32,46	0,00	NA	NA

Figure 90 Calculated obstacle loss on the two areas. Right with manual z value -6m.

In the left calculation in Figure 90, the obstacle z-level is taken from TIN, so the obstacle follows the terrain. Observe how both the green and red Solar PV areas experience similar obstacle shading losses.

In the right-side calculation in Figure 90, the obstacle uses a manually entered z-value (z= -6 m), meaning the obstacle does not follow the terrain. This changes little for the red areas shading losses, since it is located at a same z-value as the obstacle z-value (manually entered). However, the green area (z=2 m) is now clear of any shading losses as the entire obstacle is now located below the green solar area.

Very important: Obstacle corners are following the terrain if z-value is taken from TIN but is assumed horizontal if the z-value is manually entered! On a hilly site, there might be wind breaks or forests following the terrain up and down. This will not be correctly modelled with one long obstacle. Multiple shorter obstacles are the recommended workaround.

In a photomontage, the obstacle will always take the Z-level from TIN, displaying the obstacle as following the TIN-calculated terrain.

14.7.2.3 From shading to loss

The shading on PV panels is projected onto the surface of the PV module as geometric figures, hence it is possible to determine exactly which part of the panel is shaded in each time step. This must be converted to power loss.

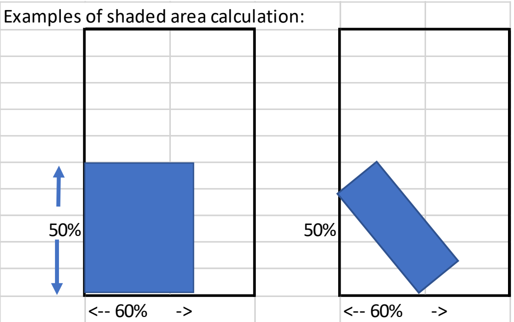


Figure 91 Shading on a panel is converted to vertical and horizontal shares each time step.

First, the shade cover is converted to vertical and horizontal coverage.

Next, the optional by-pass diode setup decides how much the direct radiation is reduced. A threshold can be set, e.g., less than 3% shading will not have an effect. As soon as the shading covers more than this, the by-pass diode configuration decides how much the direct irradiance will be reduced.

In Figure 91, this will be the case if there is a module string that is free of shading. If three by-pass diodes are on the short side, there will be one module string free of shade (33%) and the reduction factor on the direct irradiance is set to 0.667.

Diffuse irradiance is not reduced by direct shading from obstacles or turbines, but for panel shading, see next section. This might later be revised, although in most cases it will be marginal.

14.7.2.4 Diffuse irradiance reduction by panel angles

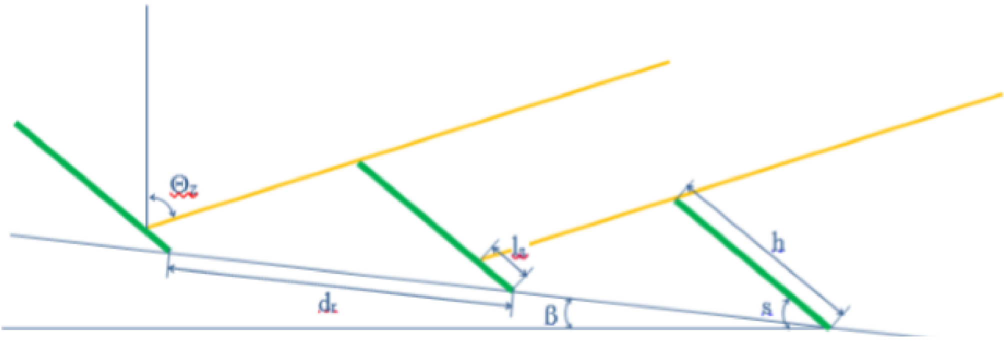


Figure 92 Diffuse shading reduction.

The angles within which the panels see the sky relative to a 180-degree view decide the diffuse reduction. If the panels are located on a hill or non-planar surface, this will be handled in the calculation. **If shading from panels is unchecked in the loss form, diffuse shading reduction is not calculated, even though this is not only caused by panels.**

14.7.2.5 Albedo

Albedo is a property of the ground around the PV object, used for calculation of reflected irradiance. It is particularly relevant for calculations of Bifacial panels.

It is possible to specify a constant value of albedo as well as monthly values to e.g. account for increased albedo due to snow cover in the winter months. To specify monthly albedo values, *Userdefined – monthly* must be selected in the dropdown menu, as shown Figure 93. When selected, a window where the monthly values can be specified will automatically open - Figure 94. To make modification after specifying the monthly albedo values the ... can be used.

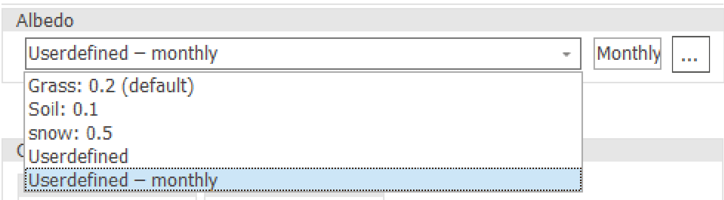


Figure 93 Selecting monthly albedo values in the Calculation Setup

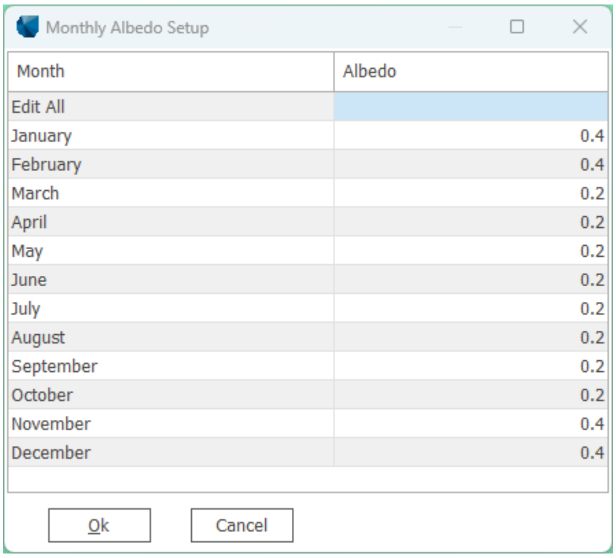


Figure 94 Monthly albedo setup window

14.7.2.6 Bifaciality factor

The Bifaciality factor specified in the calculation setup is used as default, if the Area is selected to be calculated as bifacial but Bifaciality factor is not specified in the Panel setup.

14.7.2.7 Other losses

In addition to inverter and shading losses, losses due to DC wiring, degradation, soiling/snow, etc. are also losses before the inverter, and thus are subtracted before the DC input to inverters is found.

Starting from windPRO 4.1, it is possible to specify the **soiling losses** as **monthly values**. It enables to specify e.g. increased losses due to snow in the winter months. Monthly values can be defined by selecting the button ... next to the soiling loss – see Figure 96. This will open a new window where losses for each month can be specified as shown in Figure 95. If this is done, the field in the Soiling/Snow losses will say *Monthly*.

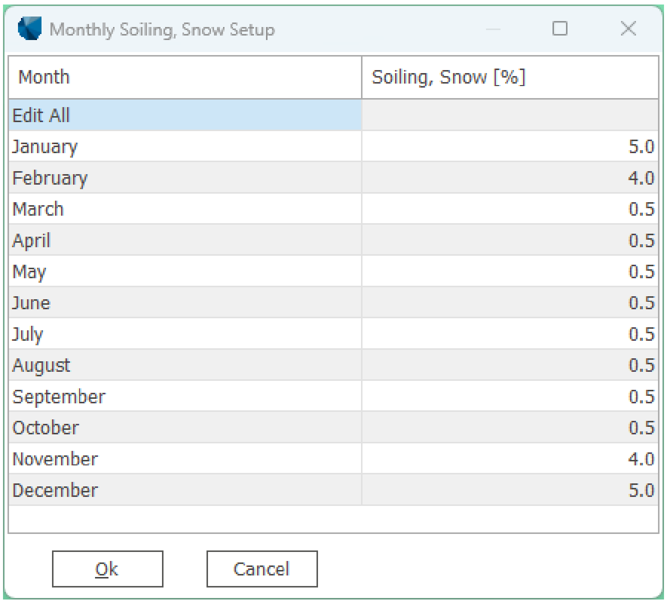


Figure 95 Monthly Soiling/Snow losses setup window

After inverter losses are availability, substation loss, etc., which are subtracted after the inverter AC output.

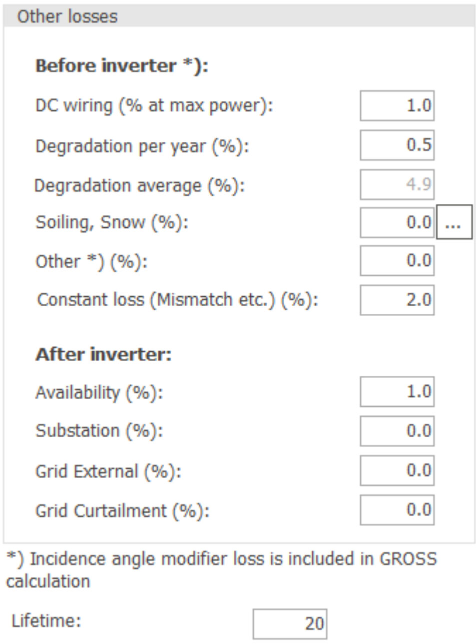


Figure 96 Entering other losses.

An important modification from windPRO 3.6 is the addition of Constant loss (Mismatch etc.). Validations have shown that this is important to include, as the low irradiation months yielded too high production relative to the high irradiation months. The constant loss is a power reduction in all time steps based on maximum power. This means that the default of 2% loss will convert to a higher annual loss, typically a little more than double, much depending on the irradiation level and annual distribution.

Another change is that the DC-Wiring loss, starting from windPRO 3.6, is based on the calculated power in each time step. The DC-Wiring loss is proportional to the square of the current flowing through the wiring. Hence, if the power is 50%, the calculated loss is 25% of the input value. Default value is 1%.

The degradation loss has a special status as it increases over time. In the AEP calculation there will be two options of outputs:

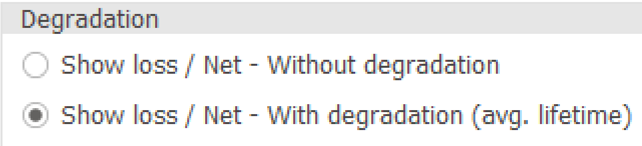


Figure 97 Two output options.

- First year without degradation
- Average year with average lifetime degradation

14.7.3 Including costs in the calculation

Starting from windPRO 4.0, it is possible to include costs in the Solar PV calculation. The cost calculation is done based on a cost model. A cost model can be selected for all the Areas in the *Cost* tab of the *Calculation Setup* – see Figure 98. To perform the cost calculation *Use cost calculator* must be selected by the user. Once it is done, the Cost Model to be used can be selected in the *Cost model* column of the table. If the same cost model should be selected for all areas, this can be done in the *Edit all* row. Otherwise, a different one can be selected for each area separately in the corresponding row. The cost model is selected in the dropdown list, where it is also possible to edit the cost model. Below the table, the Discount rate, CAPEX investment year and Lifetime can be selected. All of these are used to perform the cost calculations.

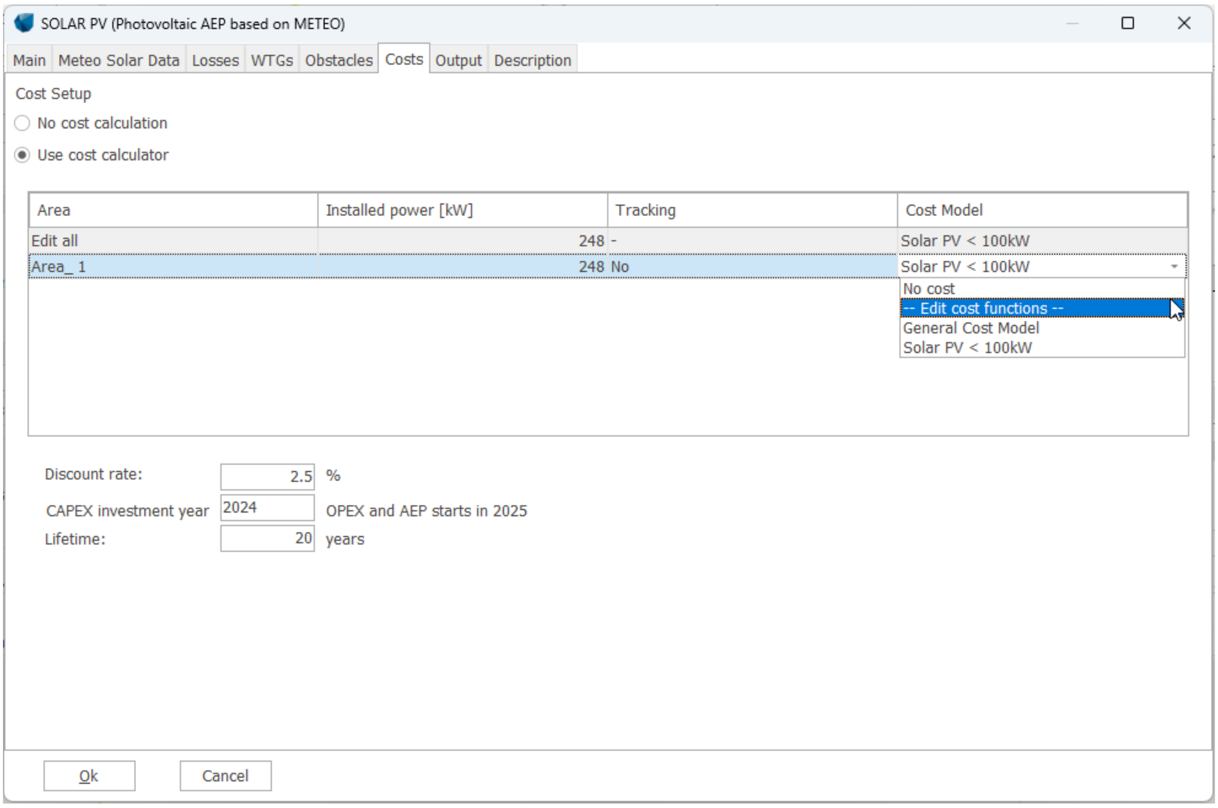


Figure 98 Cost tab of the Calculation Setup.

When *Edit cost functions* is selected in the dropdown, a window with cost model is opened. Here the costs can be modified by the user. The *Edit Cost Model* window is shown in Figure 99. The left part of the window holds a list of saved cost models, it is also possible to Clone, Delete and create New. The middle part of the window presents the costs per category, three mains are: DEVEX, CAPEX, OPEX and ABEX. In each category, different costs are defined and the Cost function value can be modified by the user. The right side of the window presents an example of the cost calculation for the PV plant used in the Calculation Setup with a default capacity factor of 20% - this is solely for presentation purpose. It is possible to load an existing PV calculation if one is available in the project by clicking on Load example data from PV calculation. If this is done, the results in the table in the right bottom corner will be based on the performed calculation. Read more about cost models in section 2.18 of Basis manual.

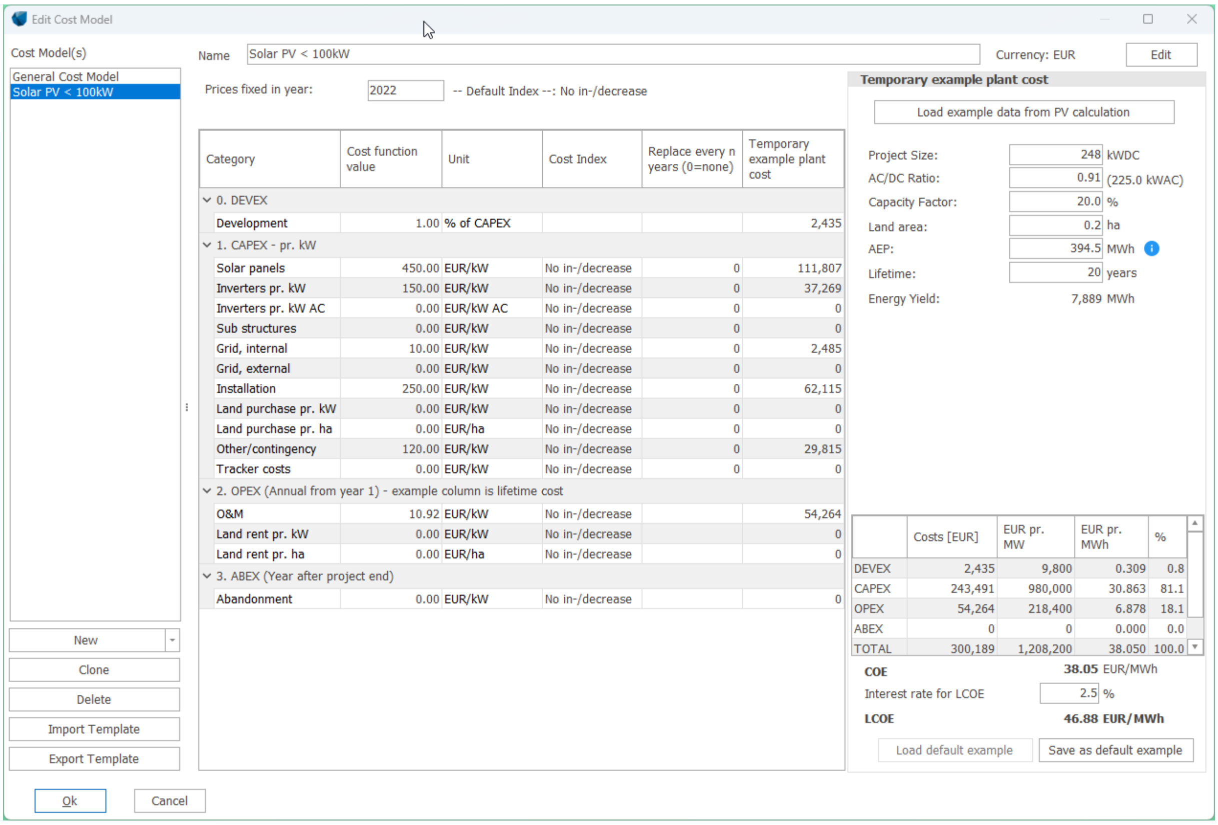


Figure 99 Edit Cost Model window.

The cost calculation can be done as part of the Solar PV calculation, but it is also an essential input for Solar Optimize – see more about it in section 14.10 .

14.7.4 Output

In the Output section the user can select if gap filling of the irradiance data should be performed. It is also possible to choose between AEP and Time series energy calculation.

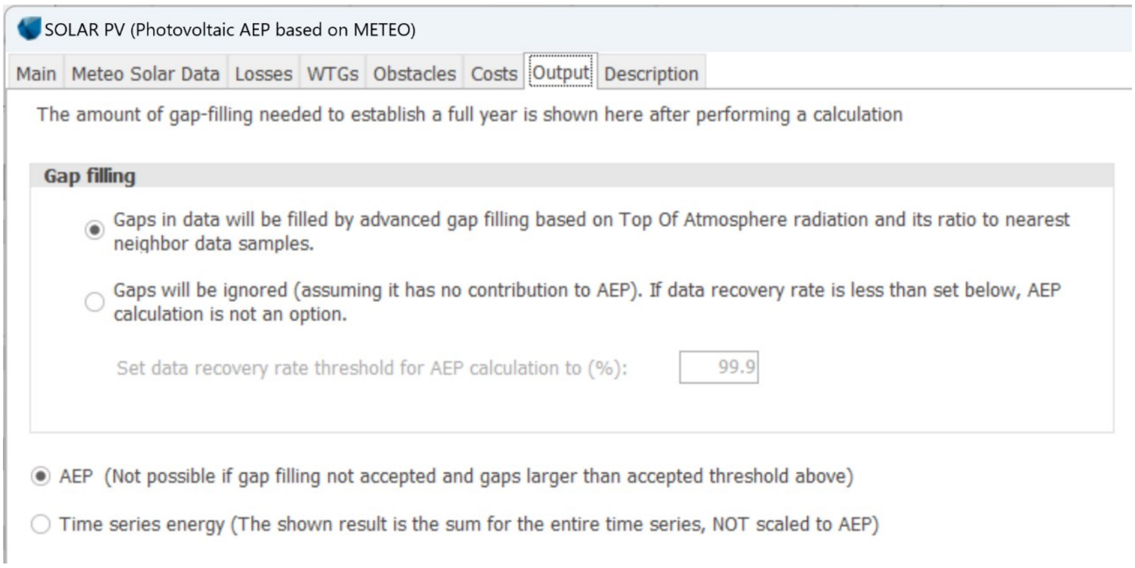


Figure 100 Output options, use Gap-filled data.

Normally the most interesting result will be the expected Annual Energy Production (AEP). Calculating a full year requires that there are data for each time stamp for one full year. If there are, for example, 1½ years of data, the average of each time step from different years will be used. E.g., 05/05/2018 03:00 and 05/05/2019 03:00 will be averaged and if just one of the years has data, there will be a value for this time step. If there are gaps, these can be filled as described in section 14.7.4.1 . This also includes extension of data, if less than a year is available.

A threshold, e.g., minimum 97% recovery rate can be set. If the gap filling is within this threshold, an AEP calculation is performed WITHOUT gap-filled data, but with zero production in the missing values, where none of the selected years have data. This is the very conservative approach.

Using Heliosat (SARAH) data, there will typically be around 5% gaps, while the data uses satellite images to construct the data sets, and there will be time steps with no photos. If gap filling is not used with these data, an underprediction will be seen.

If gap filling is NOT within the threshold, AEP calculation is not an option, and the calculation will be performed for the time period with the data available. In reports, AEP headers will be replaced with energy and the fraction of the year for which the calculation was made is shown.

Areas	DC Capacity (kW)	AC Capacity (kW)	GROSS MWh (24.41 years)
Area_ 1	721	650	24,228
Show more results	721	650	24228

Figure 101 Example with time period production, here calculated for 24.41 years.

14.7.4.1 Gap Filling approach

The gap filling/extension of time series is based on calculating the Top of Atmosphere (TOA) irradiance from time of the year, latitude and longitude, and dividing the result with the nearest data points in the time series.

The identified factor (local data/TOA) is used on TOA to fill the gaps. A minimum of three data points is taken before/after the missing point. If more points in a row are missing, the number of data points is extended, although never longer than using +/-1 month. Thereby, short gaps will be filled very precisely while the actual data will dominate. For longer missing periods, e.g., one month, the two neighboring months will have a strong influence. This can lead to high uncertainty of the AEP calculation. If data is to be extended outside the data period, a similar approach is used, working like this: Having February to November and a full year calculation is wanted, but two months are missing. Then the October, November, February and March data are used to construct December and January. Two months are missing, and the ratios to TOA for the two months before and after are used to multiply on the TOA for the missing months. More than three months before/after a missing period will never be used to perform gap-filling.

14.7.4.2 AEP and time series energy

When calculating energy production **time series**, it is calculated for each time step. Therefore if, for example, January 2nd, 2019, has no data at 11:00 and gap filling is not selected there will not be calculated any production (= 0).

If the AEP calculation is chosen, calculation method is as follows: If data for multiple years are available, the average of each time step from all years is used. If a time step, for example, January 2nd at 11:00, has no data in any year, no calculation is performed for this time step (=0). However, if there is a value at that time in just one of the years selected for the calculation period, this is used for all years.

Due to these defined procedures, there can be smaller deviations between the irradiation shown in the "Meteo Solar Data" tab or report and in the summarised data in the result to file output.

The recommendation is always to use gap-filled data. For solar irradiance, there is a physical logic, that makes gap filling consistent and precise, as opposed to wind data, which are more random in their variations. EMD is aware that some users out of principle, do not allow the use of artificially-generated data, therefore we offer the feature to not use gap filling.

14.8 Calculation approach

14.8.1 Calculation of Plane of Array irradiance

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. Solar irradiance is measured in W/m^2.

The input to energy calculation in Solar PV module in windPRO is the measurement of Global Horizontal Irradiance (GHI). The GHI comprises of direct horizontal irradiance and diffuse horizontal irradiance. Since the PV panels are usually tilted, the horizontal irradiance must be translated to the Plane Of Array (POA) Irradiance, which can be later used in energy calculations. The direct (BHI) and diffuse (DHI) components are translated differently since they have different physical properties – see Figure 102.

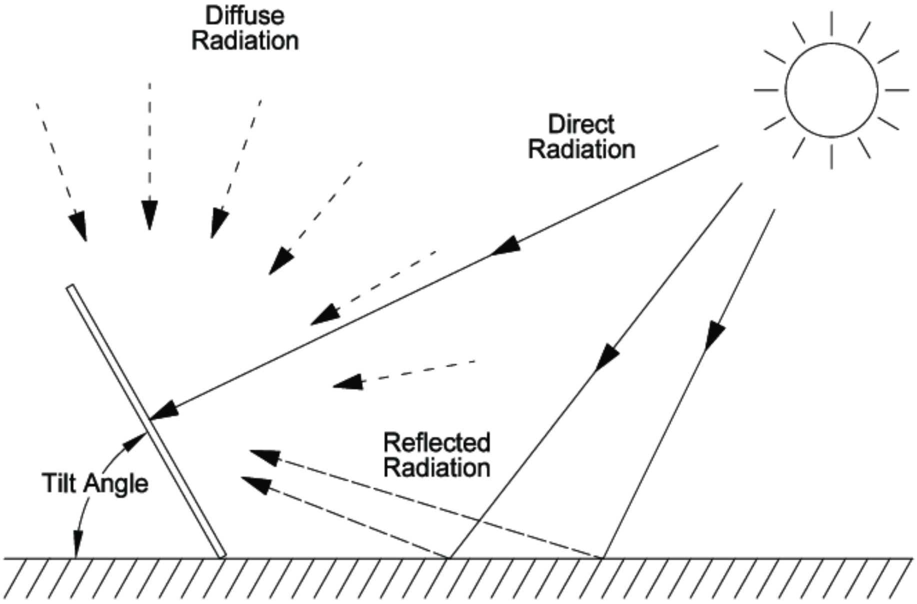


Figure 102 Irradiance components.

The schematic of calculation from GHI to POA irradiance is shown in Figure 103. Starting from windPRO 3.6 new methods and defaults are available for subdividing global horizontal irradiance into direct and diffuse, and for converting horizontal to inclined irradiance. The new default model for subdividing the irradiance into direct and diffuse is the Erbs model. The new default for transforming to inclined plane is the Perez model – as alternative also the Hay and the Reindl models are available.

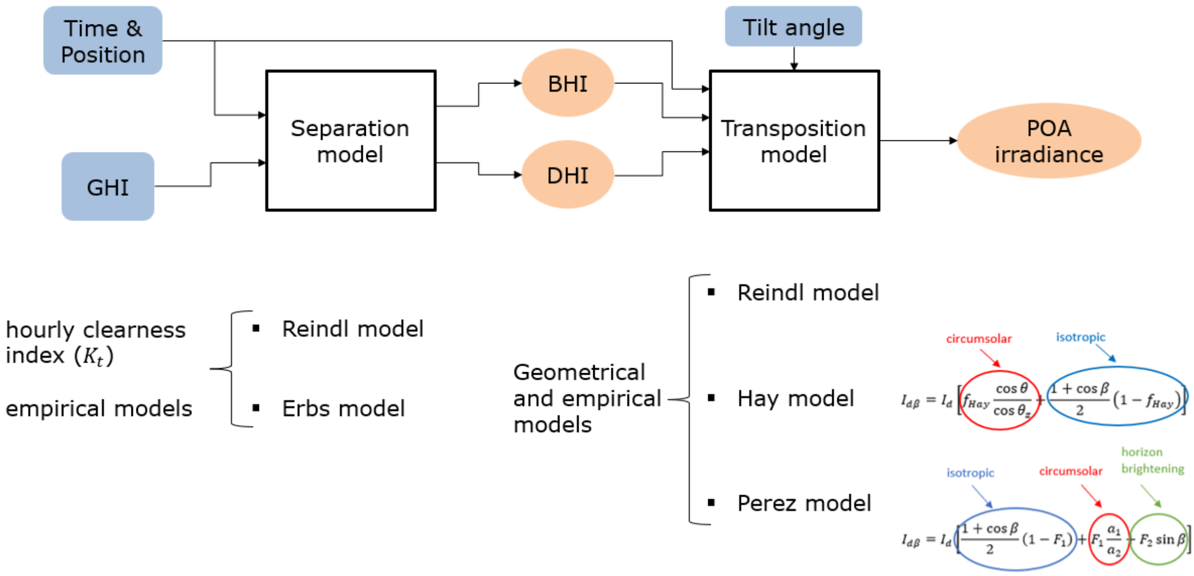


Figure 103 Calculation of POA from GHI.

These models are today used in other commercial tools, like PVSYST. The previous model used in windPRO and PVSYST was the Reindl model, which is still available and is described in the documentation of windPRO's sister software, energyPRO: [Solar collectors and photovoltaics in energyPRO.pdf]

Did you know?

EMD also develops a software suite called energyPRO.

energyPRO is used for modelling and analyzing complex energy projects across the world.

Combining different markets, storage and demands with the supply of electricity from any kind of energy technology (solar, wind, hydro etc) and/or thermal energy (process heat, hot water and cooling) for techno-economic modelling of any energy project.

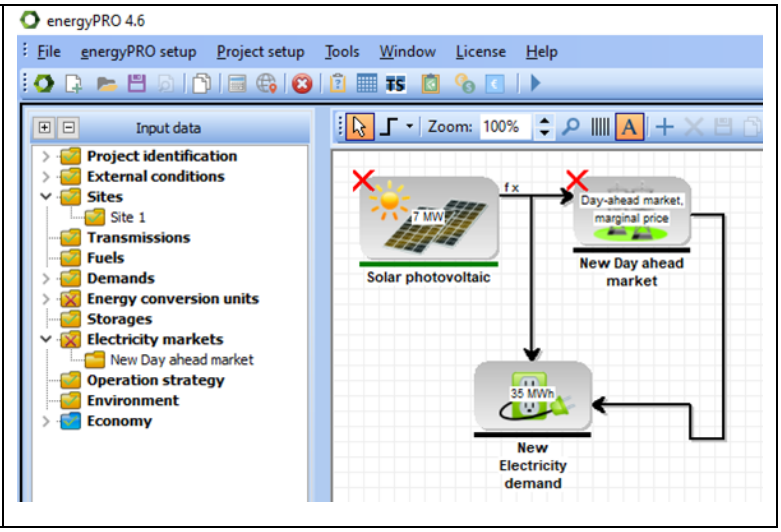


Figure 104 Image of energyPRO.

14.8.2 Calculation procedures for hourly AC power output

The calculation of both AEP and Time series energy is based on the hourly AC power output calculations performed for all timesteps in the selected *Output Interval*. The input to power output calculation is the Plane of Array (POA) irradiance, which is calculated as shown in section 14.8.1 . The calculation flow from POA irradiance to DC power output is demonstrated in Figure 105.

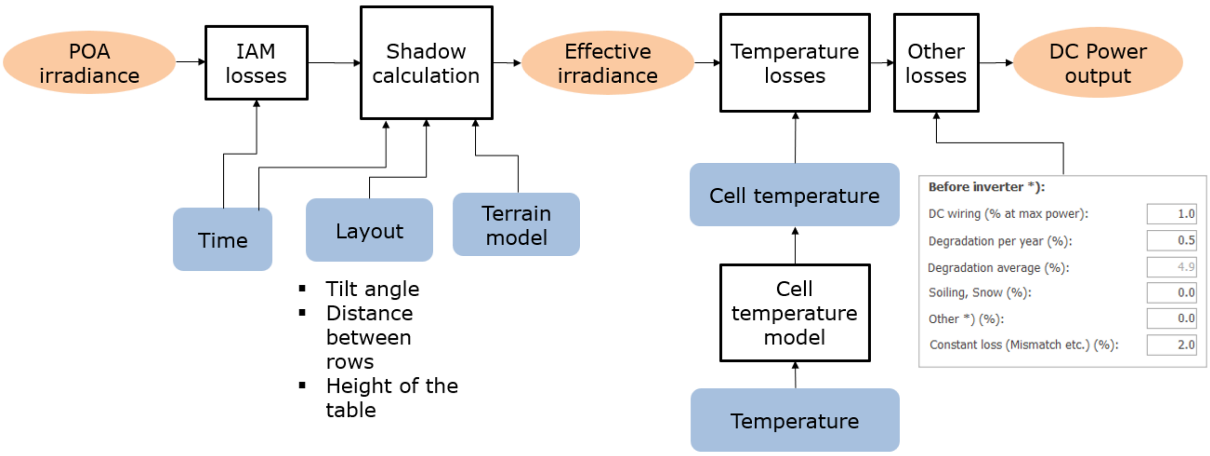


Figure 105 Calculation flow from POA irradiance to DC Power Output.

The Incidence Angle Modifier losses are applied to both the diffuse and direct irradiance. For diffuse irradiance, IAM for 60º incidence angle is used, which is the recognized approach in literature. The IAM for direct irradiance depends on the hourly incidence angle, which is the angle between normal to the PV panel surface and the incoming sun ray. The IAM used in windPRO calculations is shown in Figure 106.

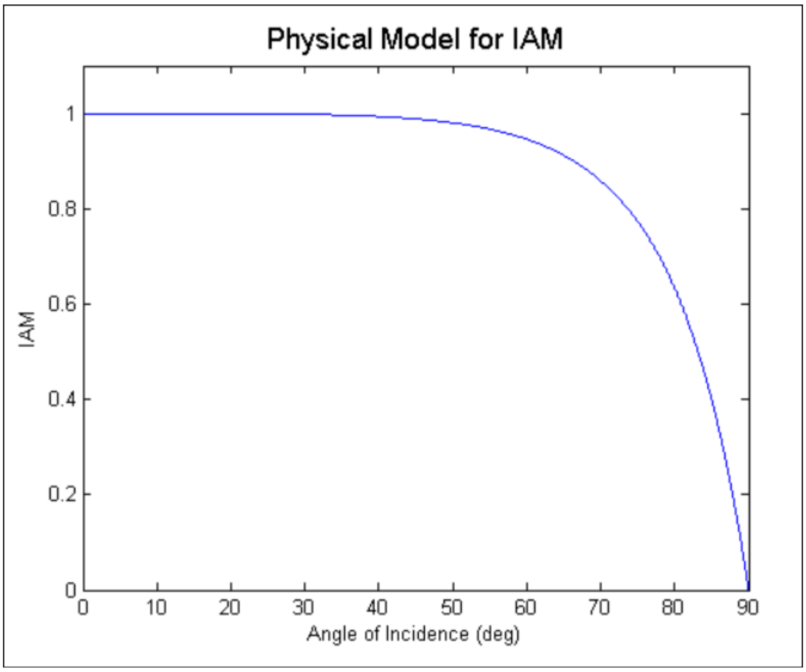


Figure 106 Incidence angle modifier used in windPRO calculations.

The shadow calculations are specified in detail in sections 14.7.2.1 - 14.7.2.4 .

The cell temperature model calculates the cell temperature based on the following equation:

$$T_c = T_a + I_{eff} \cdot \left(\frac{NOCT - 20}{800}\right)$$

Where:

T_a – ambient temperature

I_{eff} – effective irradiance

$NOCT$ – nominal operating cell temperature

The reduction of power output due to cell temperature is accounted for as shown in the below equation:

$$P = P_{NO\,Tloss}\left(1 + {}^{\alpha_P}/_{100} \cdot \left(T_c - T_{c,STC}\right)\right)$$

Where:

$P_{NO\,Tloss}$ – power output not considering the temperature loss

$T_{c,STC}$ – cell temperature in STC conditions = 25ºC

α_P – temperature coefficient of maximum power output (can be found in datasheets)

A detailed description of the Other losses is included in section 14.7.2.7 .

The DC power output, which is calculated based on the approach illustrated in Figure 105, needs to be converted into the AC power output to be able to proceed with AEP calculations.

The calculation steps from DC power output to AC power output are illustrated in Figure 107.

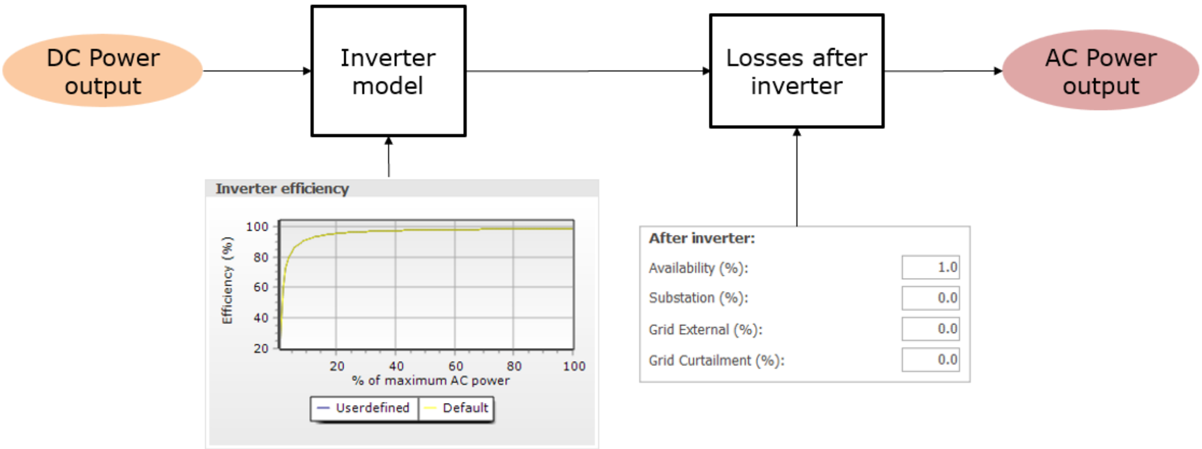


Figure 107 Calculation flow from DC Power output to AC Power output

The inverter model holds information about efficiency depending on the load of the inverter. It is used in every timestep to calculate what will be the output power of the inverter depending on the DC input to it. More information about the inverter model can be found in section 14.6 .

The losses after the inverter can be specified by the user and are applied as a percentage reduction in each timestep of the calculation.

After all the above calculations are done, the AC power output of the plant is calculated.

14.8.3 Calculation time

The calculation time depends mainly on the number of panels, but also on the length of the time series used in calculation. The feature *Use reference panel* is very important for large plants. This will be, for most very large plants, just as accurate as calculating for each panel and takes less than one minute compared to more than 10 hours for a large plant with ~300.000 panels. The disadvantage of the reference panel method is that shading from obstacles or WTGs are not handled correctly. This can although be handled by establishing smaller areas near the obstacles and then not using the reference panel method for those. In that way, an accurate calculation within reasonable calculation time can be reached. For plants in non-flat terrain, there can be similar issues. For instance, if there is an eastly sloped hill and a westerly sloped hill, areas should be designed so one area covers each hill. Then the reference panel calculation will be ok assuming the hill slopes are reasonably similar. More details about using the reference panel in the calculations can be found in section 14.4.3 .

Table 2 Calculation time by number of individual panel calculations.

Power (MW)	Ha	Panels	Time series:	1 y	20 y	
10	15	30.000	Calculation time:	12	45	Minutes
100	150	300.000	Calculation time:	10	15	Hours

It is not recommended to do individual panel calculations for more than 300.000 panels. This might result in memory problem followed by failed calculation. Instead, use the Reference Panel method.

Another more comprehensive test on calculation time has been performed:

The calculation time depends mainly on the number of panels in the calculation. Using a reference panel calculation will reduce the calculation time to seconds no matter the size of the plant.

The calculation period (years) and whether obstacle and/or WTG shading is included also have an impact. Here the reference panel calculation is problematic as the shading impact will not be captured.

Below calculation time is analyzed based on full (not reference panel) calculation. The PC used is a standard modern laptop PC (Core I9 @2.4GHz from 2020).

Figure 108 Calculation time versus number of panels shows a linear increase.

Based on the found relations, calculation time is extrapolated to very large plants, where the number of panels are converted to MW based on 350 W panels:

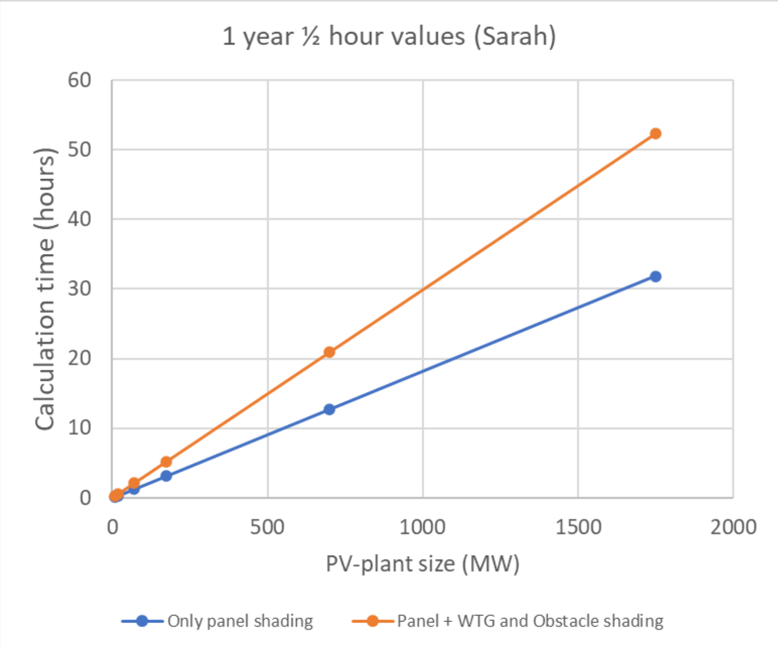


Figure 109 Calculation time for full calculation versus MW plant size.

A **500 MW** plant will take almost **10 hours** only with panel shading. With both obstacles and WTG shading roughly 50% time will be added. If only obstacle shading is included roughly 15% calculation time will be added.

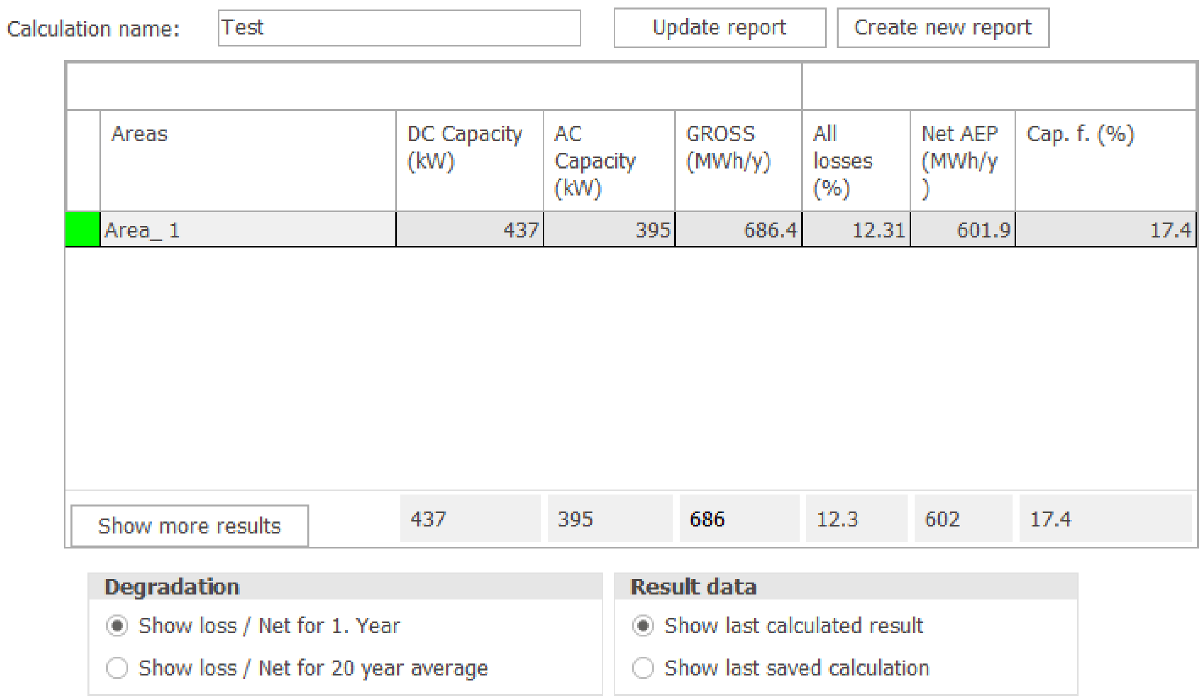
Calculating **20 years instead of 1 year** will roughly result in a **10 times higher** calculation time, although it depends on which type of shading is included. The more shading elements included, the less is the increase, as the "heavy part" of the shading calculation is a one-time calculation independent from the number of calculation years.

Using 1 hour data (ERA5) as alternative to ½ hour data (Sarah), will roughly halve the calculation time.

At EMD we are continuously working on improving the calculation time.

14.9 Calculation results

14.9.1 Calculation output in the status window



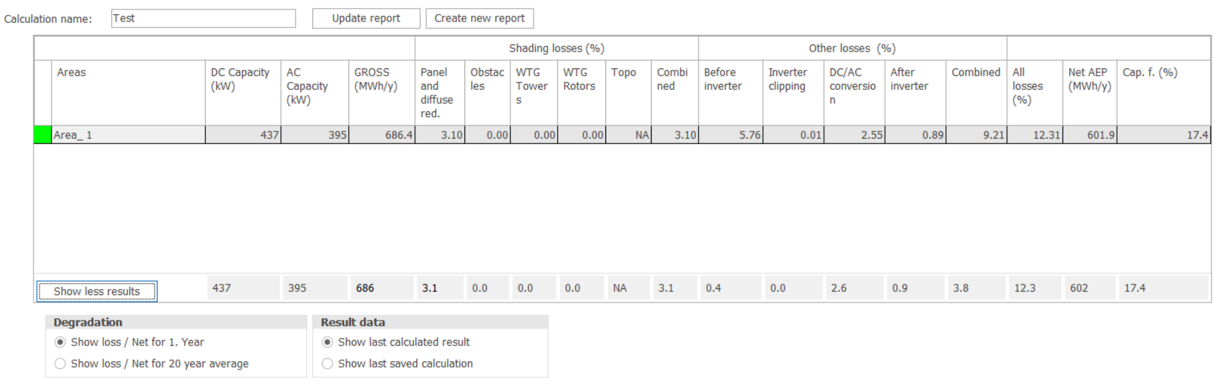


Figure 110 Calculation - results will be seen in table next to PV-design parameters when calculation is performed.

Press "*Update results*", and calculation results will become available in a table in the PV-Status window. The calculation might take some time depending on size of the plant, the time period and the shading complexity. Therefore, if it is a large plant (>30 MW), it is a good idea to start a calculation without shading calculation and for a short period (1 year), to get confident that all is setup correctly before waiting maybe hours for a full calculation. With 300.000 panels and 30-year data, the calculation time is round 20 hours on a standard PC. Therefore, a warning is seen if there are more than 300.000 panels:

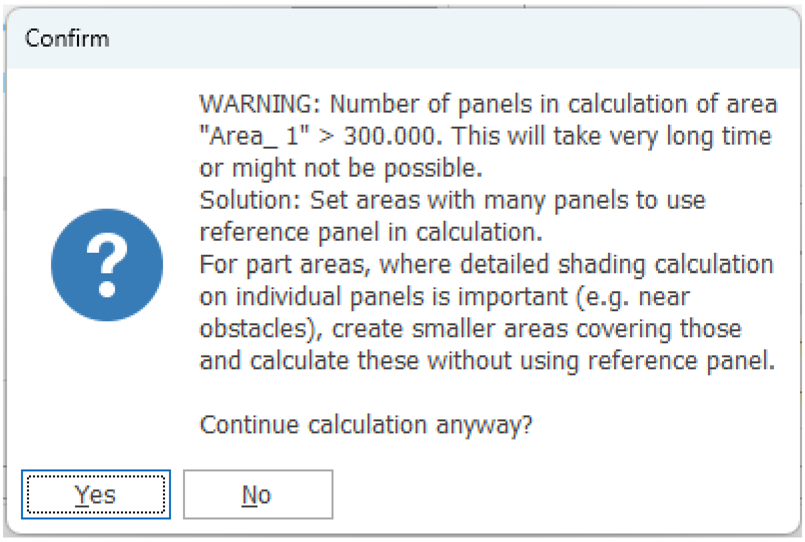


Figure 111 Warning if more than 300.000 panels are set for individual calculation.

The result table can be copied to e.g., Excel with right click on table. Figure 112 illustrates some output choices:

Results for 1. Year																		
	Areas	DC Capacity (kW)	AC Capacity (kW)	GROSS MWh (0,94 years)	Arrays	Obstacles	WTG Towers	WTG Rotors	Topo	Combined	Before inverter	Inverter clipping	DC/AC conversion	After inverter	Combined	All losses MWh (0,94 years)	Net MWh (0,94 years)	Cap. f. (%)
	Area de	324	295	378	14,3	0	0	0	0	14,28	0,84	0,01	3,16	0,8	4,82	19,1	305,8	11,6
	Area_3	156	145	182	14,3	0	0	0	0	14,26	0,84	0,01	3,21	0,8	4,87	19,13	147,2	11,4
Results for 25 y average																		
	Areas	DC Cap	AC Cap	GROSS	Arrays	Obsta	WTG To	WTG R	Topo	Combin	Before in	Inverte	DC/AC	After i	Combin	All loss	Net M	Cap. f. (%)
	Area de	324	295	378	14,3	0	0	0	0	14,28	5,87	0,01	3,12	0,75	9,75	24,03	287,2	10,9
	Area_3	156	145	182	14,3	0	0	0	0	14,26	5,87	0,01	3,17	0,75	9,8	24,06	138,2	10,7
Reduction for 25 y																		
	Area-1	0	0	0	0	0	0	0	0	0	-5,03	0	0,04	0,05	-4,93	-4,93	18,6	0,7
	In %														-102%	-26%	6,1%	6,0%

Figure 112 Result table copied to Excel and presented with more output choices.

The example shows an output based on one year compared to average of 25 years. Here degradation per year is the difference. In this case, the total loss increases from 19% to 24% due to degradation. Net energy is therefore reduced by 6%. The before inverter loss increases from 0.8% to 5.9% by including degradation of 0.5% per year and a lifetime of 25 years. Therefore, this is a very important loss figure.

Show last saved calculation is a feature making it simple to make a fast comparison of the last saved calculation result, and the last calculated.

14.9.2 Reporting

There is comprehensive reporting of the calculated results. To get to the reporting, press the Update report or *Create new report* button from the PV status window and the report can be found in the usual Calculations window:

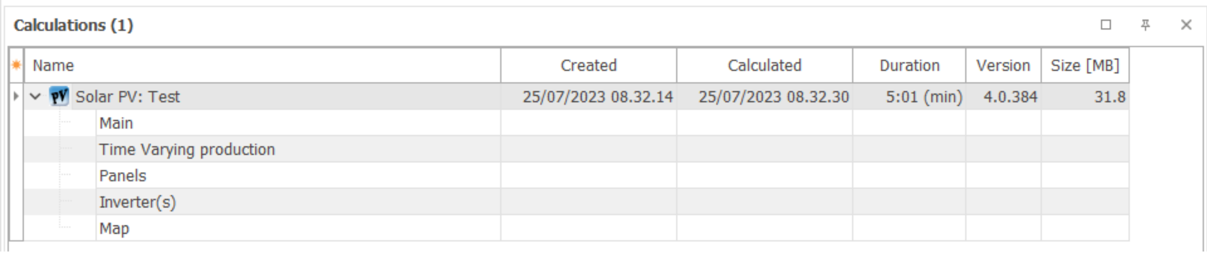


Figure 113 Reporting from Solar PV calculation.

Double click on one of the reports to preview the result or right click at the header line to get all or selected report pages printed:

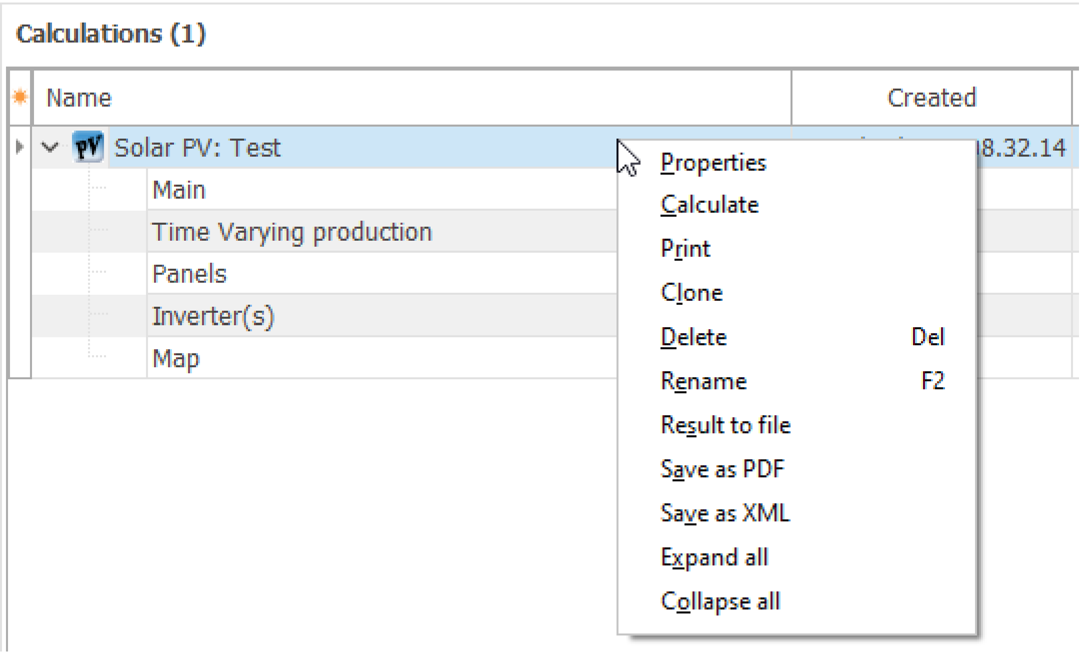


Figure 114 Right click menu at report.

Properties opens the Calculation Setup used for the calculation.

Calculate recalculates, if, for example, the Solar-PV object used or other data behind the calculation (e.g., Meteo data), have been changed.

Print opens the Report Setup, see Figure 115, from where the report can be sent to the printer, to a .pdf document or previewed on the screen.

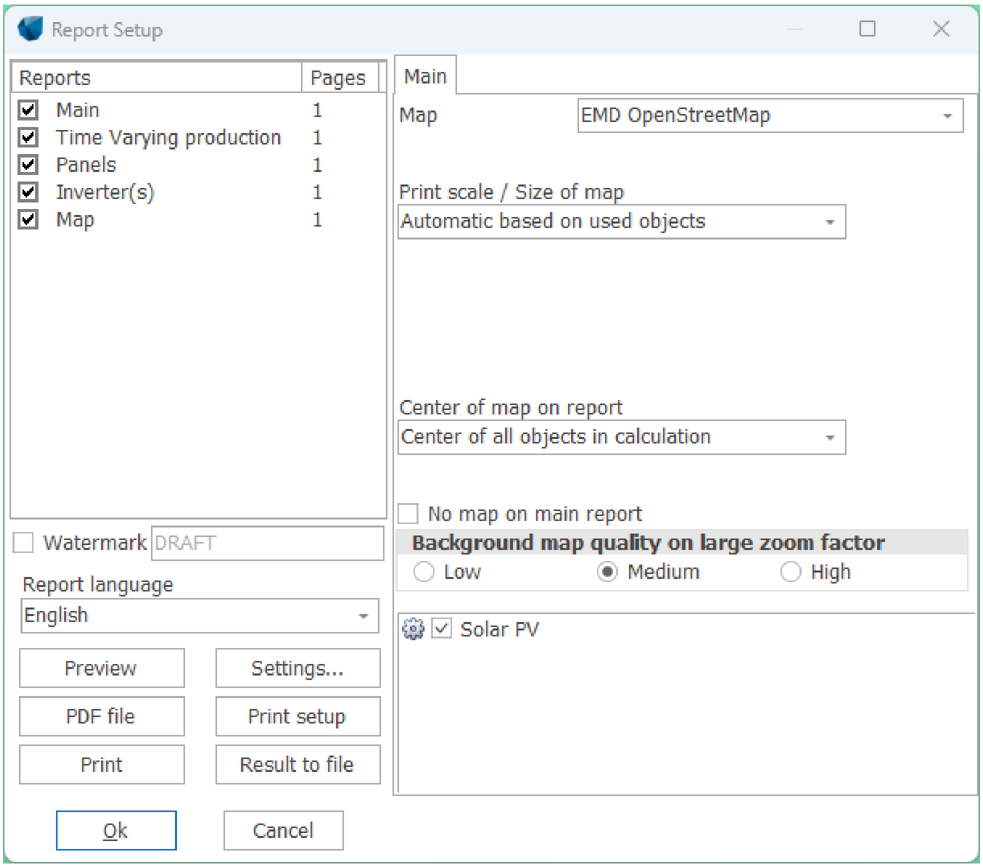


Figure 115 Print options.

Clone makes a copy of the calculation that can be used to run another scenario whilst retaining the original results.

Delete deletes the calculation (but not the associated objects).

Rename the calculation name can be changed without any other changes and no recalculation.

Result to file give access to take results to a file or to the clipboard for paste e.g., into Excel for further analyses or special reporting. See Section 14.9.3 .

Save as can direct save to a .pdf or .xml file.

Expand/collapse works on the tree structure the calculations are shown in.

14.9.3 Result to file

Result to file is an efficient way to get all assumptions and results to e.g., Excel or other internal tools for post processing or validation.

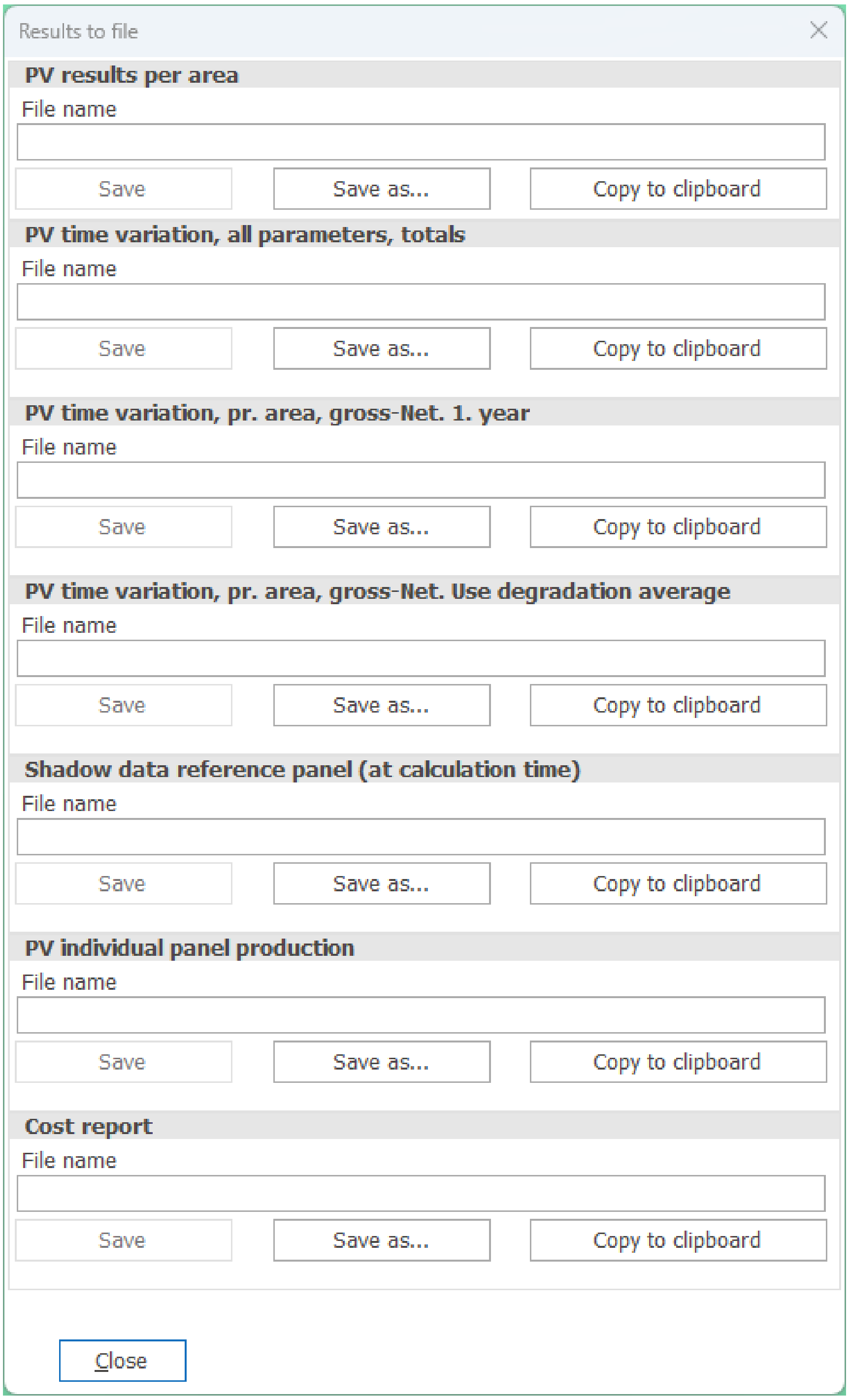


Figure 116 The reports offered as result to file.

PV results per area is the main report, having all relevant aggregated results and input used.

The report has the following rows and columns, shown transposed in table below, where row 9 is first area, followed by the other areas, if more are included in the Solar PV object. In the bottom, tracking info is depending on how many manual tracking shifts there are included (up to 52 weeks).

Table 3 Result to file columns for report "PV results per area" (transposed).

col	row_1	row_2	row_3	row_4	row_5	row_6	row_7	row_8	row_9
1	Calculation name	HEADER:	Object name:	Calc. time:	windPRO ver.	Design details per area:	Area		Area_ 1
2	Test-area-report		Solar PV (11)	07-05-2021 17:16	3.5.393		Row count		5
3							Row distance	m	2
4	Panel shadow incl.	Included WTG towers	Included WTG rotors	Rotor area reduction (%)	Included Obstacles	TOPO included	Tilt	deg	26,190201
5	NO	YES	YES	50	YES	NO	Azimuth	deg	180
6							Ground offset	m	0,4
7		Used meteo data:	Calculated with:	Time period:	Scaled:	If organised in Tables:	Table rows		1
8							Table columns		1
9			ERA5(T) Rectangular Grid_N56,25_E010,75 (3).2,00m -	1899-12-30-1899-12-30	NO	If organised in Tables:	No. Of tables		17
10			Calibrated with:		Gap filled:		Power/table	W	300
11							Type/name		Monocrystalline/EMD-Generic_2021_300W_0.99x1.96 Mono_3xBypass.PVPanel
12				2000-01-01-2000-01-01	0,00%		Orientation	Port/Land	Landscape
13							Size	m x m	1,960000x0,990000
14							Bifacial	yes/No	NO
15							Bifacial gain (%)	%	0
16							Power_max./panel	W	300
17							TC	%/oC	-0,46
18							NOCT	oC	45
19							Bypass diodes		0x3
20							Bypass orientation	long-short side	Short side
21							Degradation, %/y		0,5
22							extra1		extra1
23							extra2		extra2
24							extra3		extra3
25							extra4		extra4
26							Panel(s)	No.	17
27						Calculation results	Power	MW DC	0,0051
28							Inverters	No.	1
29							Power	MW AC	0,005

30							Area	Ha	0,015495
31							area/MW	ha/MW AC	3,099051
32						Gross	(No loss)	MWh/y	6,398363
33						Net AEP	Year 1	MWh/y	6,048214
34							20y avg.	MWh/y	5,746173
35						Net Cap.f.	Year 1	%	13,808709
36							20y avg.	%	13,119116
37							Perf.ratio		88,051141
38							Extra5		extra5
39						Loss details as % of Gross	Extra6		extra6
40							Shading	Panel and diffuse red.	0
41								WTG towers	0
42								WTG rotors	0
43								Obstacles	0
44								Topo:	0
45								All shading, combined	0
46								1y Loss before inverter	1
47								1y Inverter clipping	0
48								1y DC/AC conversion	3,51677
49								1y Loss after inverter	0,955701
50								1y All NON shading loss	5,472471
51								1y Total loss	5,472471
52								20y average Loss before inverter	5,804606
53								20y average Inverter clipping	0
54								20y average DC/AC conversion	3,480452
55								20y average Loss after inverter	0,908019
56								20y average All NON shading loss	10,193077
57								Total 20y average	10,193077
58								BF	0,75
59								Albedo	0,2
60								Tracking	No
61								Back tracking	
62								Min angle	
63								Max angle	
64							Manual tilt angles	Date:	Angle:

65								01-jan	
66								06-jan	

The other reports have time series output, which in length and time resolution match the selected data in the Meteo tab in the Calculation setup.

PV-time variation, all parameters, totals

Table 4 Header part in report "PV time variation…".

Area description:	Area description 1
TimeMeridian:	15
Inclination:	39,161
Orientation (south):	0
Ar:	0,18
NOCT:	45
Degrade Factor:	1
Pmax:	300
TempCoef:	-0,46
Soilfactor:	1
SampleTime:	30
Meteo solar irradiance:	HelioSatSolar_N56.450_E008.150 Hv.2,00m -
Meteo Temperature:	20
Meteo Humidity:	EmdEuropeEra5_N56.444656_E008.132690 Hv.2,00m -
Meteo Local scaling data:	
Meteo period type:	Interval
Meteo data start:	01-01-2013 00:00
Meteo data end:	01-01-2014 00:00
Meteo data Last years:	7

Table 5 Columns in the report in report "PV time variation…" (transposed).

Local Std Time		01-01-2013 01:12:00
GapFilled		-1
Radiation W/m²		0
Diffuse W/m²		0
Direct W/m²		0
$T_{ambient}$ °		5,994
Humidity		90,386
Diffuse Panel W/m²		0

Direct Panel W/m²		0
Reflected Panel W/m²		0
Area Production W		0
TempReduction		1,115
Incidence Angle		0
IAM		1
IAM60		0,953
$I_{eff}1$		0

PV time variation, pr. Area, gross-net. one year (similar variant for average of lifetime)

Table 6 Columns in report "PV time variation, per area gross-net…" (transposed).

Local Std Time	01-01-2013 01:12	01-01-2013 01:42
Years used	1	1
Gap-filled	YES	NO
P_Gross_	0	0
P_Net_	0	-73,0125
P_Gross_	0	0
P_Net_	0	-35,8875

Shadow data reference panel (at calculation time)

This report gives a unique documentation of how the shading loss calculation works.

The report includes the shading calculation detail for the reference panel. The timesteps listed in the report are all timesteps the shading calculation was performed for. This depends on the setting chosen in the calculation setup, where it is possible to choose if the calculation should be done for every day or month and 10 min or 1h.

Table 7 below shows an example of the result to file, where the hourly shading factors and resulting array efficiencies are summarized. In the top lines of the file the exact panel position is shown for all corners of the panel, followed by the diffuse shadow factor calculated for the panel. In the columns, the sun position (Azimuth and Altitude) and the shading factors for the panel are shown. All (H) and All (V) are the horizontal and vertical shading factor on the panel, considering all shadow cast on the PV panels. *All, efficiency* is the total efficiency of the panel considering the calculated shading. Similarly, the following columns present the same calculations separated per shadow source – panel, WTG tower, WTG rotor, Obstacles and Topographic shadow. In the table below, the result for the panel marked in orange in Figure 117 are shown.

Table 7 Detailed shading output for specific panel.

LocalStdTime	Azimut	Altitude	All (H)	All (V)	All, efficiency	Panel and diffuse red. (H)	Panel and diffuse red. (V)	Array, efficiency
Panel LL:	12.406435	43.941282						
Panel LR:	12.406451	43.941282						
Panel UL:	12.406435	43.941294						
Panel UR:	12.406451	43.941294						
Diffuse shadow, ef	0.602							
01/02/2001 06.00	98.6	-16	0	0	1	0	0	1
01/02/2001 07.00	108.6	-5.5	0	0	1	0	0	1
01/02/2001 08.00	119	4.4	1	0.79	0	1	0.79	0
01/02/2001 09.00	130.4	13.3	1	0.58	0	1	0.58	0
01/02/2001 10.00	143.2	20.7	1	0.49	0.5	1	0.49	0.5
01/02/2001 11.00	157.7	26	1	0.45	0.5	1	0.45	0.5
01/02/2001 12.00	173.6	28.7	1	0.43	0.5	1	0.43	0.5
01/02/2001 13.00	189.9	28.3	1	0.44	0.5	1	0.44	0.5
01/02/2001 14.00	205.5	25.1	1	0.46	0.5	1	0.46	0.5
01/02/2001 15.00	219.7	19.2	1	0.51	0	1	0.51	0
01/02/2001 16.00	232.2	11.5	1	0.61	0	1	0.61	0
01/02/2001 17.00	243.3	2.3	1	0.87	0	1	0.87	0
01/02/2001 18.00	253.6	-7.7	0	0	1	0	0	1
01/02/2001 19.00	263.5	-18.3	0	0	1	0	0	1

As seen in Table 7, the horizontal shading is calculated as 100% and vertical as 58% at 9:00. This leads to an efficiency of the panel in this hour of 0%. The panel used in the calculation has 2 bypass diodes on the long side and it is installed in portrait mode. Hence, vertical panel shadow of above 50% will result in no power output from the panel. In the following hour, the horizontal shading is calculated as 100% and vertical at 49%, what leads to efficiency of the panel of 50%. The factor is multiplied on direct irradiance. The shading can also be seen by visualizing the shadow on the array using the *Shading visualizing*. The shadow at 9:00 is shown in Figure 117 and at 10:00 in Figure 118.

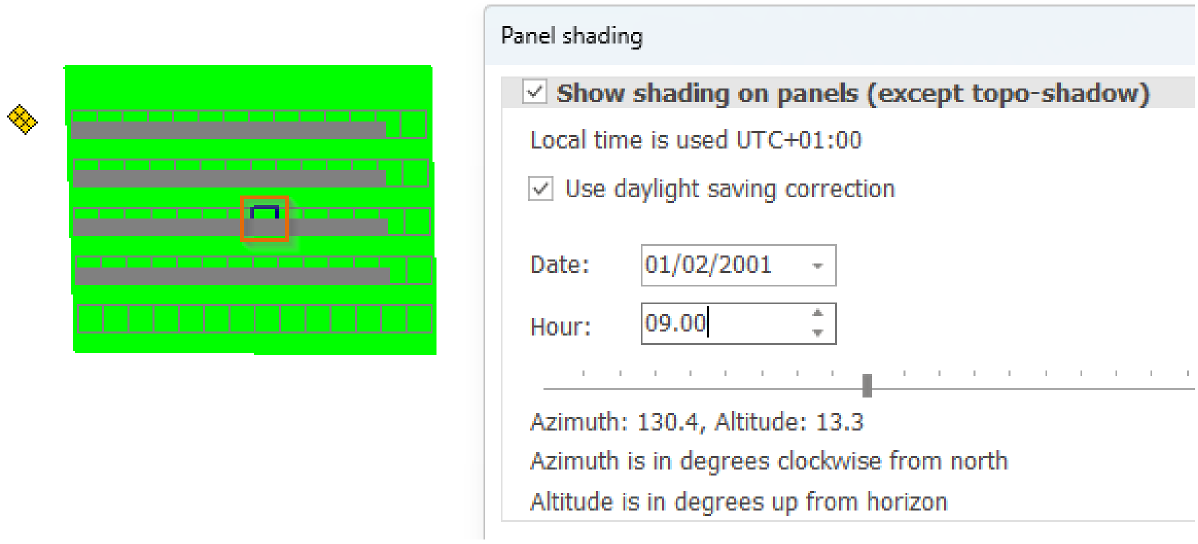


Figure 117 Shading visualization at 9:00

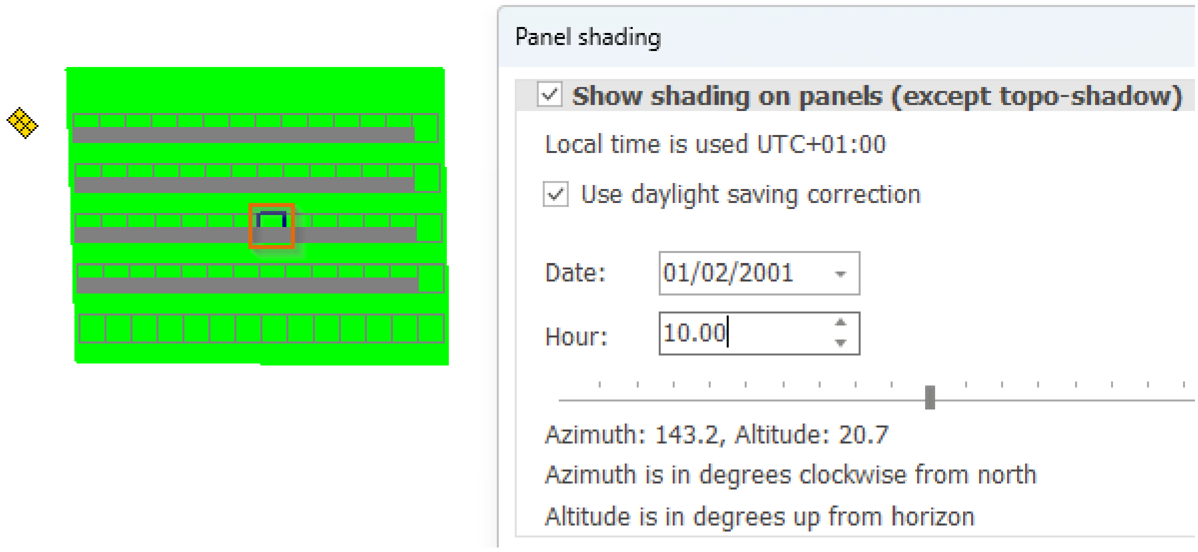


Figure 118 Shading visualization at 10:00.

PV individual panel production

This is an .xyz file with coordinates (GEO decimal degrees in the WGS84 datum) for each panel and the most relevant shading calculation results. This makes it possible to evaluate if there are panels that should be taken out of construction plans, due to low production based on shading loss. Note if Bifacial, the panels will appear twice, first a block for the front side, then one for the rear side.

Table 8 Result to file with individual panel positions and shading loss.

x	y	z	Gross (kWh/y)	Panel (%)	Obst (%)	Tower (%)	Rotor (%)	Topo (%)	Gross-Shading (kWh/y)
10,707003	56,170683	0,4	365,38	3,031	0,4	1,933	7,954	0	320,432
10,707035	56,170683	0,4	365,38	3,337	0,338	1,253	7,341	0	321,564
10,707066	56,170683	0,4	365,38	3,399	0,338	1,239	8,532	0	316,971
10,707098	56,170683	0,4	365,38	3,432	0,338	2,708	8,532	0	315,449
10,70713	56,170683	0,4	365,38	3,432	0,338	2,505	8,841	0	315,711
10,707161	56,170683	0,4	365,38	3,432	0,338	2,505	8,715	0	316,167
10,707193	56,170683	0,4	365,38	3,432	0,338	3,676	10,003	0	311,444
10,707225	56,170683	0,4	365,38	3,432	0,338	3,795	10,003	0	314,21
10,707257	56,170683	0,4	365,38	3,432	0,338	5,698	10,003	0	312,302

Here, the first lines in the file are shown, where an Obstacle and a WTG is placed by the PV plant.

Cost report

This report contains the results of cost calculation for Solar PV. The project’s cost for each of the listed items is shown, together with the total project’s cost over the lifetime.

Area_1							
Category	Type	Cost function value	Unit	Cost Index	Replace every	Project cost	Currency
DevEx	Development	1	% of CapEx	No in-/decrease		2,435	EUR
CapEx	Solar panels	450	EUR/kW	No in-/decrease	-	111,807	EUR
CapEx	Inverters pr. kW	150	EUR/kW	No in-/decrease	-	37,269	EUR
CapEx	Inverters pr. kW AC	0	EUR/kW AC	No in-/decrease	-	0	EUR
CapEx	Sub structures	0	EUR/kW	No in-/decrease	-	0	EUR
CapEx	Grid, internal	10	EUR/kW	No in-/decrease	-	2,485	EUR
CapEx	Grid, external	0	EUR/kW	No in-/decrease	-	0	EUR
CapEx	Installation	250	EUR/kW	No in-/decrease	-	62,115	EUR
CapEx	Land purchase pr. kW	0	EUR/kW	No in-/decrease	-	0	EUR
CapEx	Land purchase pr. ha	0	EUR/ha	No in-/decrease	-	0	EUR
CapEx	Other/contingency	120	EUR/kW	No in-/decrease	-	29,815	EUR
CapEx	Tracker costs	0	EUR/kW	No in-/decrease	-	0	EUR
OpEx	O&M	10.92	EUR/kW	No in-/decrease		54,264	EUR
OpEx	Land rent pr. kW	0	EUR/kW	No in-/decrease		0	EUR
OpEx	Land rent pr. ha	0	EUR/ha	No in-/decrease		0	EUR
AbEx	Abandonment	0	EUR/kW	No in-/decrease		0	EUR
	Total					300,189	

14.10 Optimizing the design - Solar Optimize

A good choice for a field project in northern Europe could be this configuration, used in our validation project (see section 14.13), which is optimized for a Danish site:

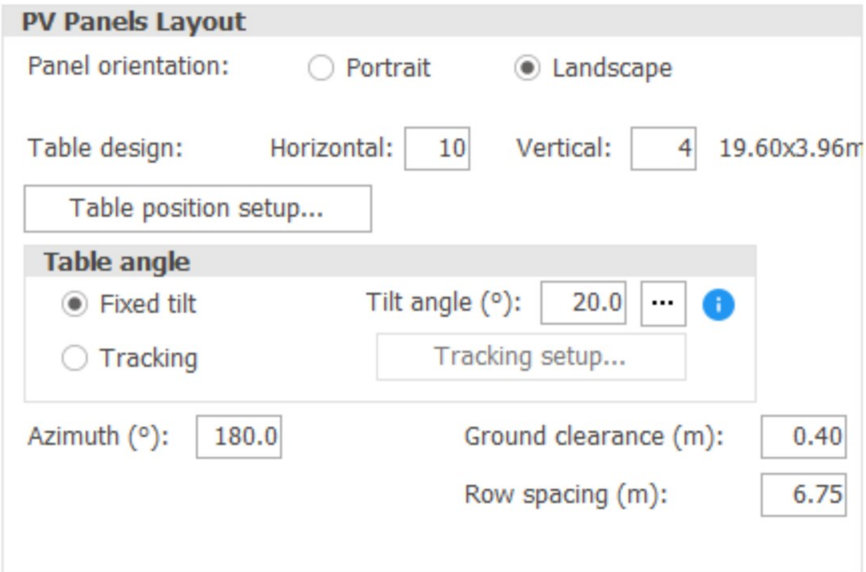


Figure 119 Layout design parameters.

Sites at other latitudes will require different tilt and distances.

Here four landscape panels are mounted vertically, see example photo in Figure 120:

Figure 120 Photo of mounting details.

Many parameters are in play when optimizing. As an example, the tilt angle that gives highest production for a free panel can easily be calculated. However, how much array shading loss can be avoided by a lower tilt angle, and how is this influenced by the distance between arrays? In addition, how much does the substructure cost increase by increasing tilt, partly due to higher wind loads? How much does varying prices diurnally and by season influence the optimal design? What are the land costs, and will there be benefits from a larger array spacing, e.g., access to agriculture subsidies while the area between the panel rows can be utilised for agricultural purposes?

The aim of the Solar Optimize tool is to answer most of the above questions.

Solar Optimize is a tool which enables finding the optimal layout of the plant depending on the input data. The parameters, which can be optimized with the tool are:

- Tilt angle
- Vertical table panels
- Row distribution
- Azimuth
- AC/DC ratio

The Solar Optimize tool is a first step towards layout design optimization in windPRO. Improvements and new features will be introduced in the next versions of the software.

Limitation: In the current version of the tool, it is not possible to optimize East-West PV layouts. We will be working on including it in the future.

14.10.1 Structure of the tool

The structure of the tool is kept consistent with the Wind Optimizer, where the optimizer has a session list keeping all the calculations. A session opens a new window, where the inputs are defined in a tree structure. The tree is located in the left side of the Optimizer window and is gradually build-up by the user with the required input information for the optimization. Many settings and inputs need to be defined prior to running the optimization. The tree structure contains Site, Area, Panel and Run. Each of the windows has a Setup & Run and Result tabs. First, all the inputs are to be specified in the Setup & Run for each of the levels in the tree. When the optimization is finished, the results can be viewed in the Result tab. See more detailed descriptions below.

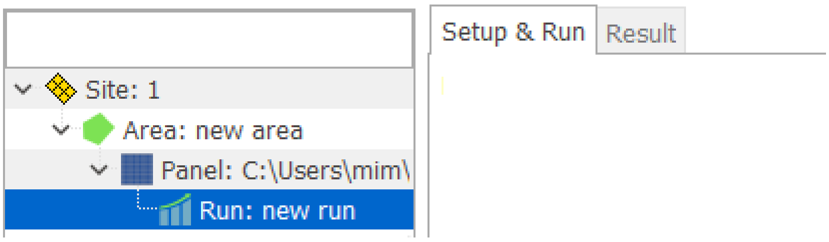


Figure 121 Tree structure and tabs in the Solar Optimize

14.10.2 Setup & Run of the Solar Optimize

The Setup & Run tab of the Solar Optimize is where all the inputs necessary for performing the calculations are specified. For each level, a different window is available, in which the inputs need to be specified. This is described below.

Each level of the tree structure can be renamed by the user. It is advised to consider appropriate naming to keep better track when more components are added to the tree structure.

Site

The Site level is the fundamental level of the optimization, but there can be multiple Sites in the tree to allow studying the effect of different basic assumptions.

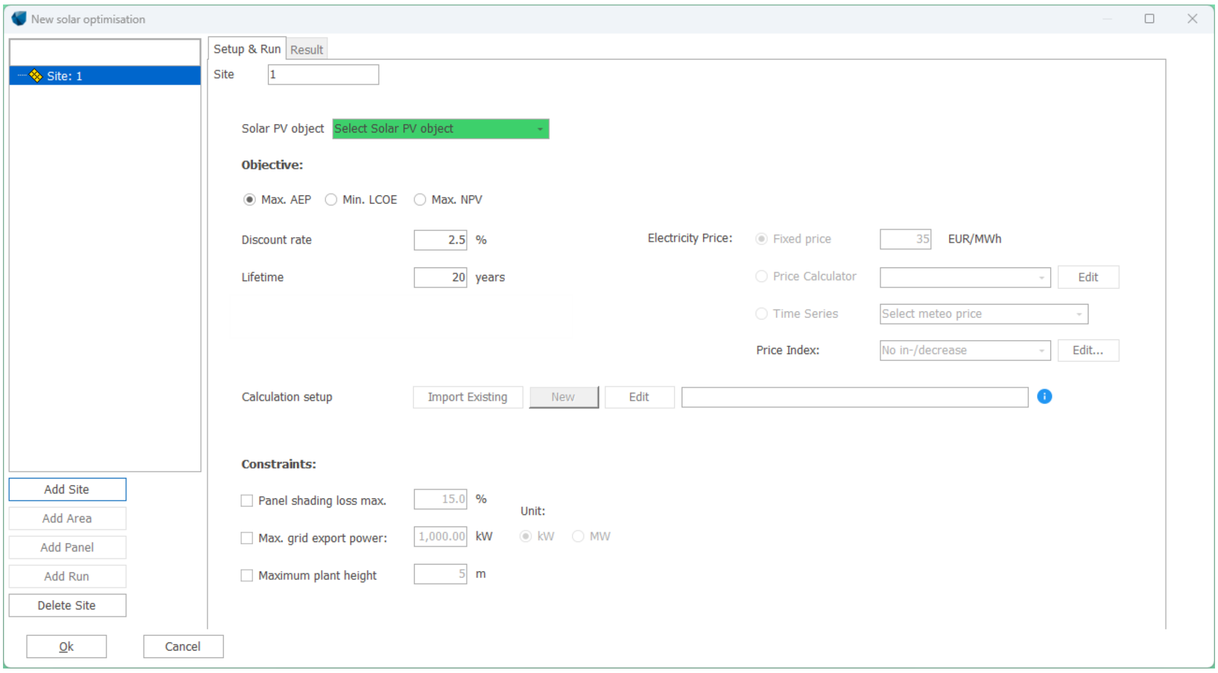


Figure 122 Site level of the Solar Optimize

In the Site, the following information and settings must be defined:

Solar PV object - here the Solar PV object for which the optimization is to be performed needs to be chosen. It is only possible to choose an already existing Solar PV object.

Objective – here the user must choose what is the objective of the optimization:

- Maximum Annual Energy Production (Max. AEP)

- Minimum Levelized Cost of Electricity (Min. LCOE)
- Maximum Net Present Value (Max. NPV)

No matter the objective, the Lifetime of your project must be specified. If LCOE or NPV was chosen, the discount rate is required. It is only possible to modify these parameters before selecting the Calculation Setup for the calculation, after that, the fields are not available for editing anymore.

Finally, if the objective is *Max. NPV* the electricity price needs to be specified. Here, multiple options are available:

- Fixed price – the same price will be used for all hours.
- Price calculator – an annual table can be created, where different prices can be defined for specific times of the day, days in the week and months. If Price Calculator is selected, the assumption will be that for all years in the calculation the prices will be the same – as specified in the Price Calculator.
- Time Series – a time series of prices loaded through the Meteo Object can be used. The prices should be specified for the same period as the calculation period. In the calculation of NPV, it will only be used the concurrent period between prices time series and calculation period. If e.g., the user selects the calculation period to be 01.01.2000 – 31.12.2022 and specifies the prices for the period 01.01.2003 – 30.04.2023, the NPV calculation will be performed for the concurrent period: 01.01.2003 – 31.12.2022.

Additionally, it is possible to define a Price Index, which will increase or decrease the price for the following years. If Time Series of prices is selected, the user should either decide to include the index in the time series or to only specify it as an index. It should not be specified in two places. The two approaches will lead to slightly different results due to the handling of time varying prices in the NPV calculation.

See more about the Objective function in section 14.10.6 .

Calculation setup – here a Solar PV calculation setup needs to be defined. If an existing calculation for the selected Solar PV object is available on the calculation list, the same can be imported into the Solar Optimize. Alternatively, a new Solar PV calculation setup can be created. It holds all the information needed to perform a calculation as described in section 14.7 . Lifetime and discount rate are also part of the Calculation Setup; hence, a decision was made to always use the values specified in the Site level of the Solar Optimize over the values specified in the chosen Calculation Setup.

Constraints – here the constraints for the optimization can be selected. It is possible to choose from:

- Panel shading loss max. – maximum shading loss from other panels allowed for the layout.
- Max. grid export power – the maximum allowed export power from the plant.
- Maximum plant height – the maximum total height of the plant from the ground

See more about Constraints in section 14.10.7 .

Area

Here the Area of the Solar PV object, which is to be optimized needs to be chosen. If LCOE or NPV, a cost model to be used for the Area in the calculations must be selected. Additionally, the user can choose to use reference panel in the calculation or not. It is advised to use the reference panel calculations to limit the time of calculation, which can be significant for big plants.

Panel

In the Panel level, the user can choose which panel and inverter should be considered in the optimization. By default, the panel and inverter chosen for the area in the Solar PV status window is used.

Run

The Run level is used to define, which of the plant parameters should be optimized. The parameters, which can be optimized are:

- Tilt angle [º]
- Vertical table panels [#]
- Row Distribution
- Azimuth [º]
- AC/DC ratio

The remaining parameters of the Area such as Panel orientation (portrait or landscape), horizontal number of panels in a table and Ground clearance are set to be the same as specified in the Solar PV status window for the optimized Area.

The parameters to optimize are organized in a table, where the default values, minimum, maximum and step can be defined. The default values are automatically set to the values specified in the Area at the time of creating the Run. To optimize a parameter the user must check the checkbox next to it. The minimum and maximum are set automatically based on the default values but can be changed by the user. The step can also be changed and is used to define for which values between Min and Max the calculations will be done. If the step is set to a small value, more calculations will be performed allowing for more detailed analysis, however increasing the time for the optimization. The number of the calculations to be performed can be viewed below the table.

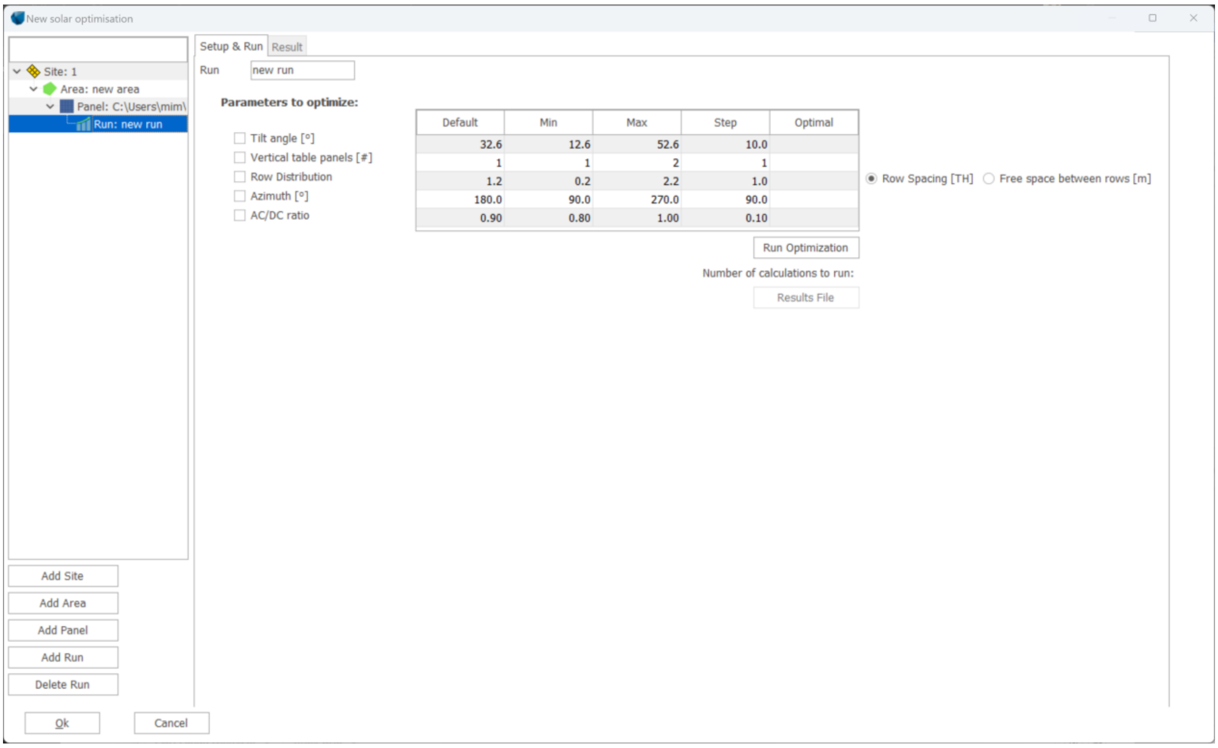


Figure 123 Run level of the Solar Optimize window.

The Row Distribution can be optimized considering two different parameters:

- Row spacing [TH] – distance between the end of one row and the end of the next, expressed in the table heights [TH] (number of vertical table panels multiplied with a height of one panel).
- Free space between rows [m] – distance between the end of one row and the beginning of the next row, expressed in meters.

The choice between Row spacing [TH] and Free space between rows [m] can be done by the radio button next to the Row distribution row of the table. The default values for both parameters are calculated based on the Row spacing [m] specified in the Solar PV status window. The explanation of the parameters is shown in Figure 124. To calculate the defaults the following equations are used:

$$\boldsymbol{Row\ spacing}\ [\boldsymbol{TH}] = \frac{\boldsymbol{Row\ spacing}\ [\boldsymbol{m}]}{\boldsymbol{height\ of\ the\ table}\ [\boldsymbol{m}]}$$

$$\boldsymbol{Free\ space\ between\ rows}\ [\boldsymbol{m}] = \boldsymbol{Row\ spacing}\ [\boldsymbol{m}] - \boldsymbol{TH}\ [\boldsymbol{m}] \cdot \cos(\boldsymbol{tilt\ angle})$$

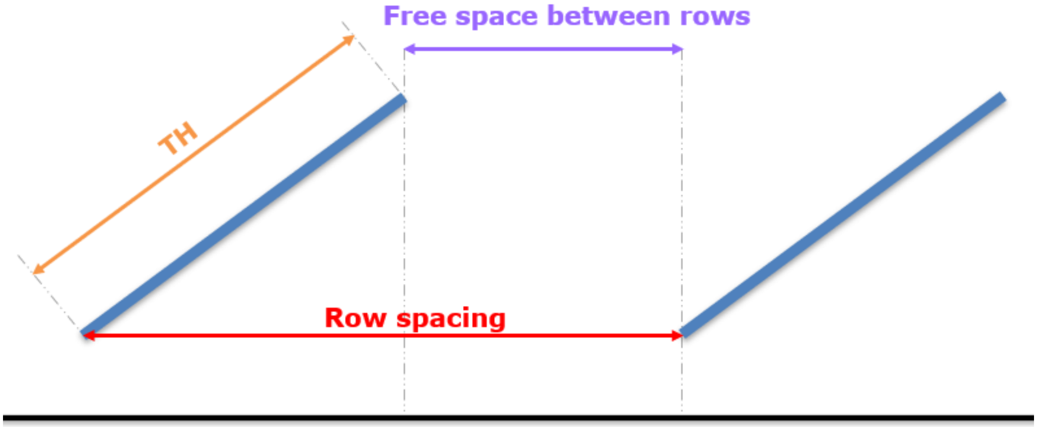


Figure 124 Explanation of Table Height (TH), Row spacing and Free space between rows.

To run the optimization the Run Optimization button must be used.

When the optimization is finished, the results are displayed in the Optimal column of the Parameters to optimize. Moreover, a table with the optimal values and values to apply is shown below.

14.10.3 Viewing the results

The results can be viewed on all levels of the tree structure. However, the most comprehensive comparison is available in the Run level.

Run

When the optimization is completed, the main results are displayed in the Setup & Run tab of the window. In the last column of the table – Optimal, the found optimal values of the parameters are displayed. If a parameter was not chosen for optimization, the default value will be displayed in the Optimal column. Results of all calculations can be saved by clicking on Results File. A new window will open where the user can choose to save the results in a file or copy them to clipboard.

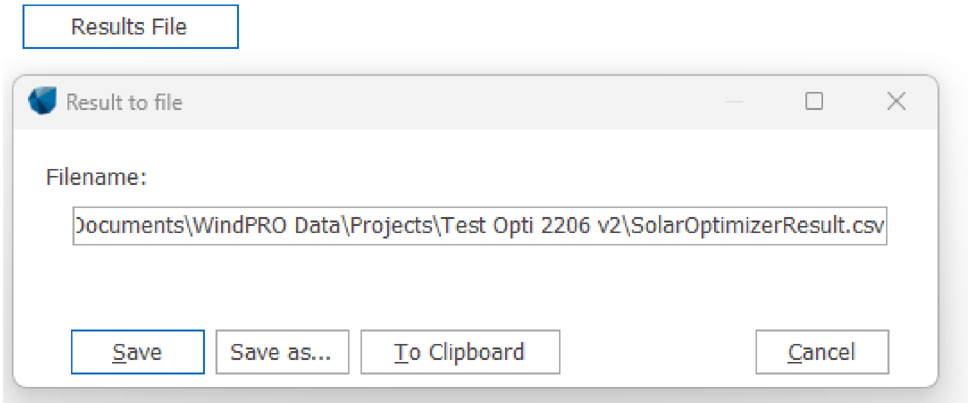


Figure 125 Saving or copying the results of all calculations.

The results file contains the information about all the runs performed in the optimization. The parameters and the objective function values are all stored together with the installed capacity and information about the constraints.

In the Result tab of the Run level, the results are displayed graphically as can be seen in Figure 126. The top table summarizes the results by showing the optimal objective function value, together with all the parameters – the ones which where optimized are marked in blue. Below the table, graphs representing the objective function value depending on the parameters are included. If LCOE or NPV was chosen as the objective function, AEP will also be included in the graph. This provides more insight for the user to analyse the results. The number of graphs in this window will depend on the number of optimized parameters. The first graph shows all the calculations, the remaining graphs show the objective function results depending on the value of the optimized parameter. The parameter is shown in the description of the x-axis. For displaying the data in the graph, all the remaining parameters are kept at the optimal value. Hence, in the example shown in Figure 126, the top-right graph shows the variation of NPV (the objective) and AEP depending on the Tilt Angle, while the remaining parameters are set to be the one shown in the table above the graphs.

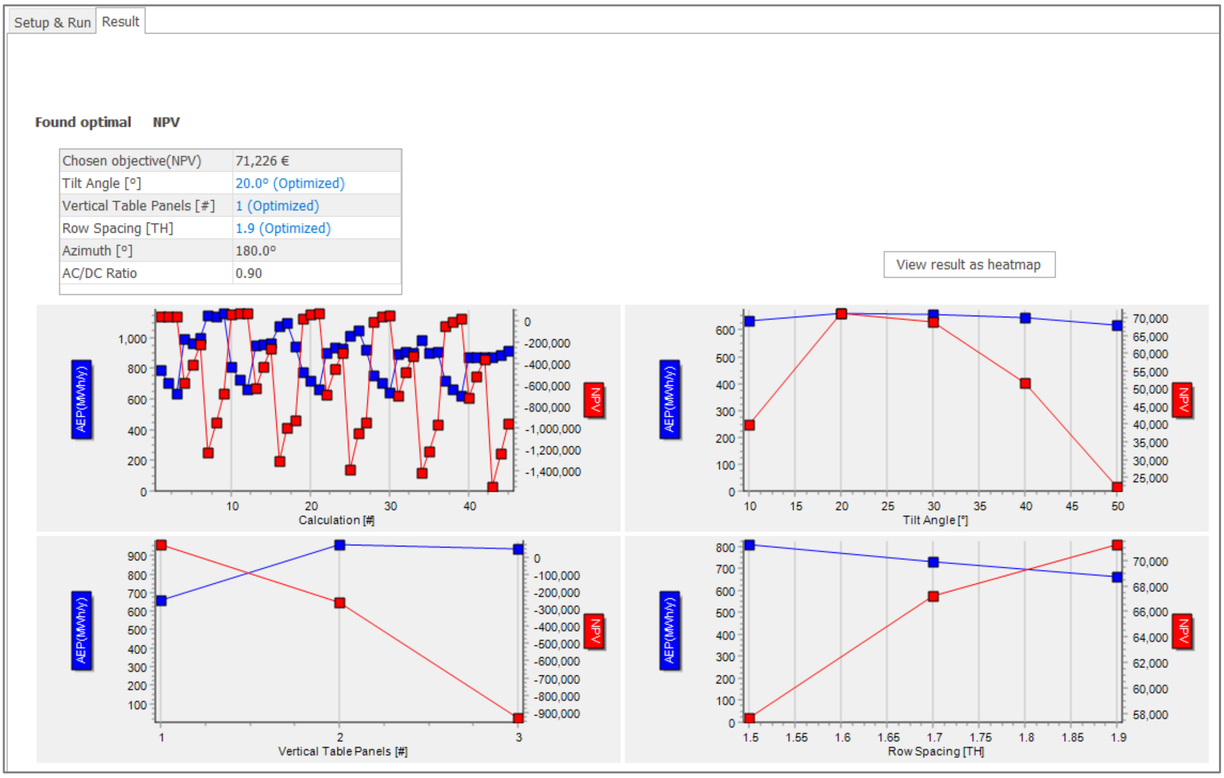


Figure 126 Result tab of the Run level. Results presented in graphs.

By clicking on View result as heatmap, another way of viewing the result is available – heatmap. The table has one parameter value as a column and another parameter value as a row. The values shown in the cells are the objective function values for each combination of the parameters. By default, the remaining parameters are set to optimum values, but it is possible to view the table for other values by selecting it in the drop-down menu below the table. The parameters in the rows and columns can be changed. This way, the user can have a have a full overview of all the results. The values in the table are color coded with a gradient from red to green – green marks the best objective value, whereas red, the worst. See an example of a heatmap in Figure 127.

AEP depending on parameters

Parameter 1: Tilt Angle [°]

Parameter 2: Vertical Table Pa

Result for objective: AEP LCOE NPV

View result in table and graph

Tilt Angle [°]/Vertical Table Panels [#]	10.00	20.00	30.00	40.00	50.00
1	39925.84	71225.97	68830.12	51635.44	22335.90
2	-219801.85	-260165.72	-296692.01	-333561.72	-361728.31
3	-680324.78	-931766.86	-951460.69	-973070.84	-963081.53

Row Spacing [TH] 1.9(Optimized)

Figure 127 Result tab of the Run level. Results displayed in a heat map.

Panel

In the Panel level of the tree structure, in the Result tab, it is possible to view a comparison of all Runs done for the Panel. For each run, the configuration with best objective value will be displayed in the table together with basic information about the setup – see Figure 128. This allows for quick identification of the run with best objective function value.

Optimal values per Run using Generic 675W:

Objective value: **AEP**

Objective	General	Detailed tilt
AEP	2,626.97 MWh/y	2,683.12 MWh/y
Chosen objective(AEP)	2,626.97 MWh/y	2,683.12 MWh/y
Area	Main area	Main area
Site	1	1
Tilt Angle [°]	12.9 (Optimized)	5.0 (Optimized)
Vertical Table Panels [#]	3 (Optimized)	3
Row Distribution	1.1 (Optimized)	1.1
Azimuth [°]	180.0	180.0
AC/DC Ratio	0.90	0.90

Figure 128 Comparison of Runs in the Panel level of the Result tab.

Area

In the Area level of the tree structure, in the Result tab, it is possible to view a comparison of all Runs done for all Panels in the selected Area. For each panel, the run and the configuration with best objective value will be displayed in the table together with basic information about the setup – see Figure 129. This allows for comparison of different panels in one table for a better overview. It is important to remember that the values in the table do not allow for full comparison of the panels if different runs were performed for different panels. It is up to the user to keep the runs consistent if a comprehensive comparison should be made.

Optimal values per Panel in Main area (all runs)

Objective value: **AEP**

Objective	Generic 610W	Generic 460W	Generic 550W	Generic 675W
AEP	2,513.86 MWh/y	2,384.29 MWh/y	2,528.87 MWh/y	2,683.12 MWh/y
Chosen objective(A	2,513.86 MWh/y	2,384.29 MWh/y	2,528.87 MWh/y	2,683.12 MWh/y
Site	1	1	1	1
Run	General	General	Detailed tilt	Detailed tilt
Tilt Angle [°]	12.9 (Optimized)	12.9 (Optimized)	12.9 (Optimized)	5.0 (Optimized)
Vertical Table Pane	2 (Optimized)	1 (Optimized)	2 (Optimized)	3
Row Distribution	1.2 (Optimized)	1.3 (Optimized)	1.1 (Optimized)	1.1
Azimuth [°]	180.0	180.0	180.0	180.0
AC/DC Ratio	0.90	0.90	0.90	0.90

Figure 129 Comparison of Panels in the Area level of the Result tab.

For a better overview, for each panel, the Run name is included in the table.

Site

In the Site level of the tree structure, in the Result tab, it is possible to view a comparison of all Runs done for all Panels and all Areas in the selected Site. For each Area, the run and the configuration with best objective value will be displayed in the table, together with basic information about the setup. The Panel name and Run name are included in the table to easier identify the optimal configuration. This overview can be used to compare optimal configurations for different areas in the Solar PV object. If LCOE or NPV was selected, it is possible to compare different cost models for the same Area. If the same Area is selected in the Area tab, but different cost models, the comparison will show the NPV or LCOE calculated with the different cost models – see Figure 130. This is possible if the Panel and Runs are kept consistent in the Areas.

Optimal values per Area (all panels, all runs):

Objective value: **NPV**

Properties	Solar Cost Model	General cost model
AEP	950.36 MWh/y	881.26 MWh/y
Chosen objective(NPV)	-198,729 €	-1,306,777 €
Panel	410 W	410 W
Run	Solar 1	General 1
Tilt Angle [°]	32.9 (Optimized)	12.9 (Optimized)
Vertical Table Panels [#]	1	1
Row Distribution	2.9	2.9
Azimuth [°]	180.0	180.0
AC/DC Ratio	0.90	0.90

Figure 130 Comparison of Areas in the Site level of the Result tab.

14.10.4 Applying the results

Once the results are well analysed, it is possible to apply the found optimum values to the optimized Solar PV Area. This function is available in the Run level. Hence, the first step is to identify the best Run from all the performed ones. This one should be opened on the Setup & Run tab, where a table is available, as shown in the picture below.

Values to apply to the Solar PV object:

	Optimal	Value to use
Tilt angle [°]	32.9	32.9
Vertical table panels [#]	1	1
Row Spacing [TH]	2.9	2.9
Azimuth [°]	180.0	180.0
AC/DC ratio	0.9	0.9

Apply Changes

Figure 131 Table used to apply the results to an Area.

The table holds information about the found optimal parameters in the *Optimal* column. Another column, which by default is set to the Optimal column, is available – *Value to use*. Here, the user can modify the values before applying changes. The changes are applied to the optimized Area. The *Row spacing [TH]* or *Free space between rows [m]* is recalculated to *Row spacing [m]* before applying the results. If the user wishes to apply the same parameters to all Areas in the Solar PV object, they should open the Solar PV status window on the modified Area and select *Update ALL areas*, as shown below:

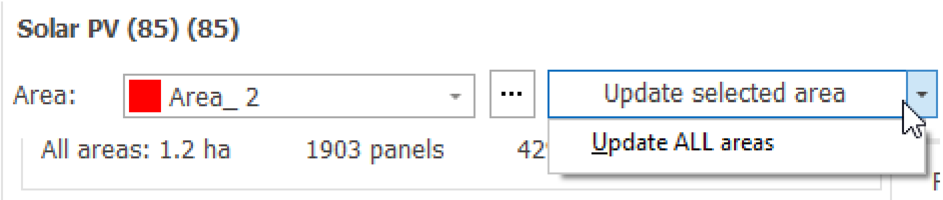


Figure 132 Updating properties of all Areas.

14.10.5 Optimization approach

The current approach to the optimization is using a grid search algorithm. The points in the grid, which are to be calculated are determined based in the inputs to the table in the Run level in the tree structure:

Parameters to optimize:

Parameter	Default	Min	Max	Step	Optimal
☑ Tilt angle [°]	32.9	12.9	50.0	10.0	
☑ Vertical table panels [#]	1	1	2	1	
☑ Row Distribution	2.9	1.9	3.9	1.0	
☐ Azimuth [°]	180.0	90.0	270.0	90.0	
☐ AC/DC ratio	0.90	0.80	1.00	0.10	

Figure 133 Setup of parameters to optimize in the Run level.

Based on the inputs specified in the table all combinations of parameters are created. If the parameter is not chosen for optimization, the default value from the *Default* column in the table will be used. If a parameter is chosen for optimization, the calculation is done for the minimum value specified in the *Min* column and for the values between minimum and maximum with the step specified in the *Step* column. The maximum value in the Max column limits the last value for which the calculations are performed. The values for which calculations are performed are found by the following formula:

$$Min + n \cdot Step \leq Max$$

Where:

n - integer number, the last n value is determined by the inequality above.

In the example in Figure 133, the calculations would be performed for Tilt angle values of 12.9, 22.9, 32.9 and 42.9; Vertical table panels value of 1 and 2 and Row distribution of 1.9, 2.9 and 3.9. Resulting in 4 (from tilt) * 2 (from VTP) * 3 (from row distribution) = 24 calculations.

For first estimations of optimal parameters, it is advised to select a course step for the parameters to identify the approximate optimum value. Once this is done, a calculation with finer step can be performed in a separate run to find the real optimum value. The aim is to further develop the optimization algorithm in the following releases, to automate further the optimization.

14.10.6 Objective function

As mentioned previously, it is possible to choose between three objective functions: Maximum AEP, Minimum LCOE and Maximum NPV. Here the calculation approach is explained.

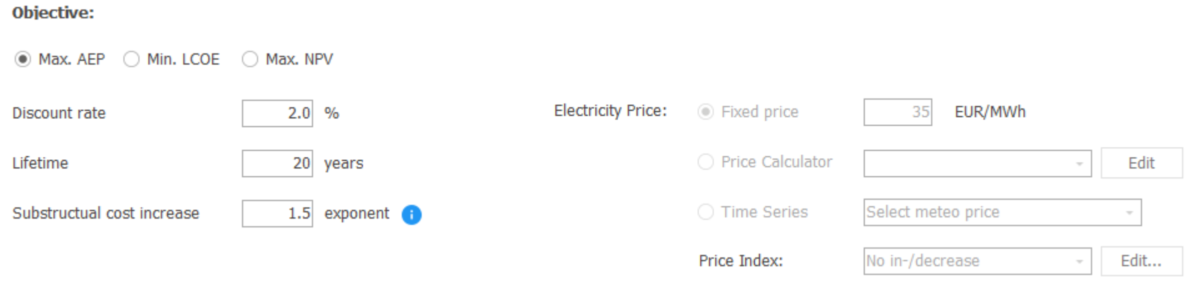


Figure 134 Selection of objective function and necessary settings in the Solar Optimize Site level.

AEP

AEP is the annual energy production, including all the losses specified in the calculation setup – these include shading losses, DC wiring losses, soiling, inverter, availability etc. The AEP calculation is based on the input of irradiance and temperature and the physical model of the plant.

When AEP is chosen as the objective, the result will be biased towards installing as many panels as possible in the area. If row distribution is chosen as the parameter to optimize, the rows will be applied as close as possible. The array shading loss will in this case limit the number of panels that can be installed for improving the AEP.

LCOE

LCOE is the levelized cost of electricity. It is calculated based in the AEP and cost of the plant. Selecting LCOE as the objective of optimization allows to include the effect of costs, especially CAPEX, on the optimal plant setup. On the other hand, it does not require assumptions about the electricity price in the future years.

LCOE provides information about the cost of producing electricity. It is the ratio of the plant’s costs and the produced electricity. To calculate the costs, the discount rate must be considered. The discount rate is a baseline interest rate often representing the average interest rate for secure investments such as bonds or set as the baseline return of investment in a company. windPRO uses the so-called real discount rate, which is corrected for the general inflation (i.e., it excludes inflation). Hence, future costs in the windPRO cost tool should not account for inflation.

In LCOE the future AEP is discounted similarly, which might seem counter intuitive. However, the AEP of each year through the lifetime will lead to a cash flow via the sale of the produced electricity. In this regard, the AEP produced next year worths more than AEP produced in say 15 years (for positive discount rates), assuming a constant electricity price. Thus, LCOE accounts for the discount effect of both future costs and future sale of electricity and calculates the average levelized cost of electricity from these, as expressed in the equation below:

$$LCOE = \frac{\sum_{n=1}^{N} \frac{Costs_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{AEP \cdot (1 - g \cdot (n-0.5))}{(1+d)^n}}$$

Where:

N - lifetime

$Costs_n$ – cost in year n

AEP – annual energy production where **the degradation is not considered**

g – degradation

d – discount rate

NPV

The Net Present Value (NPV) for a PV plant project is simply the total profit of the PV plant through its lifetime converted to present day value. NPV bares many similarities with the LCOE, and addresses the main drawback of LCOE, that it under evaluates the value of larger projects. Still NPV includes the penalizing effect of CAPEX costs for spread-out layouts. The main difference between NPV and LCOE is the fact that the AEP in future years is explicitly converted to a cash flow. This requires the assumption of a future electricity price. In the Solar Optimize, the prices can be defined in three ways – Fixed price, Price Calculator and Time Series. While Fixed price is straightforward to include in NPV calculation, time varying prices are included using an effective price to be able to account for the variations. The NPV is calculated based on the equation below:

$$NPV = -I_{cost} + \sum_{n=1}^{N} \frac{P_{eff} \cdot AEP \cdot \left(1 - g \cdot (n-0.5)\right) - Costs_n}{(1+d)^n}$$

Where:

I_{cost} – investment cost

P_{eff} – effective price, if Fixed Price is chosen it is equal to the fixed price, otherwise it is calculated based on the time varying prices and energy production

AEP – annual energy production where **the degradation is not considered**

g – degradation

d – discount rate

Effective price is calculated as shown below:

$$P_{eff} = \frac{\sum_t P[t] \cdot E[t]}{\sum_t E[t]}$$

Where:

If *Price Calculator* is chosen:

t – time step in the period specified in the Calculation Setup.

P – price, variable in time. The prices are created with the Price Calculator for one year and this price is repeated in all years for which the energy yield is calculated. Energy production is calculated based on the settings in the calculation setup.

E – energy production, variable in time. Energy production is calculated for the period specified in as Output interval in the Calculation Setup.

If *Time Series* is chosen:

t – time step in the concurrent period of the prices Time Series and defined Output Interval in the Calculation setup.

P – price, variable in time. Specified as a time series in the Meteo object.

E – energy production, variable in time. Energy production is calculated based on the settings in the Calculation Setup.

If a Price Index is selected by the user, this is applied to the Effective price in the NPV calculation. As mentioned previously, if Time Series is selected as the price input, the index can be applied directly to the time series (before it is imported to windPRO) or can be selected as Price index. The two approaches will result in slightly different results. If the index is applied to the Time Series, it will be used in the effective price calculation and in that case the specific years production will be used as a weight for the increased price. Otherwise, if the index is selected in the Solar Optimize, it will be only used in the NPV calculation, where the AEP will be used as weight for the increased price.

NPV is the most flexible objective function of the three objectives supported in the Solar Optimize. In fact, NPV can give similar results to both AEP optimizations and LCOE optimizations. The performance is controlled by the trade-off between costs and AEP, which is defined by the assumed electricity price. For very high electricity prices, costs lose importance and the NPV objective approaches the AEP objective. For very low electricity prices, AEP loses its importance and the optimization will be driven mainly by costs to minimize expenses. If the electricity price is set to be equal to the LCOE from another optimization, then the performance of the NPV objective will yield results very similar to the LCOE optimization.

14.10.7 Constraints

There are three constraints that can be activated for the Solar PV optimizations: Panel shading loss maximum, Maximum grid export power and Maximum plant height. These are described in this section.

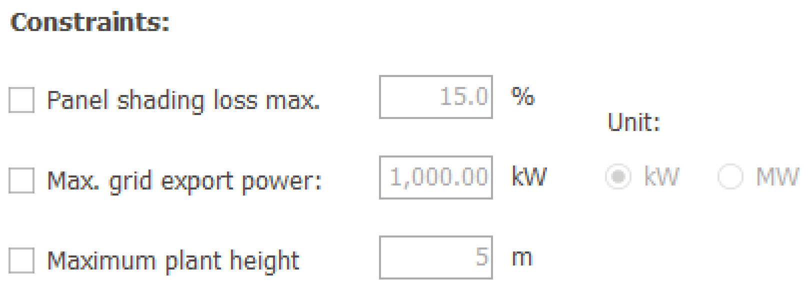


Figure 135 Constraint selection and setup section in Solar Optimize Site level.

Panel shading loss maximum

This constraint excludes all the runs where the panel shading loss exceeds the specified value. This is especially relevant when AEP is selected as the objective function. To avoid reducing the row spacing to unrealistic levels to increase the AEP, this constraint can be activated and the limit in % can be specified.

Maximum grid power export

This constraint limits the AC output of the plant to the specified limit. It is possible to select the unit of the constraint – kW or MW and specify the value. In the hourly calculation, if the AC power output is above the specified limit, the output power is limited to the specified value. This allows to consider the grid export limit as the factor influencing the optimization. Since the constraint is applied on the AC power output after the inverter and does not influence the number of inverters installed in the system, the calculation approximates the actual result if the power output is limited by the inverter size. It is advised to investigate reducing the AC/DC ratio on the calculation if a limit on the export power is specified.

Unlike the other constraint, this will not exclude runs but affect the AEP and hence also LCOE and NPV results.

In the *Results File*, the total curtailed power of the PV panel, due to the specified Maximum grid power export constraint, can be seen in the column *Total Export power curtailed*.

As this constraint is currently only implemented in the Solar Optimize, it will not be possible to reproduce the same result in a Solar PV calculation directly. It can be done by exporting the time varying production and limiting the power output in each hour in an external calculation.

Maximum plant height

This constraint will exclude plant setups, which exceed the maximum plant height specified in the constraint. Sometimes, the local regulations will not allow the plant to exceed a specific height. To avoid this problem, this constraint can be activated. The plant heigh is calculated before performing the calculations, hence the runs where the plant height is exceeded will not be considered. The plant height is calculated as:

$$H_{plant} = GC + TH \cdot \sin(tilt\ angle)$$

Where:

GC – the ground clearance, specified in the Solar PV status window for the Area.

TH – the table height (see Figure 124)

14.11 Shading visualisation

Visualizing the shading partly validates the calculation method but is also an efficient method of checking the data.

14.11.1 Panel, obstacle and WTG shading

windPRO can calculate the shading from the following elements on the PV panels based on an accurate 3D model, respecting the terrain elevation variations:

- Arrays (panels shading)
- WTG tower/nacelle
- WTG rotor (separated while not the full rotor area shall be including – percentage can be set)
- Obstacles (defined by Obstacle object)

Click the *Shading visualizer* button on the Solar PV status window.

Here you can control the date and time you want to simulate:

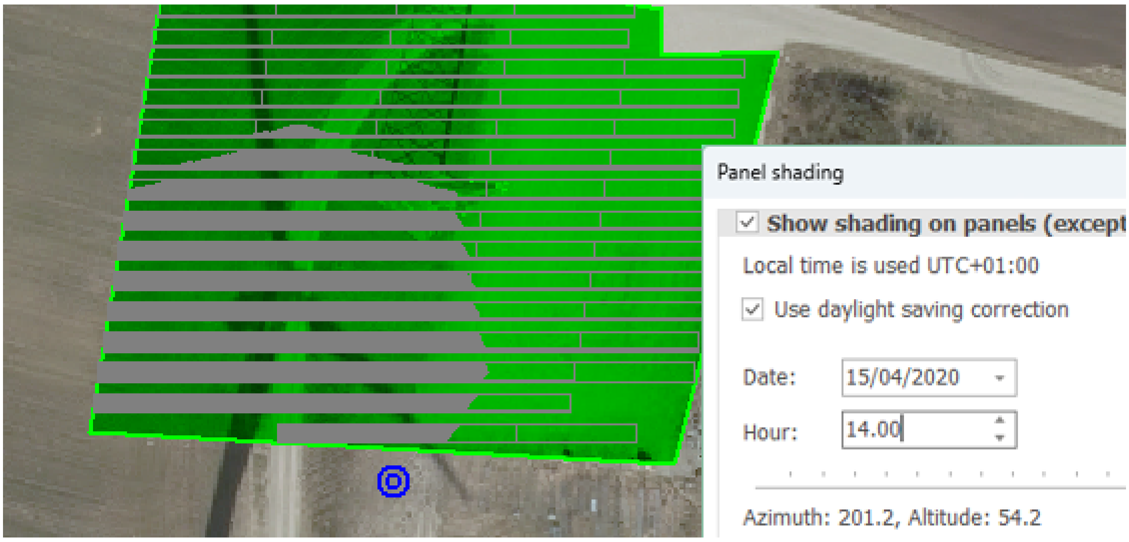


Figure 136 Shading visualisation per time and date.

Any panel falling in the shade of a shading element, panel or turbine, will be coloured darker. Here the turbine with the "real shade" is seen on the background map. The visualised shade is calculated with a 55% rotor area reduction. In lower parts of the panels, also panel shading is seen.

Tip: If you want to step in time on minute basis, highlight the minute numbers with mouse:

, then the step arrows (which also can be controlled from keyboard), will only step one minute at a time. Similarly highlighting the hour figures to step one hour per step.

By tracking, the visualizer automatically adjusts the panel tilt to the time step the shade is visualized. And thereby it also changes the appearance of the panel height on the map.

14.11.2 Topo(graphic) shading

Topographic shading is calculated from the elevation data. If the project is in a valley surrounded by mountains, the topo shading can be essential. The topo shading calculation is coarser than the panel, obstacle - and turbine - shading calculations, so it is NOT recommended to model obstacles near panel areas by elevation data and let the topo shading do the job. Topo shading is meant to handle larger landscape elements.

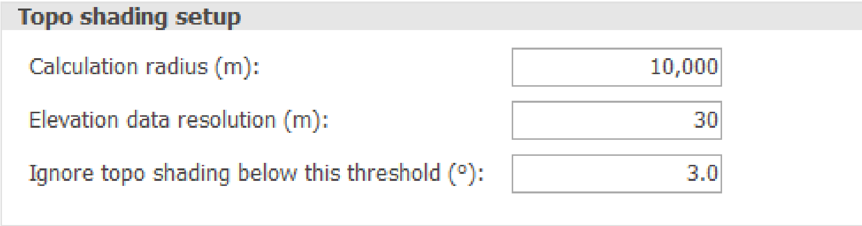


Figure 137 Specific settings for Topo shading.

The settings reduce the data amount to make calculations faster. However, if the relevant mountain is 11000 m from the site, the radius must be expanded, and if the calculation is based on smaller, but relevant terrain variations, it might be necessary to lower the elevation data resolution. The 3,0° default threshold is the same as used in WTG shadow calculation due to the weak radiation at low sun angles, which makes the calculation irrelevant.

To activate the topo shadow visualization, click *Shading visualizer* and select *Show on map from where Topo shading will be active* – this will highlight the terrain, which is causing topo shading. Click on Show topo shading profile with sun path on mouse move on panel area to activate interactive topo shading visualization for panels. See Figure 138.

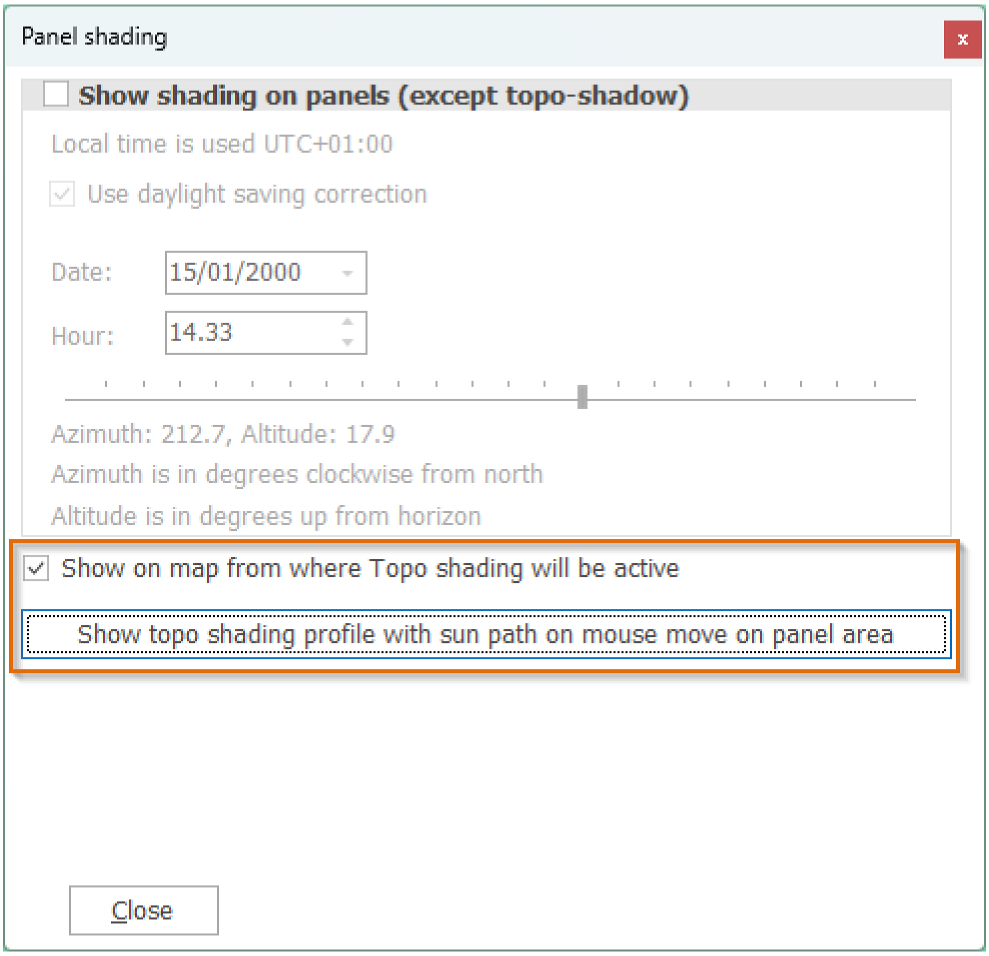


Figure 138 Activating Topo shading visualization.

A small test project is used to illustrate the topo shadow calculation. First, it is needed to make sure that the relevant elevation data is used. If the project only has one object with elevation data, this will by default be set to the TIN object.

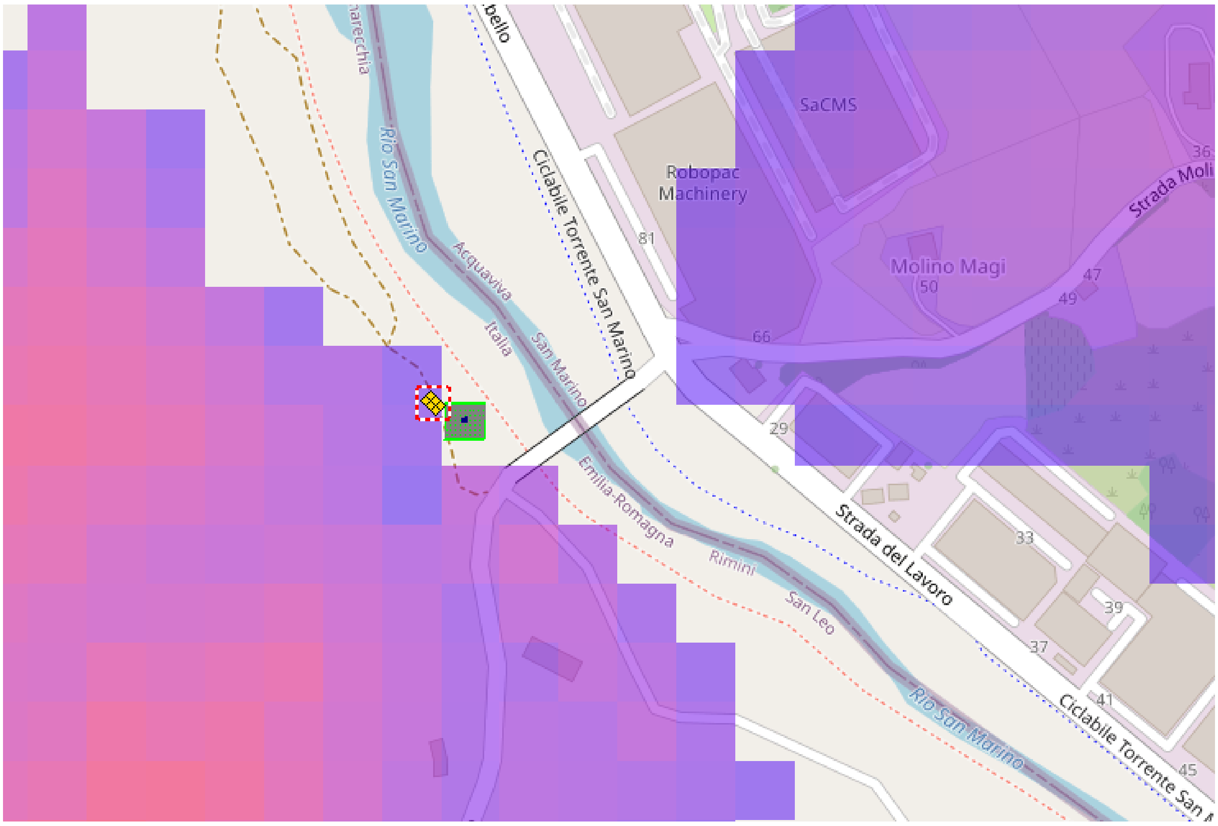


Figure 139 The Topo shading area visualized on map.

On the map in Figure 139, it can be seen where the terrain is so elevated, that it creates Topo shading. The warmer the colour, the more shading.

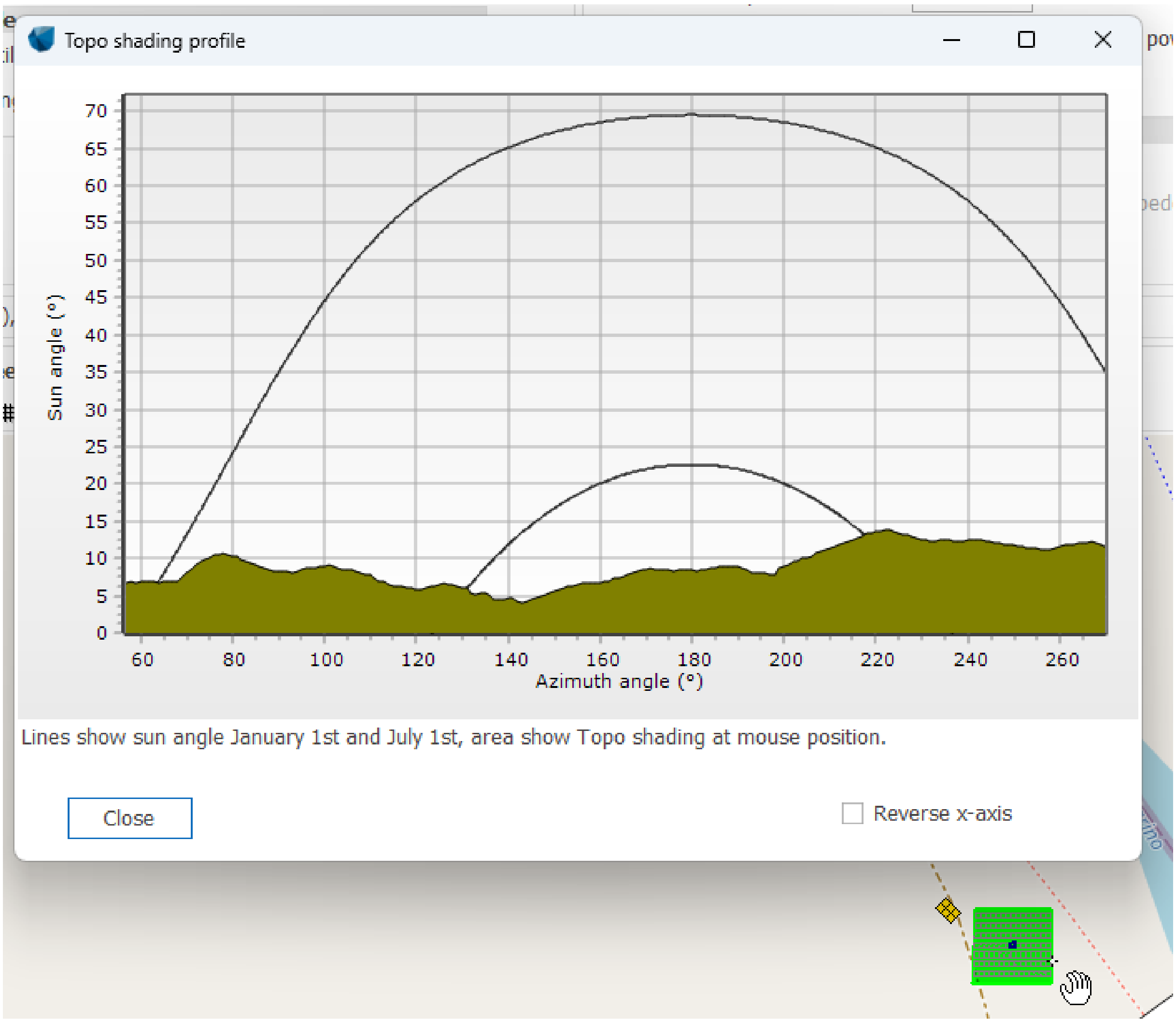


Figure 140 Topo shading on the panel selected with cursor.

Moving the cursor over the panels, the topo shading profile at each panel can be visualized as illustrated in Figure 140. The topo shading is shown together with the summer and winter path of the sun. The x-axis can be reversed for convenience.

14.11.3 Panel shading loss visualization

Using the PV individual panel production result to file, it is possible to visualize the shading loss on the map. This section describes how to do it.

Paste the result to file *PV individual panel production* to Excel and calculate the total shading loss in a new column. Save the x and y coordinate, together with the calculated total shading as a .txt file, TAB separated. The .xyz file should only contain three columns and it should not contain a header.

The next step is to rename the file with extension .xyz so the windPRO importer get it right: PV_result.xyz . Do not include header.

If renaming by adding .xyz to the file name is not working, open the file in Notepad and *Save as*, where in the *Save as type* field *All files* is selected. The file should be saved with extension .xyz manually added to the file name. This will save the file as a .xyz file.

Now the file can be imported as result layer. Right click on the Result layers list and select Import. This will open a new window where the file can be selected – see Figure 141.

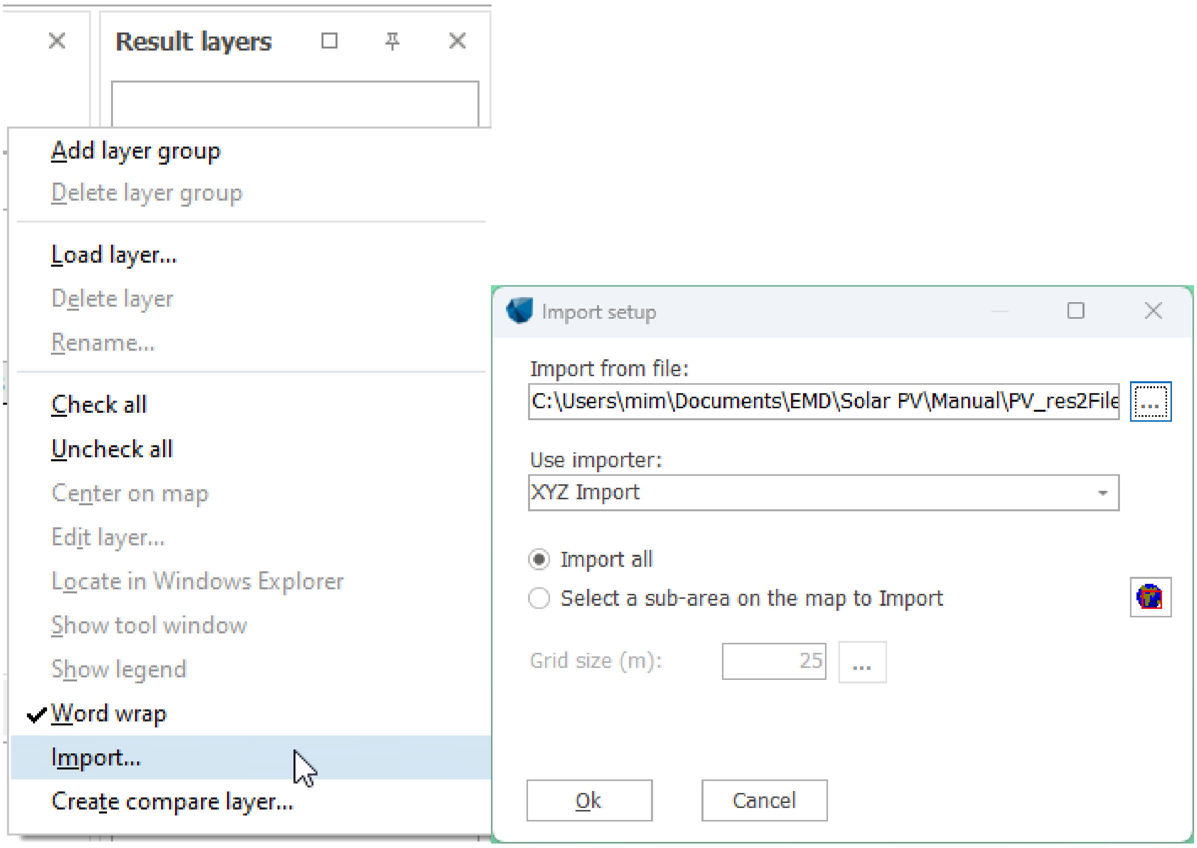


Figure 141 Import an xyz file in result layer.

The next step is to select the coordinate system, GEO coordinate system, WGS84 should be selected. Pressing OK will open another window, where the importer settings can be selected – see Figure 143. The importer is a flexible importer, originally developed for importing elevation data in non-regular grid, with a number of settings so it is able to handle most data. Depending on the Solar PV project complexity, especially terrain complexity, the default settings might be enough to handle the import correctly. If this does not result in correct display of the results, the import should be done again, this time modifying the settings in the Import Options window. The settings in this window are related to the grid of the imported .xyz. file. The .xyz file to be imported holds one value per each panel installed at the plant. Hence when selecting the correct grid size for the import it is important to account for it. First, the method must be changed from Auto detect to one of the other options, the options describe how are the imported values in the cells handled when the number of cells in the created grid is different from the number of cells in the imported file. If the option Fill Empty Cells is selected, the locations for which values are missing will be replaced according to the selected method. Finally, the grid size should be set to the size of the panel to accurately represent the shading losses from each panel.

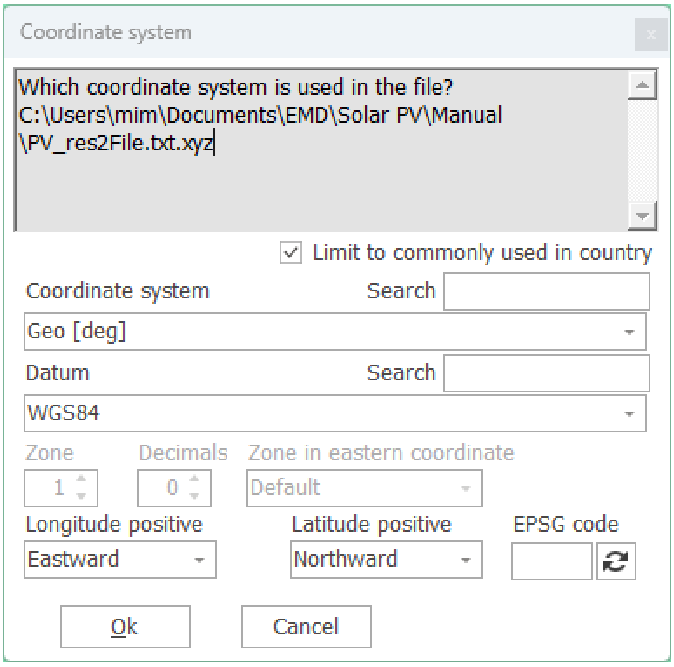


Figure 142 Choose GEO coordinate system, WGS84.

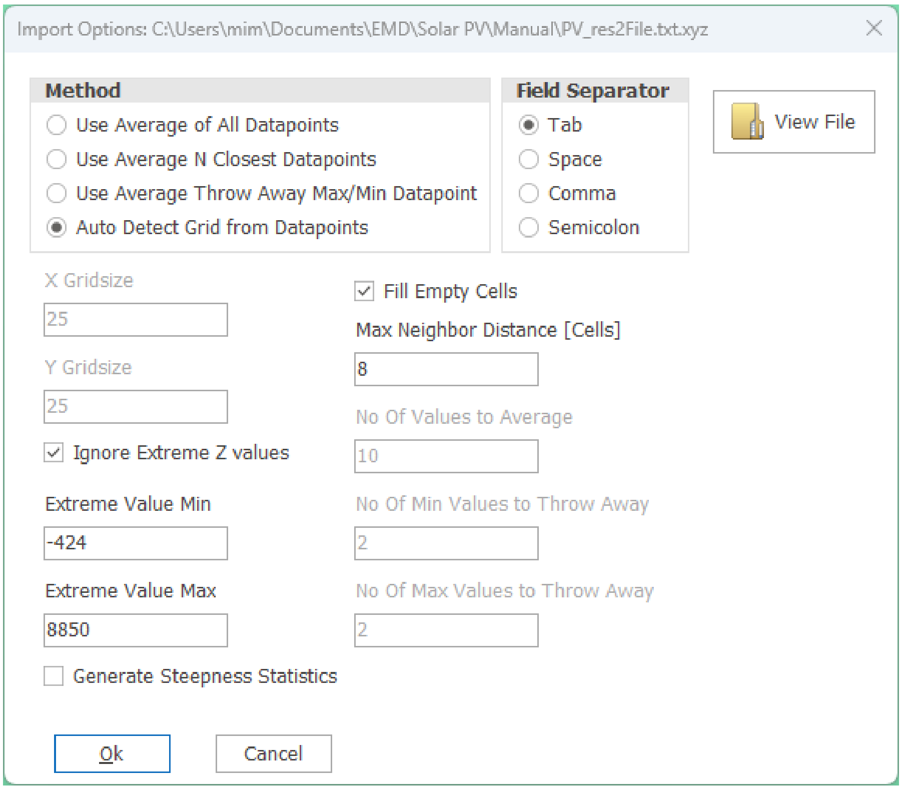


Figure 143 Import Options the xyz file.

When imported, the result file can be shown on the map. It is possible to modify the legend to display the results more accurately. The resulting representation is shown in Figure 144.

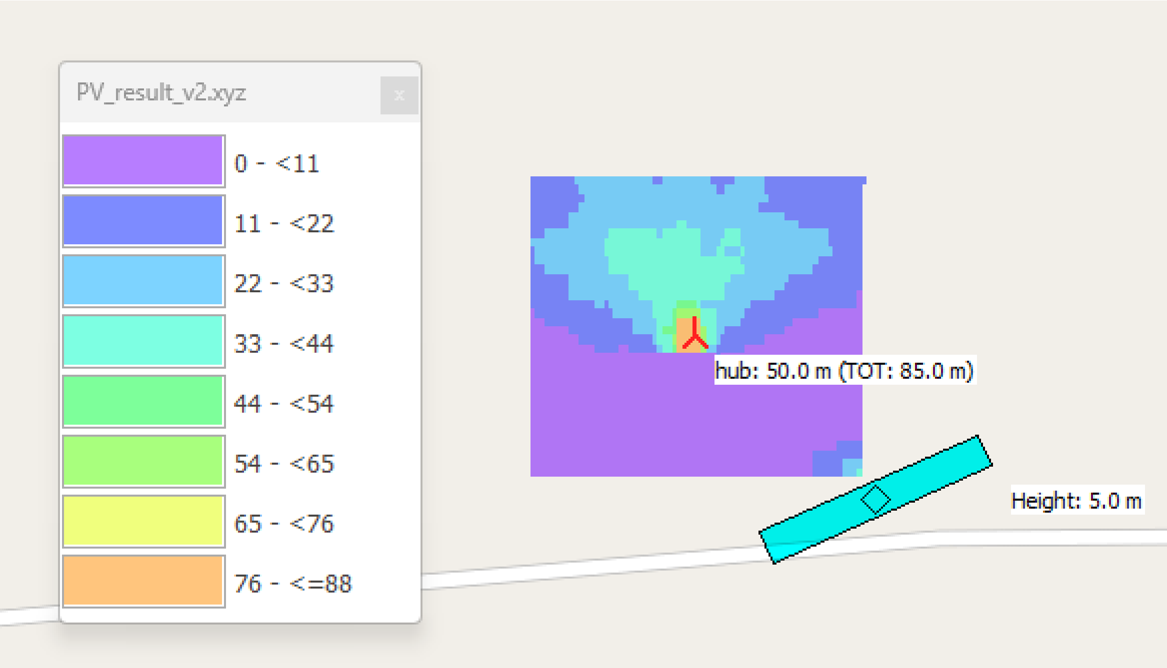


Figure 144 View of shading loss per panel on map, the shading loss is expressed in %.

The calculated shading loss can now be used to decide where panels should not be established. E.g., if more than 25% shading loss, it might not be feasible. Then exclusion areas can be established within the PV-area.

14.12 Preparations for Photomontages

Open the Photomontage of a calibrated Camera object pointing towards the Solar PV area. This will open the window as shown in Figure 145.

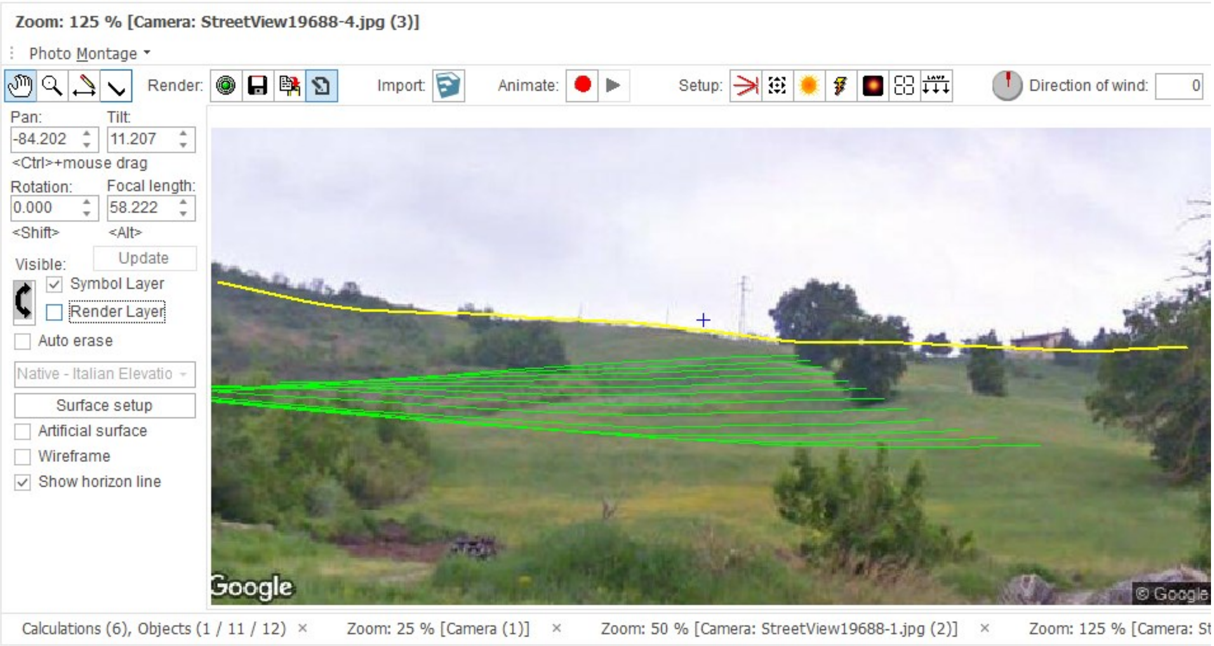


Figure 145 Photomontage window of a camera pointing towards the Solar PV area - Symbol Layer.

Click Render: and the PV panels are placed in the positions of the green lines in the Symbol Layer – see the photomontage in Figure 146.

Figure 146 Photorealistic presentation of the Solar PV project.

Creating a realistic photomontage requires additional preparations – see the VISUAL manual.

14.12.1 Panels in photomontage

Panels must be available as .dae files (compatible with SketchUp). There are .dae files available in windPRO, which can be used for visualization. These can be found in the directory: "WindPRO Data\3D.dae_models\Solar panels".

The panels are the basis for photomontages and are automatically rotated and merged in tables. So just one panel .dae file is needed for any design using this panel look. The .dae file of the panel can be selected in the panel settings as marked in Figure 147.

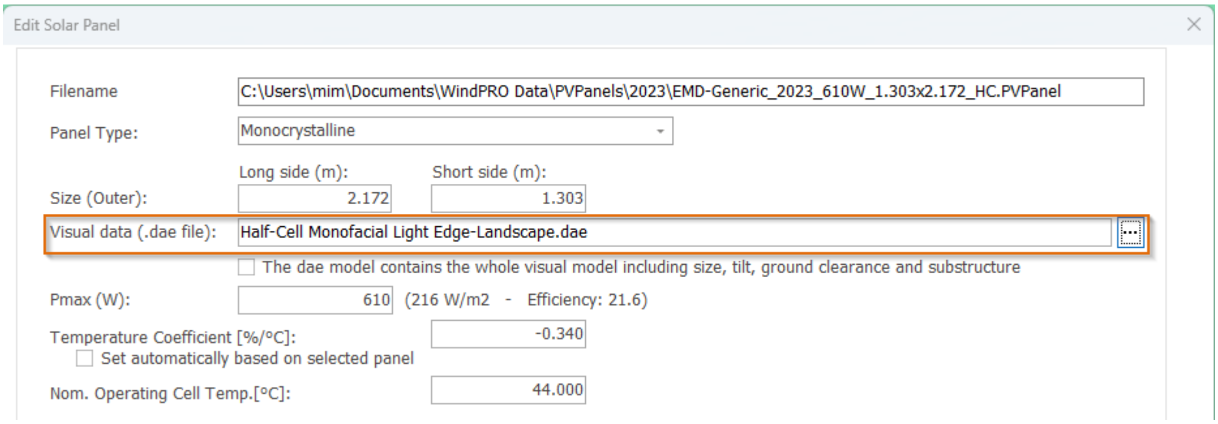


Figure 147 Choice of panels .dae file.

Starting from windPRO 3.6 a new feature is available – it is possible to externally define the entire solar table as one model. This can be set in the Edit form of the Solar Panel, see Figure 148.

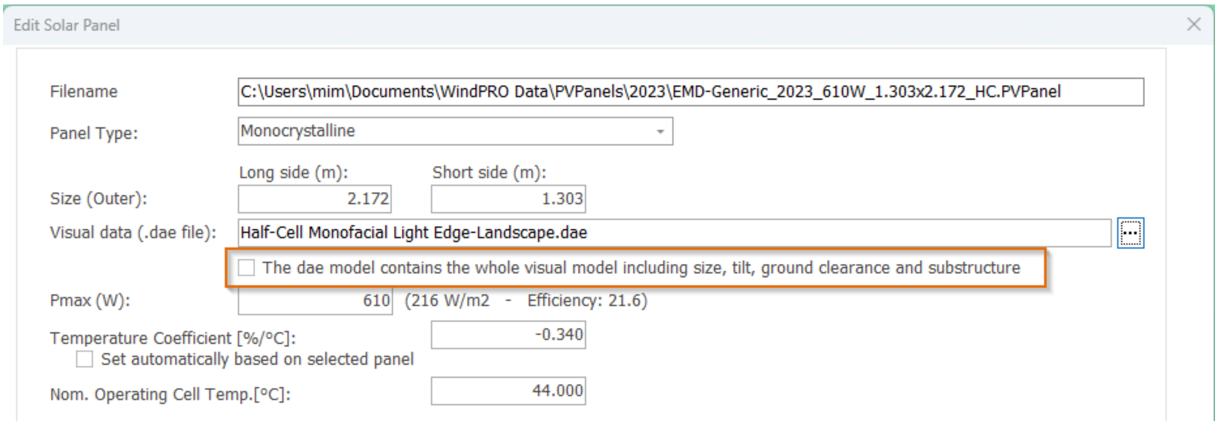


Figure 148 Option to include full panel/table .dae file with substructures etc.

If the above checkbox is checked and a full table with substructure, tilt and ground clearance is pointed out, the panel size MUST reflect the table size within the .dae file, and the P_{max} must be adjusted accordingly. If e.g., a table is 2 x 5 panels, the size must be adjusted to the full table size and P_{max} must be 10 x panel P_{max}. With this feature, the table design MUST be 1 x 1:

and the size shown must reflect the table size in the .dae file**!** Otherwise, the photomontage, energy calculation and glare calculations will be erroneous. If the panel shall be used in energy calculations, there must be added extra by-pass diodes that describe the full table, not the panel. This will typically mean that there will be by-pass diodes at both sides, if it is a table.

This feature can also be used for solely visualizations of more complex plants e.g. E-W PV panels. Together with windPRO installation additional .dae files are available, which can be used for this purpose.

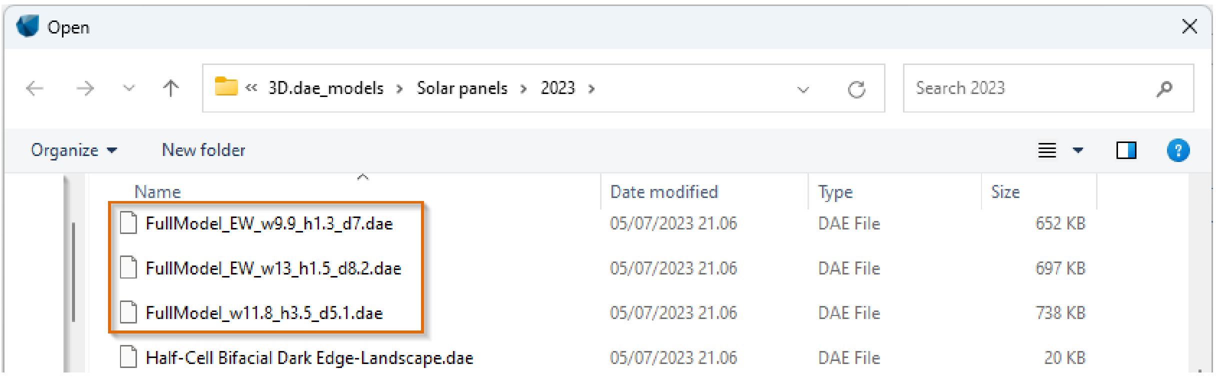


Figure 149 .dae models available together with windPRO

These contain the E-W panels structure with a fixed tilt of the panels. To use these models in photomontage, the setup of the plant must be done correctly: the size of the model is specified in the name w – size of the long side in meters and h – size of the short side in meters. Additionally, the tilt must be set to 0. The substructure can be defined and included together with the table in the photomontage – see Section 14.12.2 for more details. The table can be previewed by clicking 

- see Figure 150.

Figure 150 Preview of E-W PV panels visualization.

14.12.2 Substructures in photomontage

It is possible to add a mounting rack, or substructure to the table for photomontage purpose. Starting from windPRO 3.6 it is possible to use individually designed substructures (with a .dae file) or automatically generated generic substructures.

Generic legs

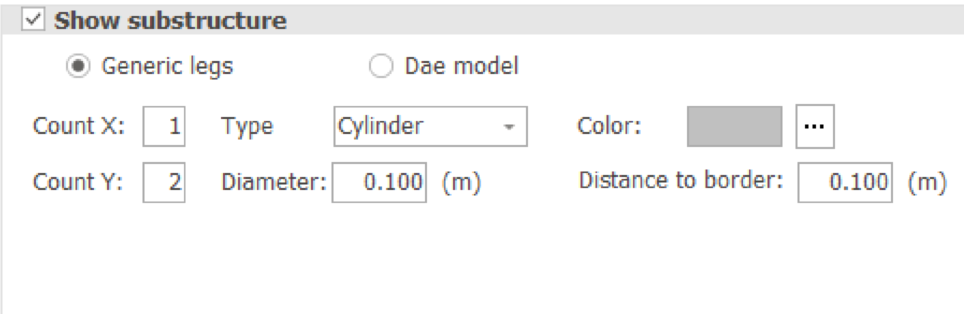


Figure 151 Substructure based on generic leg.

With Generic legs it is possible to auto create substructures based on few input specifications as seen above. The Count settings is explained in Figure 152. The type can be defined as Cylinder or Rectangular, defining the cross section of the leg. The Diameter/Side defines the size of the cross section of the leg. Color is by default set to grey but can be changed to any desired color. Distance to border can be changed as well.

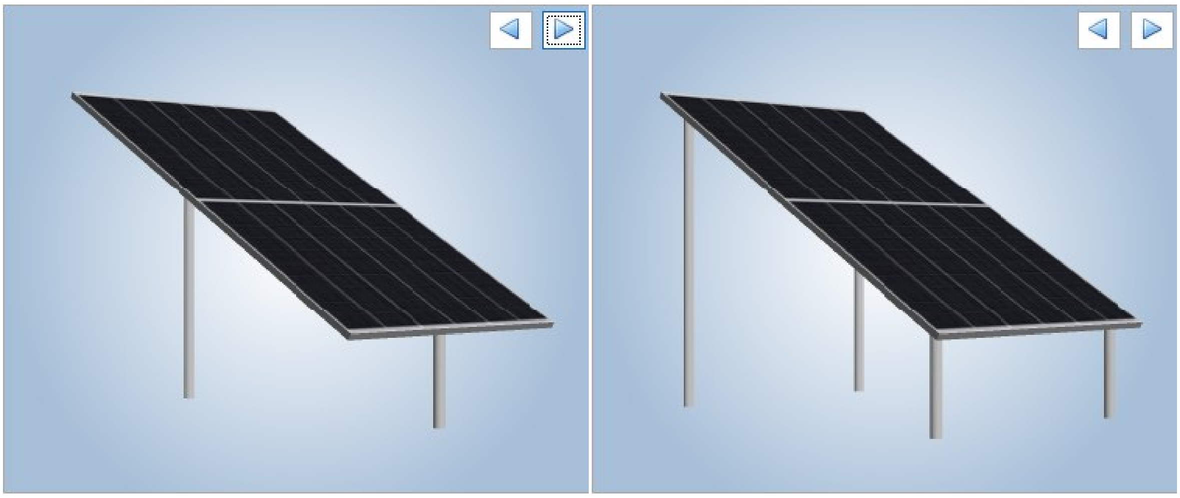


Figure 152 Preview of generic substructures. On the left Count X=1 and Count Y=2, on the right Count X = 2 and Count Y=2.

Dae. File based

If the substructure is based on a .dae file, it requires a bit of manual adjustment to fit correctly with the panel/table. Rendering a Photomontage will also take twice as long.

In this example, we use a table with just one panel. Choose *Dae model* to use the default substructure included in windPRO.

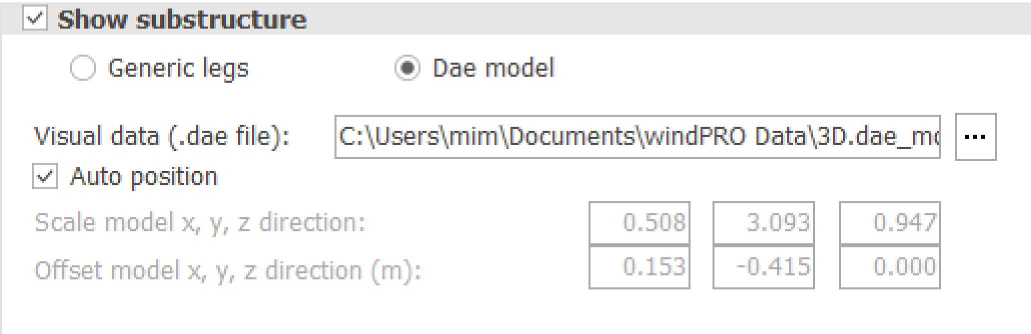


Figure 153 Substructure scaling based on .dae file.

The *Auto position* check box automatically adjusts the substructure to fit the defined table. This makes working with. dae defined substructure easier. The automatically defined scaling and offset can be further improved manually. It is important to make sure that the .dae file is adjusted well to the table by using the *Preview table* option and changing the scaling and offset. An example of well-adjusted table is shown in Figure 154, whereas not well scaled substructure in Figure 155. The substructure and panel are two independent components, which unfortunately do not scale together. If we lower the tilt angle of the panel, the substructure does not automatically adjust.

Figure 154 Panel with well scaled substructure.

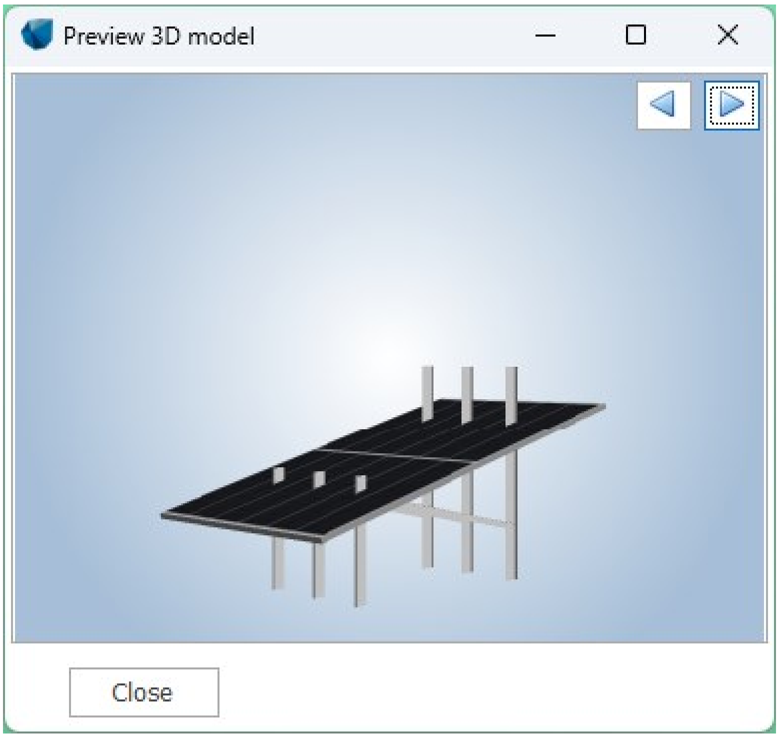


Figure 155 Panel with not well scaled substructure.

14.13 Appendix - Validation

A comprehensive validation study has been performed, where detailed shading loss calculations are validated, including WTG shading, and a full plant calculation is validated.

The full validation study can be found here:

http://help.emd.dk/knowledgebase/content/TechNotes/TechnicalNote8_windPRO_SOLAR_PV_Validation.pdf

14.13.1 Meteo data validation

Different model data sources are compared to measurements. Three locations in Denmark are tested, which reveal that measurements do not necessarily represent the truth:

Risø – very good correspondence between measurements, Heliosat (SARAH) data, ERA5, Global Solar Atlas and Danish Reference Year (DRY), but the EMD-WRF mesoscale data has 26% too high irradiation.

Kegnæs – Measurements seem to have too high irradiation, probably a calibration issue. The previously-mentioned sources all have round 16% lower irradiation. Measurements show round 16% higher measured irradiation than at Risø, which based on studies involving many measurements (DRY) is not likely. Thereby conclusions become similar to the ones for Risø.

Høvsøre – Measurements have mast shading, which seem to be the main reason for 9% lower measurements than at Risø. The conclusions are therefore also very similar to the ones for Risø, although ERA5 here seems in size order 6% too high.

Solar irradiation data evaluation

Location: **Risø** Evaluation by: **Per Nielsen, EMD**

kWh/year	GSA	ERA5	WRF E5+	Heliosat	Measured
Global horizontal irradiation	1.004	1.072	1.327	1.058	1.050
Diffuse horizontal irradiation	523		446	530	
Diffuse share	52%		34%	50%	
Bias to measured	**-4%**	**2%**	**26%**	**1%**	

DRY: MJ/m2/y, mast at X	
3700 ->	1028 kWh/y

Mast is operated by DTU, calibration quality unknown.
Data recovery ~98%, round 2 months substituted from Heliostat to make complete data set.

Left graphs below show bias to measurements and diffuse share from Heliosat data and EMD WRF EU+, right show absolute values (in W) for 6 years. In above table GSA (Global Solar Atlas) is included.

https://globalsolaratlas.info/
Data for Europe/Africa cover 1994-2015.

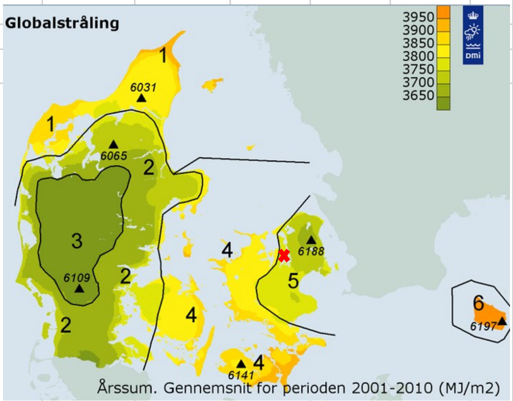


Figure 156 Solar data validation, main figures, Risø.

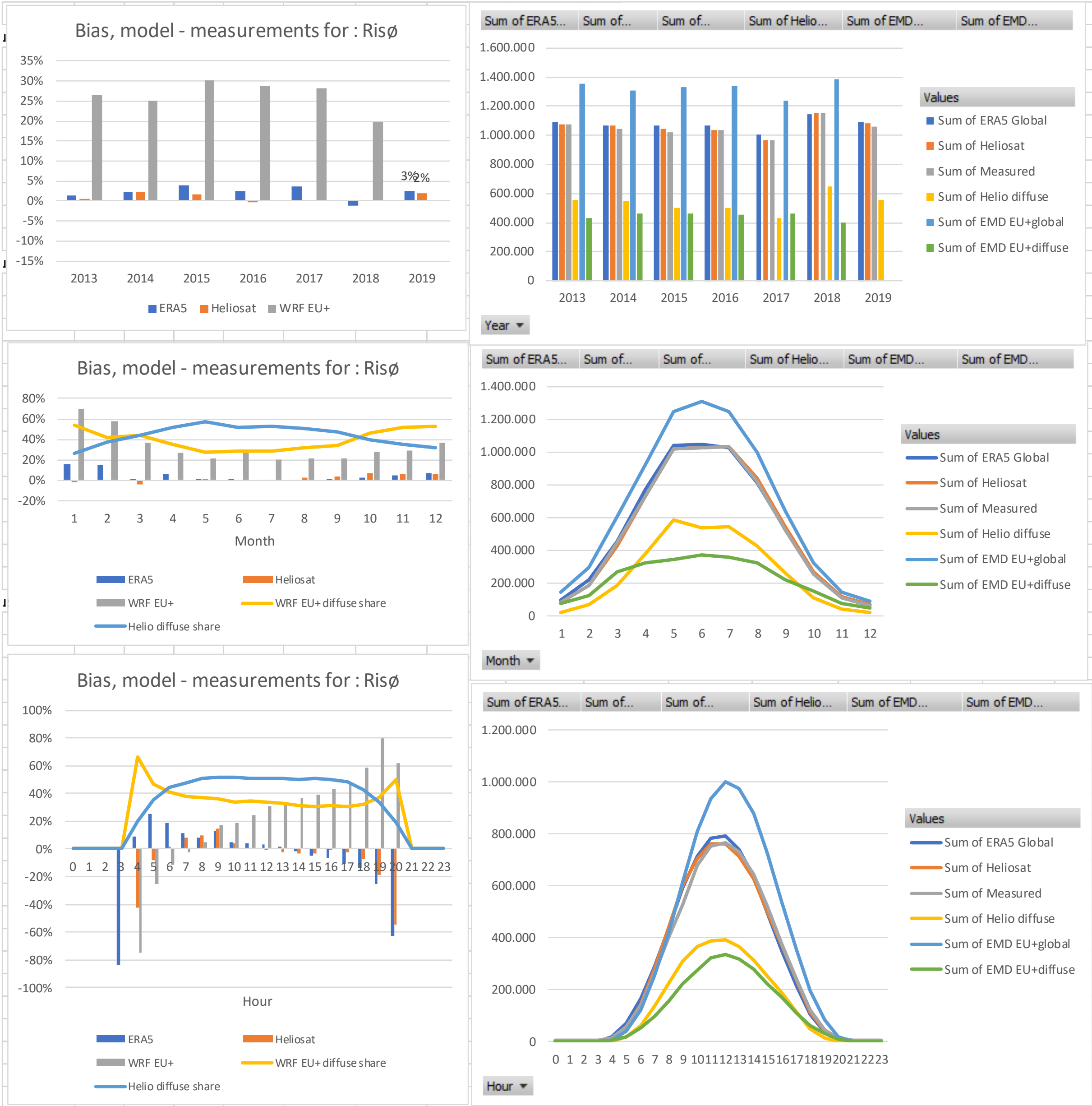


Figure 157 Solar irradiation comparison, Risø & model data.

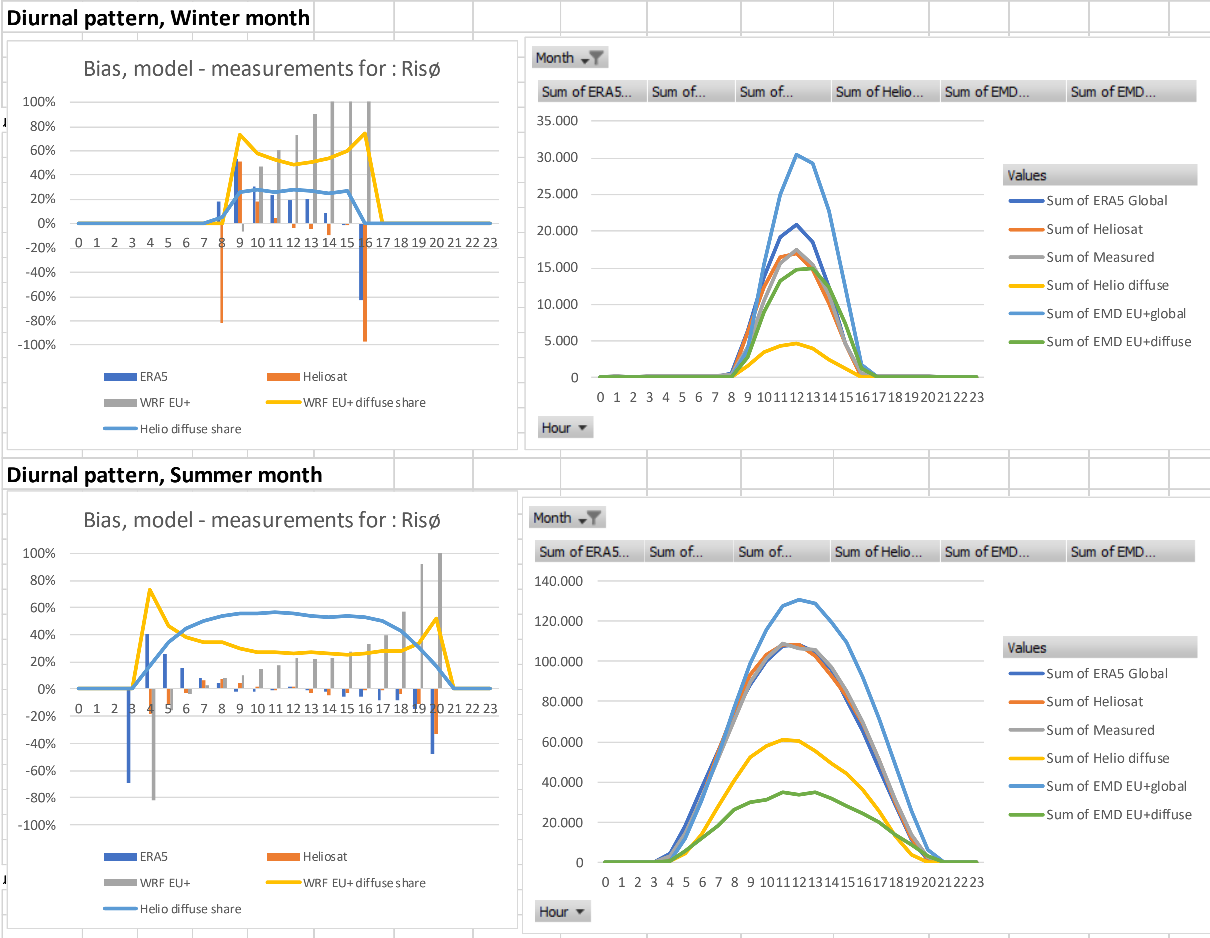


Figure 158 Diurnal patterns for winter and summer.

Overall conclusion, involving seasonal and diurnal variations: Heliosat (SARAH) data are the most precise source – and very precise for Denmark.

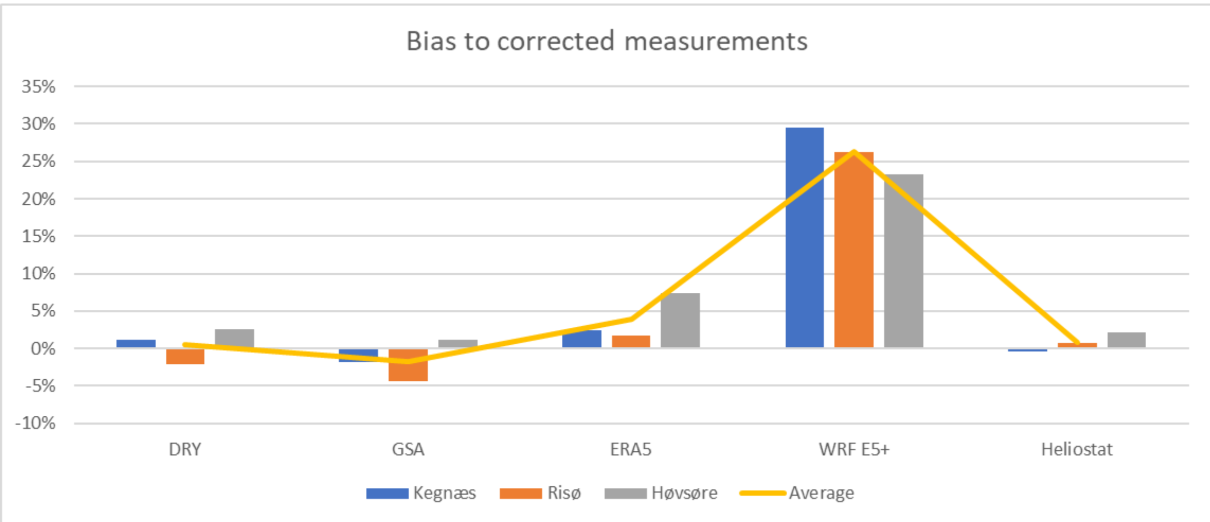


Figure 159 Bias to corrected measurements for different data sources.

In Figure 159, the Kegnæs and Høvsøre measurements are corrected based on the issues explained in these measurements, then DRY (Danish Reference Year), GSA (Global Solar Atlas), ERA5, EMD-WRF EU+ and Heliosat are all compared to the measurements. Data are not fully concurrent, but all sources represent at least 6-year data. No doubt the Heliosat (SARAH) data set should be the preferred choice, and this has a good coverage worldwide as seen in 14.3 .

Global validation of the Heliosat data set can be found here: https://www.cmsaf.eu/SiteGlobals/Forms/Suche/EN/DocumentationSearch_Form.html?cl2Categories_Typ=%22valrep%22

14.13.2 Shading loss validation

Panel shading:

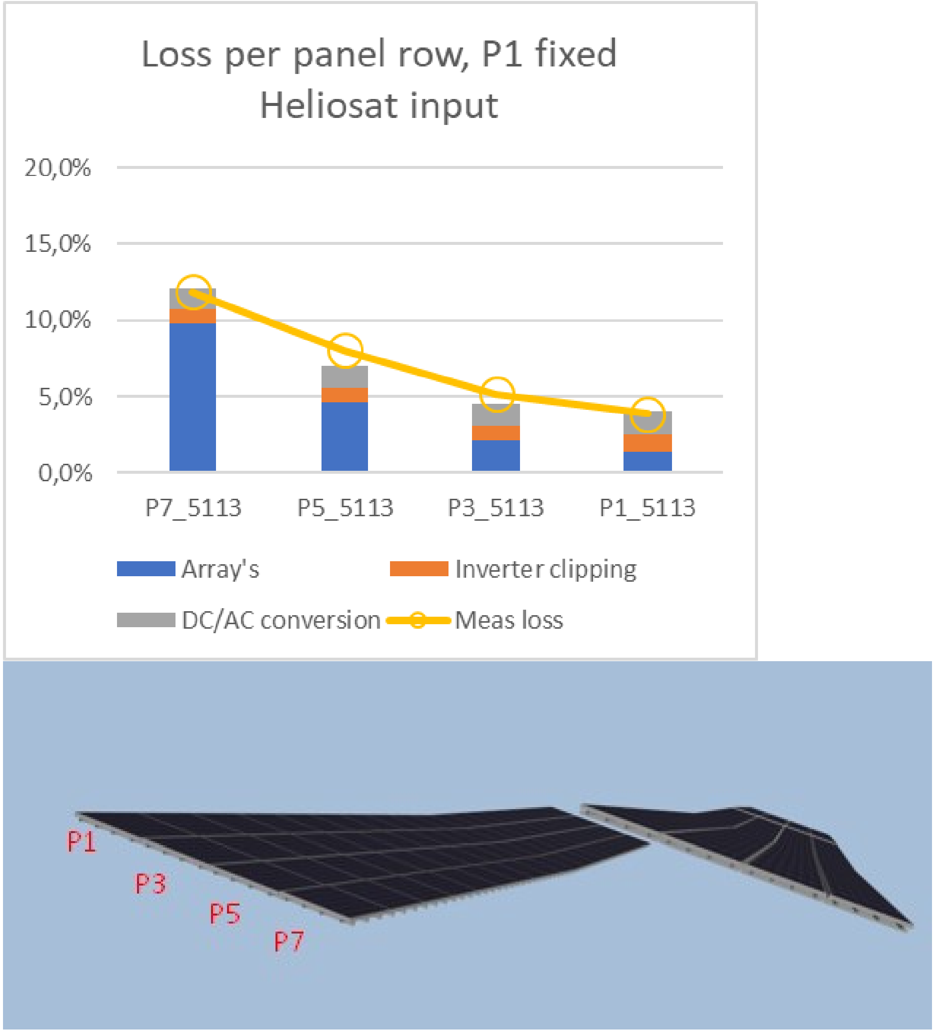


Figure 160 Panel shading loss validation.

Test setup for panel shading validation: Tilt: 20 degrees, Azimuth: 180 degrees, Table height: ~4 m, Table distance: 6,75 m.

As seen, the calculated loss per string matches the measured very accurate. See validation report for more details.

Obstacle shading:

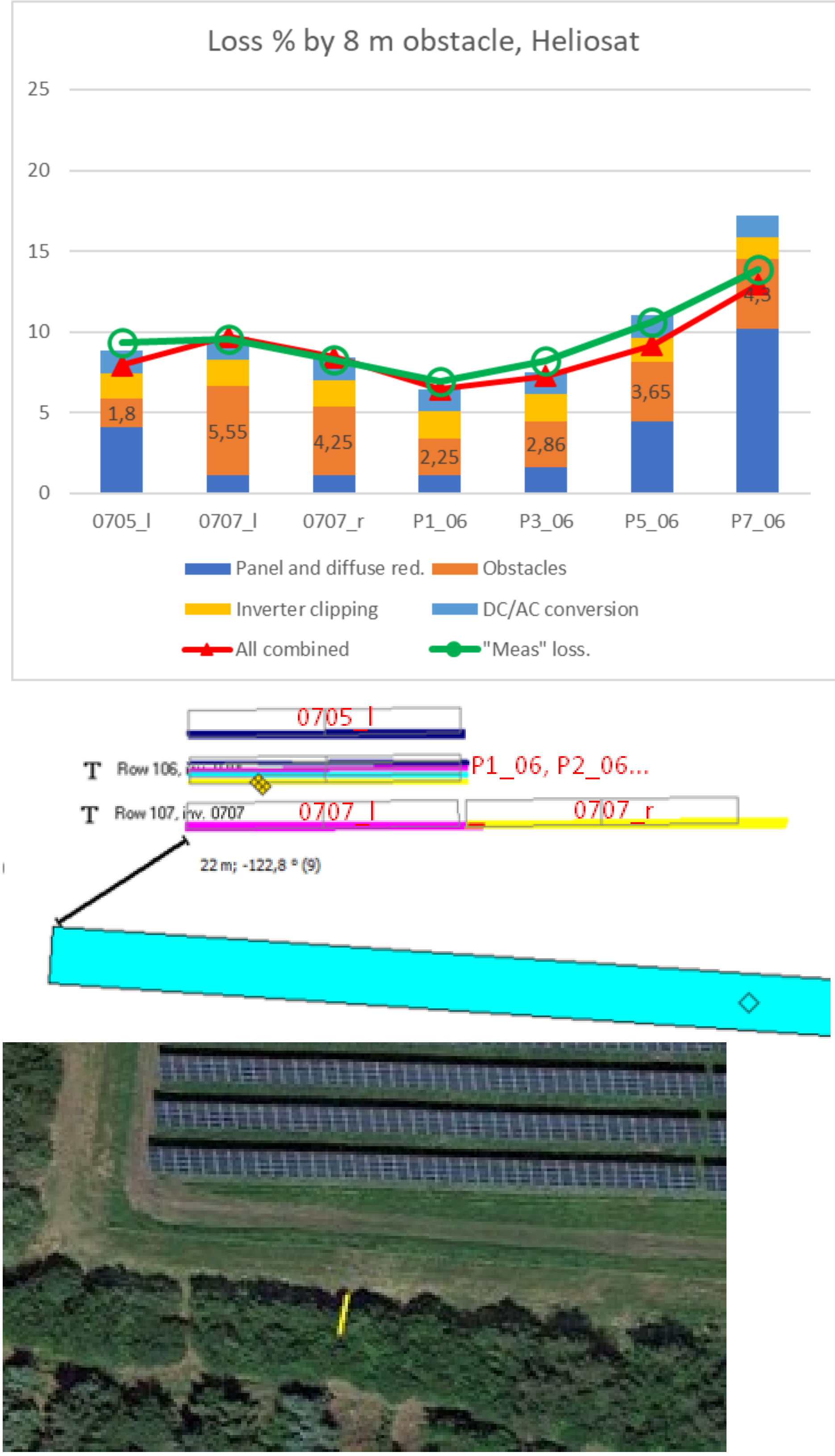


Figure 161 The obstacle shading loss validation.

Obstacle shading has been validated by three table rows, where the second is subdivided in four horizontal strings, P1-06 etc. The obstacle is assumed 8 m high.

As seen, the "measured" loss by panel string matches well with calculated combined loss. Note that while panel shading and obstacle shading loss often appear at the same time, the stacked bars do not represent the "efficient loss", but the loss calculated by the individual "shaders", where no other shaders are present.

Due to non-uniform obstacle, it cannot be expected to model the shading loss fully precise.

Turbine shading loss

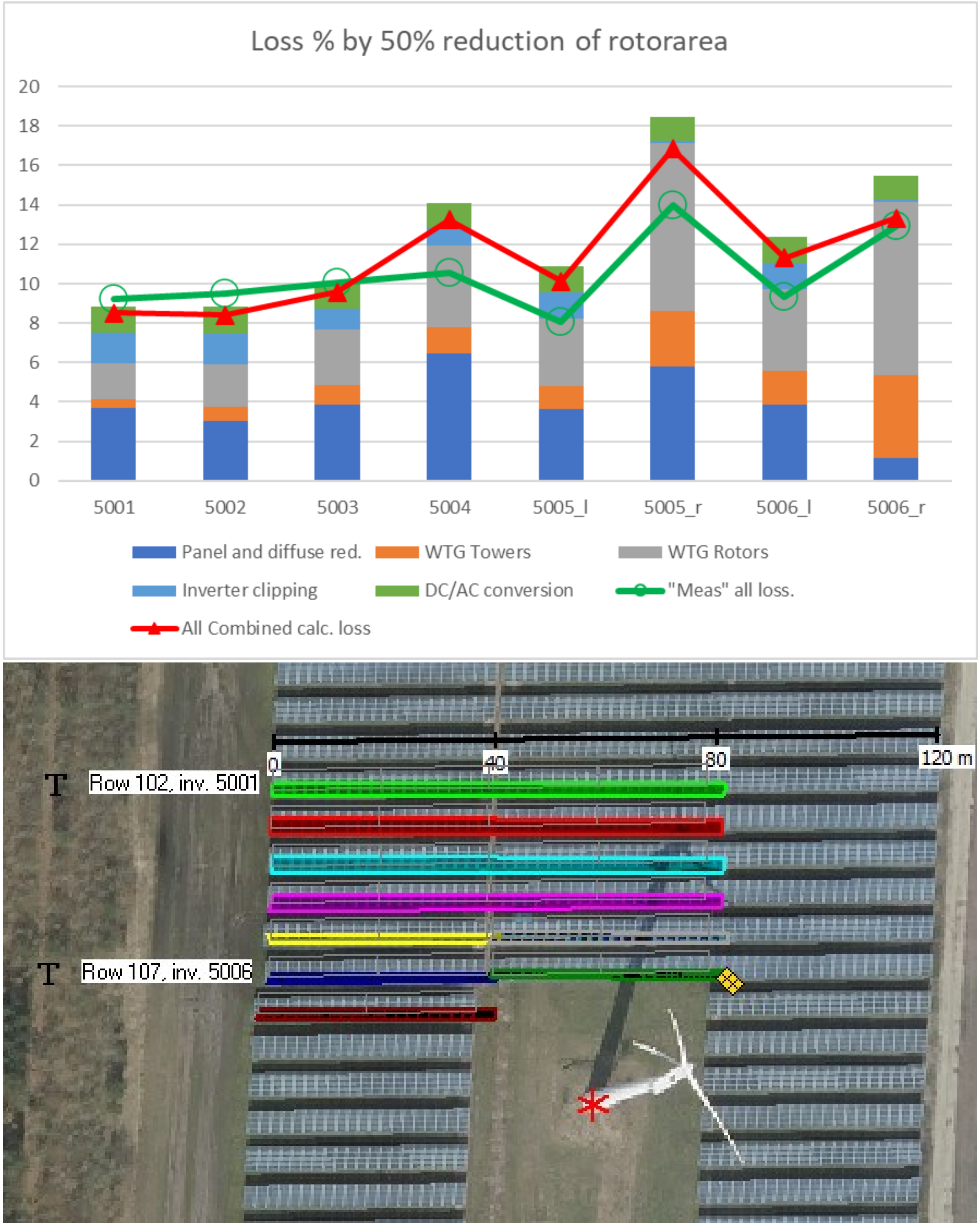


Figure 162 The turbine shading loss validation.

Experimentally, it is found that reducing the rotor area by ~50%, to compensate that the rotor is not a solid disc, works well. It should be noted that the calculation assumes the wind is always from south in the calculation. This could be refined further by taking a wind direction signal into account.

14.13.3 Full plant calculation validation

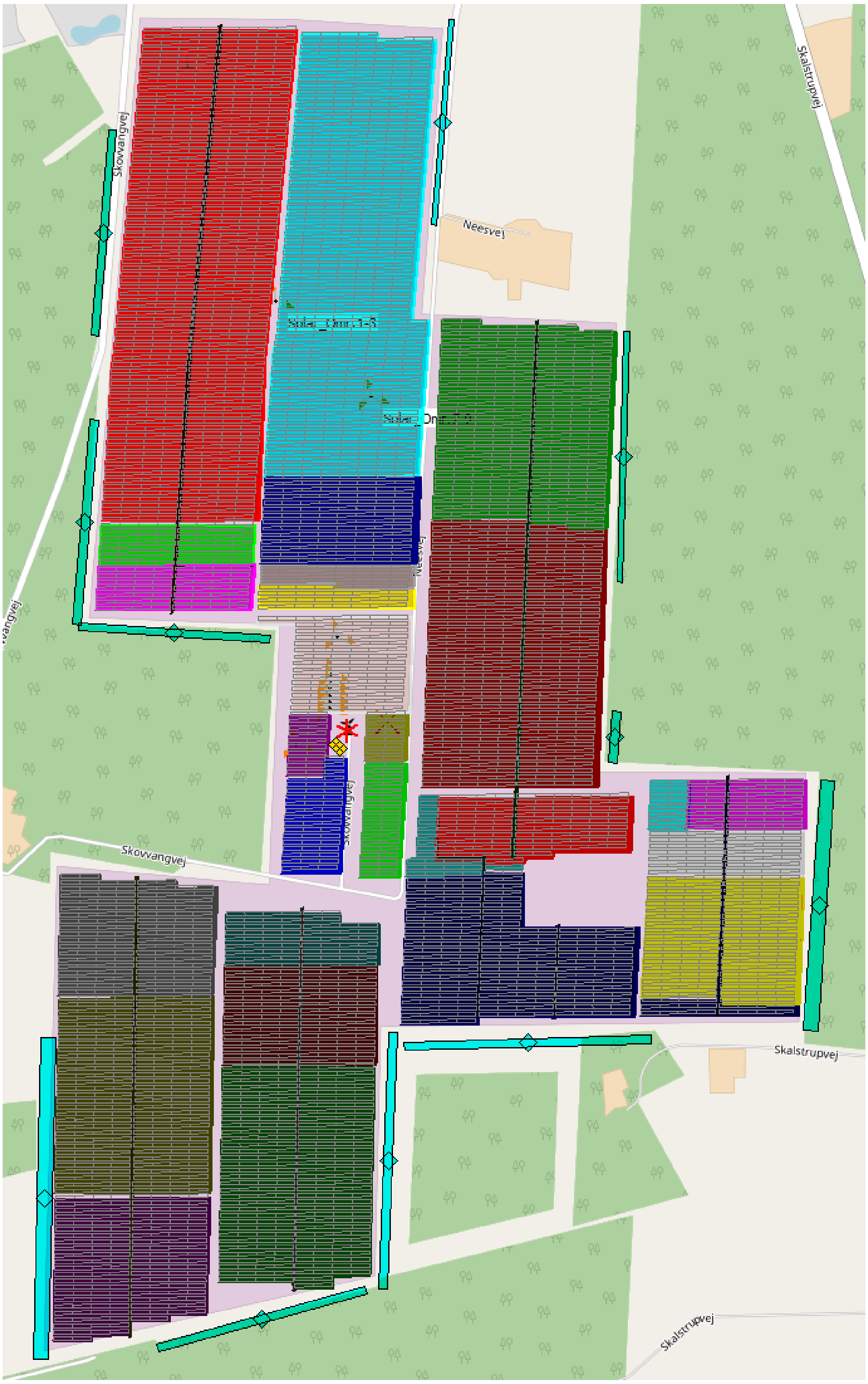


Figure 163 The plant created in windPRO with 28 areas. The WTG and Obstacles are shown as well.

A plant is established (50 MW DC, 35 MW AC), where the subdivision in areas partly reflects the inverter section, partly the panel's power, varying from 310 W to 325 W.

The plant is calculated based on Heliosat (SARAH) data for one year, 01/04/2018 - 31/03/2019, and compared to measurements for the same period. The results are:

Table 9 Calculations vs measurements with availability correction.

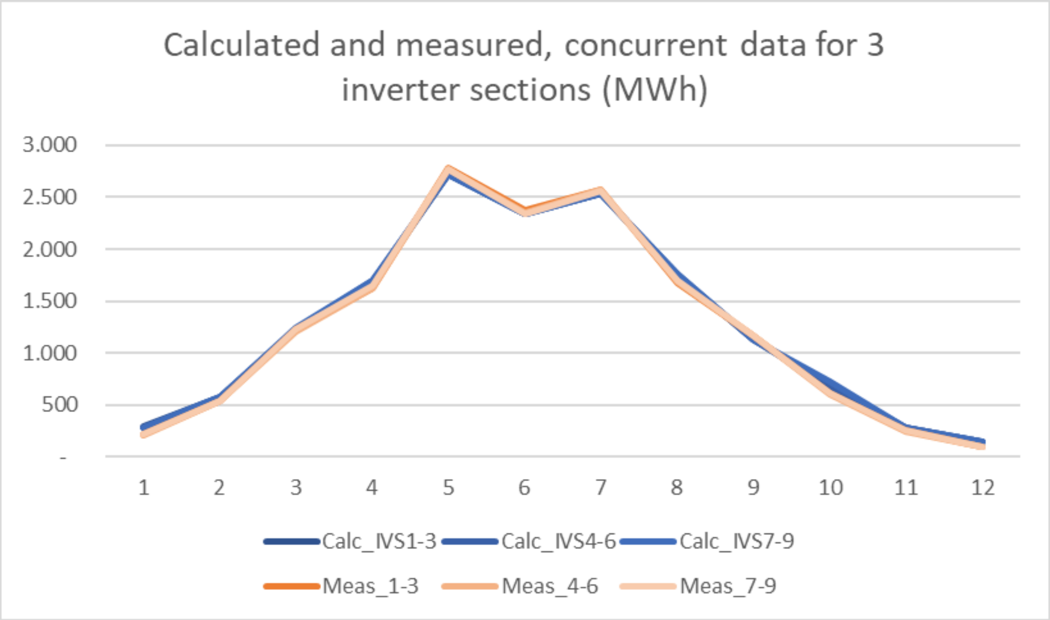
MWh	_IVS1-3	_IVS4-6	_IVS7-9	Sum
Calculated	15.713	15.706	15.712	47.132
Measured	15.146	15.060	15.170	45.376
Meas/calc	96%	96%	97%	96%
Availability corrected *)				
Avail. Loss	3,1%	3,9%	3,5%	3,5%
Meas/calc.	**99,5%**	**99,8%**	**100,0%**	**99,8%**

*) Based on advanced time step loss-based availability calculation method.

Only shading and inverter losses (incl. clipping) included in calculation.

As seen, windPRO produces a very precise reproduction of the measurements by calculation.

Figure 164 shows detailed monthly and hourly illustrations of measurements vs calculations.



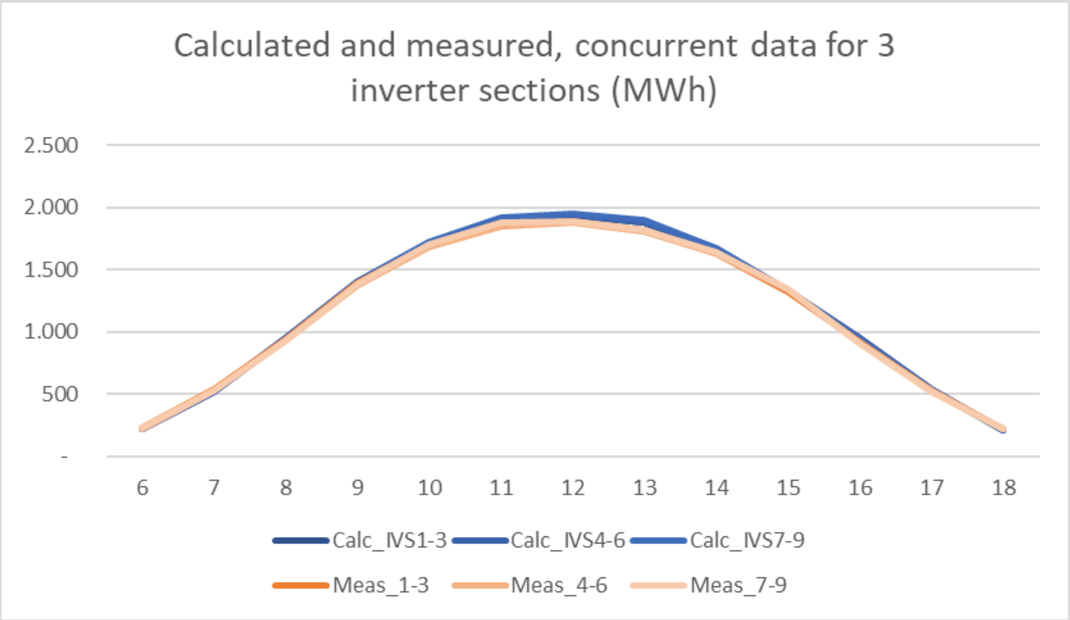


Figure 164 Monthly (upper) and hourly (lower) comparisons of measured and calculated.

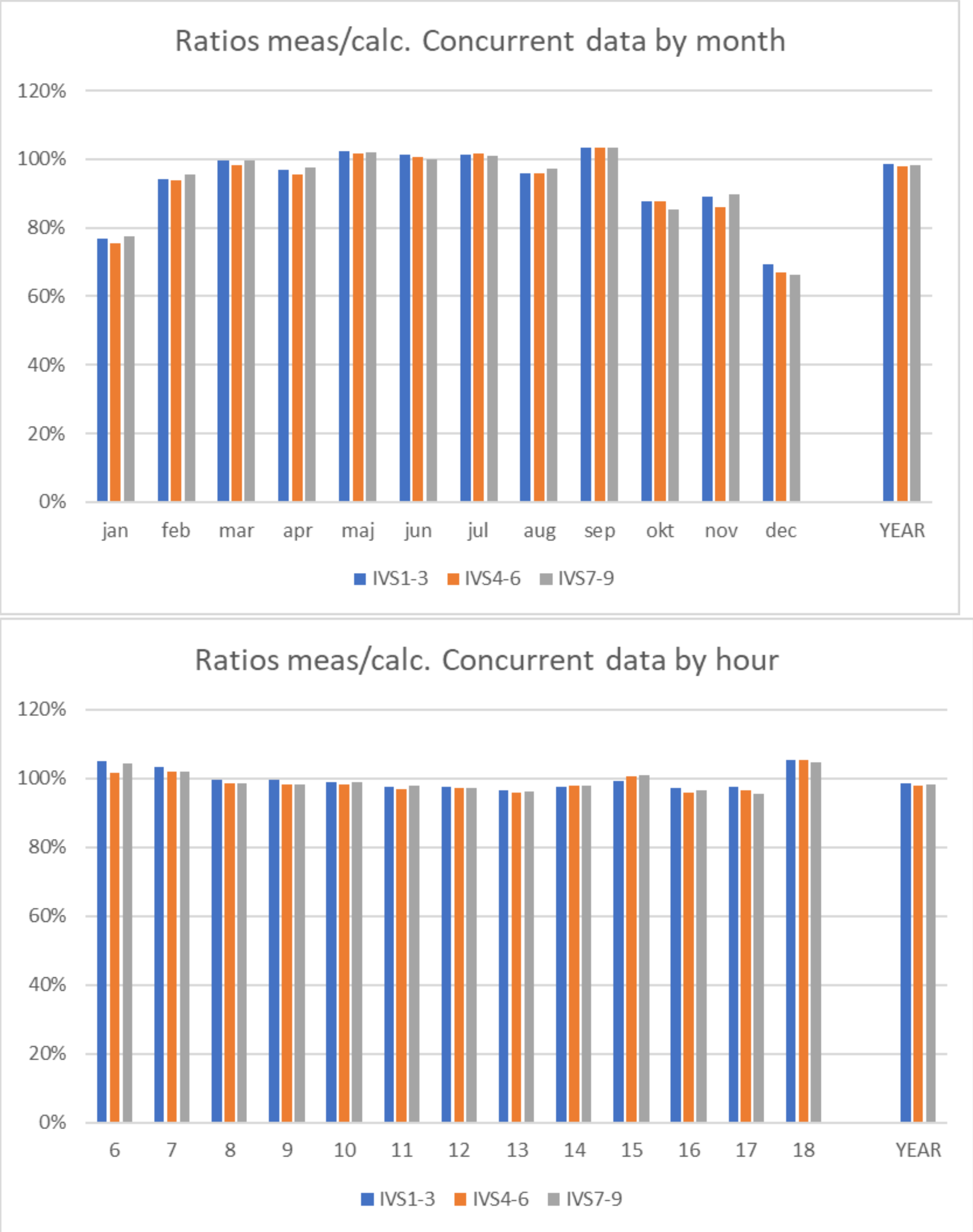


Figure 165 Monthly (upper) and hourly (lower) comparisons of ratios measured/calculated.

The smaller diurnal "skewness" can be explained by a small offset between the time stamps for measurements and calculations.

The full validation report concludes that the consequent overprediction in winter months is partly explained by a bias in the logger data used for the validation. Comparing metered data to logger data shows a significant bias, that the logger data shows too high values in the high production months and too low values in the low production months. Some of the bias could be related to lack of diffuse irradiance reduction by obstacles, a topic for further investigations. Due to very low irradiation in winter months in Denmark, just a few kWh bias will give a large error on ratios measured/calculated.

See the full validation reports here:

http://help.emd.dk/knowledgebase/content/TechNotes/TechnicalNote8_windPRO_SOLAR_PV_Validation.pdf

14.13.4 Validation with newer German plant from 2020

Some model revisions were made from windPRO 3.6: The solar irradiance data handling and the loss handling. In relation to this, a comprehensive validation is performed. Here, one example is described, where different solar irradiance handling methods are tested against PVSYST calculations.

Measured/calculated by model/configuration/solar data	Daily values, 2021			Monthly		Hourly			Calc. share	
Sarah ½ hour solar data	Average	Correl	St.dev	Correl	St.dev	Correl	St.dev 5-18	St.dev 7-17	5-18	7-17
Solar-PV, Sarah, Reindl, Reindl	102%	98,8%	35%	99,9%	11,2%	99,9%	23%	3%	99,8%	97,0%
Solar-PV, Sarah, Erbs, Hay	101%	98,9%	35%	99,9%	11,2%	99,9%	30%	3%	99,8%	97,3%
Solar-PV, Sarah, Reindl, Perez	99%	98,9%	37%	99,9%	11,3%	99,9%	42%	3%	99,9%	97,5%
Solar-PV, Sarah, Earbs, Perez	99%	98,9%	36%	99,9%	11,0%	99,9%	34%	4%	99,9%	97,3%
Experimental, lowering the 2% default michmatch loss:										
Solar-PV, Sarah, Perez 1% mm loss	95%	99,0%	27%	99,9%	12,0%	99,9%	20%	3%	99,8%	97,0%
PVsyst_Sarah_Hay	100%	99,0%	25%	99,8%	10,9%	100,0%	11%	2%	99,7%	96,6%
PVsyst_Sarah_Perez	99%	99,0%	26%	99,8%	10,6%	100,0%	13%	2%	99,7%	96,7%
Alternative solar data, hourly ERA5:										
Solar-PV, ERA5, Reindl, Reindl	104%	95,7%	75%	99,1%	10,2%	99,6%	8%	9%	99,8%	96,6%
Solar-PV, ERA5, Erbs, Hay	101%	95,5%	77%	99,0%	10,1%	99,6%	10%	10%	99,8%	96,8%
Solar-PV, ERA5, Erbs, Perez	99%	95,5%	79%	99,0%	9,7%	99,6%	14%	11%	99,9%	97,0%
PVsyst_ERA5_Hay	101%	95,8%	36%	99,2%	10,2%	99,8%	7%	6%	99,6%	96,0%
PVsyst_ERA5_Perez	99%	95,8%	39%	99,1%	9,8%	99,8%	6%	6%	99,7%	96,2%
									Meas share	
									99,6%	96,2%

Figure 166 Main results for validation case with windPRO 3.6 defaults.

Important results in the above table are:

The new Perez – Erbs defaults calculates 3-5% higher than previously used Reindl model. With the new loss defaults, Solar-PV calculates the measured production is spot on – and similar to PVSYST.

Correlations and Standard deviations are a little better with Heliosat (Sarah) data than ERA5 data. The average calculation results are similar with the new models for the two data sets, where 2% deviations are seen based on the previously used Reindl model.

Standard deviations are slightly lower for PVSYST calculations for some variants, but not all.

All in all, it can be concluded that Solar-PV with the new models and loss setup matches PVSYST for the tested example and both tools calculate production spot on.

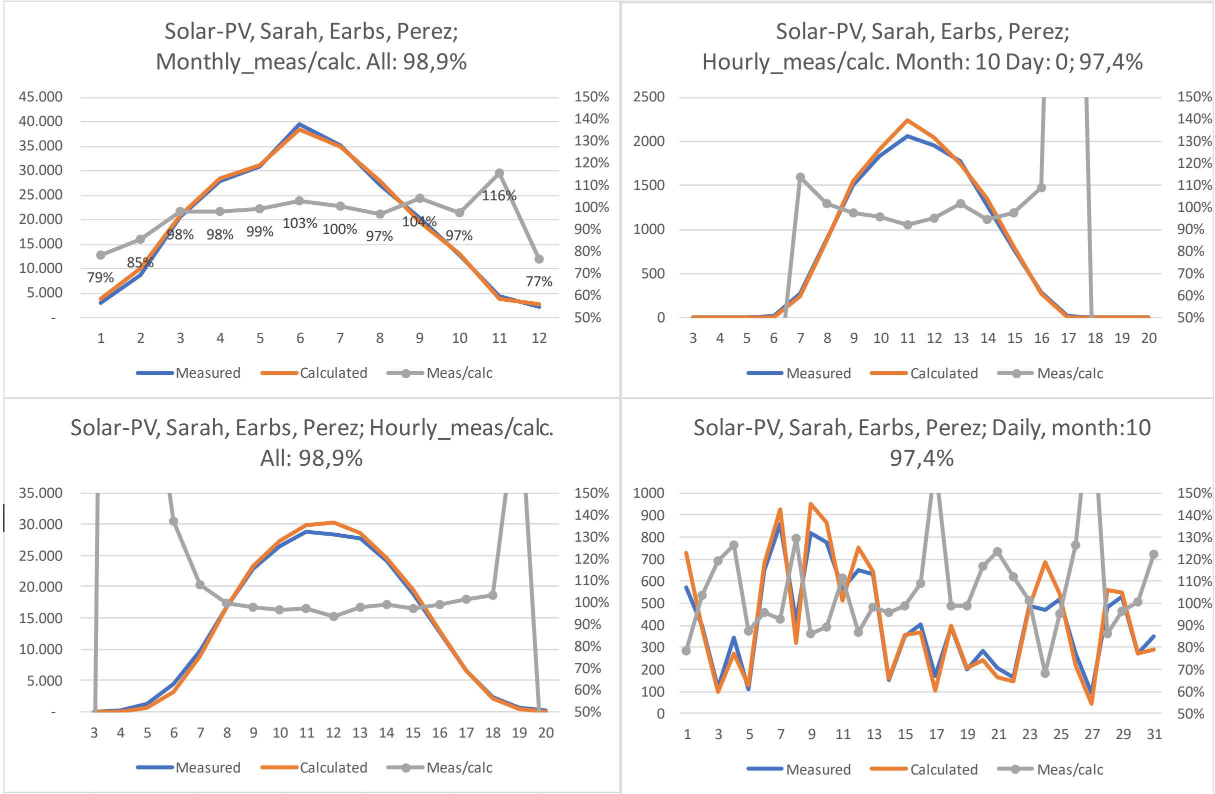


Figure 167 Measured and calculated with Solar-PV new defaults.

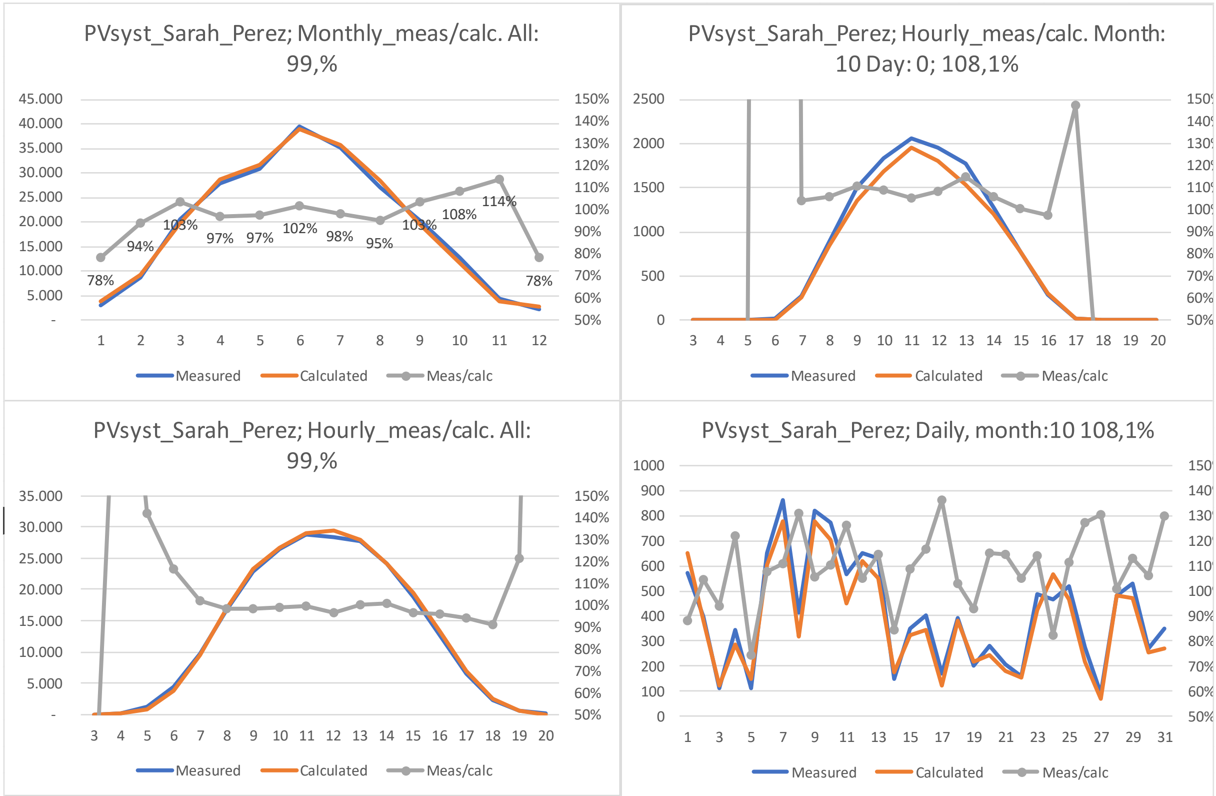


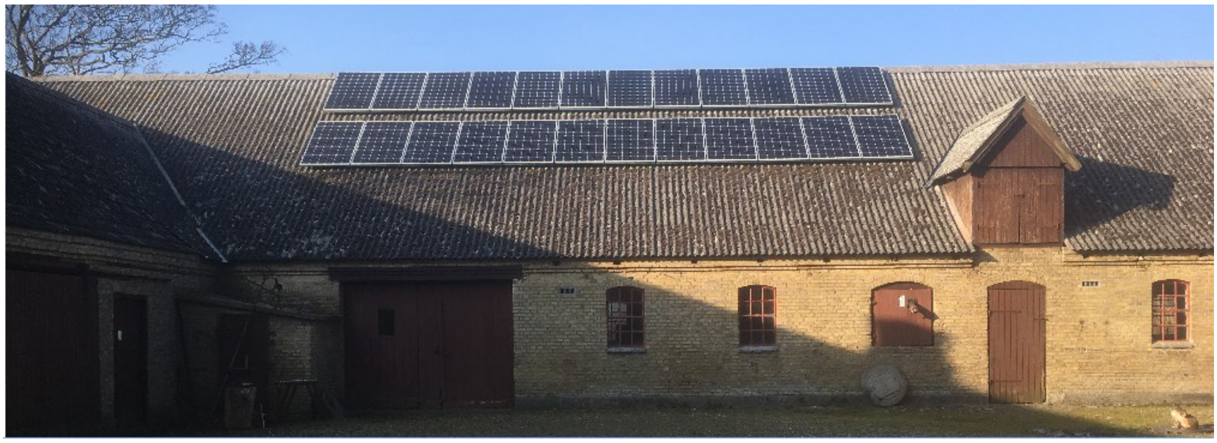
Figure 168 Similar PVSYST calculations.

The two figures above illustrates that there are differences when looking at details, but for totals the results are similar. One difference could be related to different time shift handling in the two calculations.

14.13.5 Photomontage validation

A simple validation example is shown below.

The visualized plant above, the real below.



As seen the difference is almost none. The major challenge in visualizations is the elevation data. The sensitivity to the vertical alignment is large and it can require some work to "finetune" the elevation data below the panel areas to make a correct aligned photomontage. Making the panels correctly align relative to the terrain for a correct energy calculation may also take some practice. Too detailed elevation data might give unforeseen problems, because when constructing a project, the ground will be levelled by dig and fill before construction, or the substructures will be adjusted to absorb the elevation differences.