ANALYSIS OF ELECTRICAL SHADING EFFECTS IN PV SYSTEMS

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ABSTRACT: In a PV system, partial shading of PV modules and strings leads to yield losses not only due to reduced irradiation, but also due to shaded PV cells limiting the current of a string. These so-called electrical shading losses contribute in a non-negligible way to the total losses in a PV system. The detailed calculation of these losses is non-trivial, since it is necessary to combine many IV curves from individual cell strings and determine the resulting curve which can have a much more irregular shape than the simple IV-curve of a group of unshaded strings. Hence, in-depth studies are required to understand and optimize the PV system design.

In this work, we explain the different ways in which the PVsyst software handles the electrical shadings. The detailed IV-curve calculation and three simplified models are applied to different PV system configurations, and the impact of partial shadings on the energy yield is assessed. We discuss which calculation models should be used in different situations. By comparing the results for different typical string layouts, and PV module types, we derive some strategies for minimizing electrical shading losses, that can be applied in a general way.

Keywords: Shading, PV system, Simulation, Software, Mismatch, Design

1 INTRODUCTION

Among the losses that are considered when designing a PV system, those caused by full or partial shadings are fundamental. Except for a few cases such as horizontally mounted modules, or a regular terrain allowing the use of a backtracking algorithm, at low solar elevations, shadings are usually unavoidable. Partial shadings are especially important because of the possible extra losses caused by the irradiance mismatch between strings, modules, or cells. For example, shading just a single module or even a single cell can limit the current of a whole string. This induces an additional loss on top of the irradiance deficit.

In the situation of large systems with regular rows of fixed-orientation modules, which we refer to as shed systems, mutual row shadings are the main cause of partial shading. An obvious way to reduce these losses is to increase the spacing between the rows of modules, which comes at the price of increasing the area. Since this is often not viable, we consider here only systems with a fixed ground coverage ratio (GCR).

Changing configuration of modules and strings has an impact on the electrical shading losses. Indeed, it is well known [1, 2, 3, 4], that mounting modules in landscape or portrait orientation will lead to different electrical shading losses. Other factors that influence the losses are the choice of modules (for example standard or "twin" half-cell modules), the number of modules in a string, the layout of the strings (either on a single row, or on multiple rows), the number of rows on each table/shed, etc. All these options will have an impact on the generation of electrical shading losses, and some effort has already been made to distinguish the best configurations considering some subsets of this palette (see e.g. [6, 7, 8, 9, 10, 11, 12]).

The electrical shading losses for these different options can be simulated in several ways. A complete calculation should involve the combination of the IV curves of every individual PV cell, with an accurate consideration of the respective shading conditions. However, doing this for PV systems above the MW scale, can become very time consuming. As emphasized in [10], analytical models are faster, but need several parameters which are specific to each PV module or system and are often not available. The authors of [10] argue that a simplified model using only geometrical and few module type considerations is possible in the case of simple situations, such that of regular arrays or sheds. They in fact present a simplified model, which extends earlier proposals such as [13]. As described in this work, the PVsyst software also contains such models, which can be used for a wide variety of shed systems.

In this paper we address the question of finding adequate system design choices to mitigate the electrical shading losses in the case of the mutual shadings in regular shed arrays. We also apply the models available in PVsyst to the different PV system configurations in an effort to benchmark them against each other. This allows us to present general guidelines and suggestions both for system design and modelling within PVsyst. We are able to qualitatively reproduce the field results of [10] with the detailed calculation model and present the rationale behind the simplified model.

2 METHODOLOGY

The basic idea of our study is to model and simulate a set of shed-like systems, spanning a wide range of possible module and string configurations. The simulations are run using the different types of shading models available in PVsyst: a detailed model based on the composition of IV curves, as allowed by the "module layout" definitions, and three variations of a simplified model that speed up computations for very large systems. We obtain yearly averages and hourly results for several variables of interest. This allows us to benchmark the simplified models against the detailed model and identify the configurations leading to lower electrical shading losses. This procedure is summarized in Figure 1.

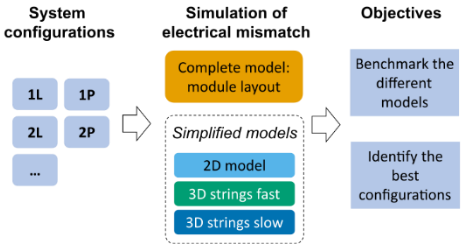

Figure 1: Procedure followed in this work. A total of 18 different configurations (listed in Table I) was studied.

Modelling with PVsyst allows one to control multiple aspects of system design. In this study we vary the configurations of PV cells, modules, and strings with the following parameters:

- Number of rows of modules in the height of the shed (1 to 4).
- Module orientation (Landscape or Portrait).
- Type of module (Standard or Twin half-cell in portrait).
- String connections layout on a single row or on multiple rows (U-shape).

The systems chosen for our study span all possibilities allowed by these four parameters. For the remainder of the work, we use the labelling described in Figure 2 for the different cases.

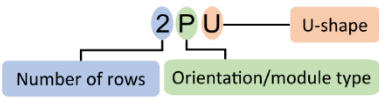

Figure 2: Configuration identifier description. The example (2PU) corresponds to 2 rows of portrait-oriented modules, with strings spanning both rows.

With this terminology, the list of simulated configurations can be found in Table I. Configurations in color are those commonly found in actual realizations; the remaining configurations are also studied to check the general character of the simplified approaches.

Table I: List of the different shed-like system configurations studied in this work. Cases in blue are those commonly used in actual realizations.

	Landscape	Portrait	Twin half-cell
1-row	**1L**	**1P**	**1T**
2-rows	**2L/2LU**	**2P**/2PU	**2T**/2TU
3-rows	**3L**	3P	3T
4-rows	**4L/4LU**	4P/4PU	4T/4TU

There are other variables which impact the losses. Non exhaustively, these are the location, the meteorological conditions, the GCR, the tilt and azimuth of the sheds. Contrary to the previous variables, this set of conditions will be fixed for all simulations. To compare yearly results and loss factors, we opt for a "realistic" setup: 20° tilt, 0° azimuth, with a GCR = 0.65, meteorological conditions synthetically generated from the Meteonorm 7.3 [14] data in Marseille (France). To study the hourly values, we opt instead for a configuration which leads to a wider range of shading conditions: 50° tilt, -90° azimuth, GCR = 0.65, and a location at 85° latitude with a manually adjusted low diffuse fraction (5-10%).

Finally special care is given to the 3D scene layout, with the goal of having the most regular shading conditions (i.e., as a horizontal band of direct sunlight deficit covering the whole shed width gradually from the bottom to the top). PVsyst allows to easily construct regular arrays; for the realistic layout we construct 2 to 6 consecutive wide sheds of 48 modules in width, with a shed-shaped rectangular shading object in front of the first shed to allow for uniform shading conditions. Instead, for the idealized setup, we also use additional shading rectangles on several rows in front and on the sides of the active sheds, to ensure that mutual shadings cover the whole horizontal width of the sheds.

Each of the electrical shading models requires further configuration. The detailed model, used as reference, requires a distribution of modules into strings, which are then distributed among the different inverter MPPT inputs. This is done through the "module layout" tool in PVsyst, and hence we will sometimes use the term "module layout model" in this work. Instead, the simplified models require either to specify the number of modules in the height of the shed for the 2D computation, or to partition the sheds into string-rectangles in the 3D scene. In some cases, for the simplified model to best match the reference, these partitions should be adjusted (i.e., not follow string boundaries anymore).

The reference and simplified models are applied to all different systems described above. The simulations run over a full year, yielding yearly average and cumulative quantities such as energies and losses, and hourly results for all the variables of interest. We are interested in the cumulative and hourly electrical shading losses, the shading fractions as well as the relative loss factors that can be derived from these.

The electrical shading factor $f_{ShdElec}$ reads

$$f_{ShdElec} = \frac{L_{ShdElec}}{P_{ArrNom} - L_{GInc} - L_{Temp}},$$

where P_{ArrNom} is the array nominal power at STC, L_{GInc} is the power loss due to the irradiance deficit with respect to the STC, L_{Temp} is the power loss due to the temperature difference with respect to the STC, and $L_{ShdElec}$ is the power loss due to electrical shadings only. The fraction of the sheds shaded from the beam component f_{ShdBm}, which we use as the main variable characterizing the shading situation, can be obtained directly as an output of the simulation. We also call it linear shading factor on beam. Finally, the electrical shading factor on beam $f_{ShdElecBm}$ requires an intermediate step: we first define the fraction of beam

$$F_{Bm} = \frac{\frac{G_{BeamEff}}{1 - f_{ShdBm}}}{G_{AlbEff} + G_{DiffEff} + \frac{G_{BeamEff}}{1 - f_{ShdBm}}},$$

where G_{AlbEff} and $G_{DiffEff}$ are the albedo and diffuse irradiances remaining after subtracting the respective shading loss, evaluated as an integral of the linear shading factor over all sky directions. $G_{BeamEff}$ is the shaded beam irradiance, obtained by discriminating the surface of shaded and unshaded active PV areas. This allows us to define the electrical shading factor on beam as

$$f_{ShdElecBm} = \frac{L_{ShdElec}}{P_{ArrRef} \cdot F_{Bm}},$$

which can be added with the linear shading factor on beam to obtain the full shading factor on beam. Here, P_{ArrRef} is the array power at unshaded beam conditions, hence used as reference for the shading factors.

All quantities on the right-hand side of the equations can be obtained as hourly and yearly outputs of a PVsyst simulation. This study has been conducted using PVsyst 7.2.

3 MODELS USED

3.1 Irradiance components

The irradiance model in PVsyst is based on a decomposition of the global irradiance into 4 main components: 1) the beam component, 2) the circumsolar component, as well as the 3) isotropic diffuse and 4) albedo components. The beam or direct component, coming directly from the direction of the sun, leads to non-uniform irradiance conditions. Instead, the albedo and diffuse components are approximated as uniform irradiance conditions on the active PV surfaces. In the end, only the beam (and optionally the circumsolar as seen below) component can lead to electrical shading losses, which are directly caused by the electrical mismatch between different system components due to non-uniform irradiance conditions, or partial shadings.

Finally, the circumsolar component, i.e., the irradiance coming from outside a 5° cone around the sun, can be treated in PVsyst as either the beam component or included in the diffuse. Our study treats the circumsolar as the diffuse and therefore as isotropic and leading to uniform irradiance conditions.

3.2 Reference model ("module layout")

The reference model for electrical shadings used for this study is the most detailed computation available in PVsyst. It combines the IV curves of each individual submodule (i.e., a group of PV cells protected by a by-pass diode) by considering the electrical connections designed and parametrized in the "module layout" tool. This allows the computation of the shaded MPP P_{ArrShd} as well as the operating point (OP) of each inverter. The unshaded MPP P_{ArrRef} is an estimate of the array power based on the sum of the plane of array shaded albedo and diffuse components, and unshaded beam component. Comparing the power at these points with that at the unshaded MPP leads to a detailed evaluation the shading losses. The electrical shading losses are

$$L_{ShdElec} = P_{ArrRef} \cdot (1 - F_{Bm} \cdot f_{ShdBm}) - P_{ArrShd} \, .$$

The use of submodules instead of cells for the combination of IV curves can be understood as follows: whatever the number of shaded cells in a submodule, its IV curve will approximately have the same shape. This is shown in Figure 3, where the submodule IV curve is drawn for different numbers of shaded cells. Basically, up to tiny discrepancies, it is sufficient to consider submodules, instead of combining individual cells.

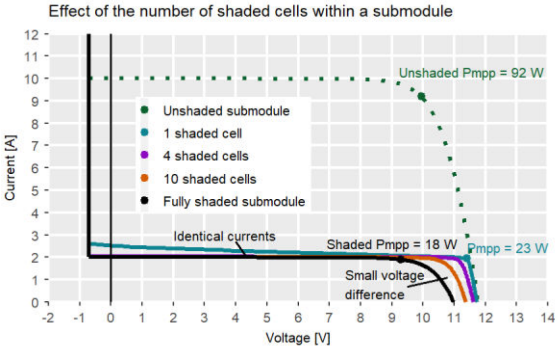

Figure 3: Submodule IV curve for different numbers of shaded cells. As long as one cell is shaded the curves are effectively the same, up to a small voltage difference.

Once the shading conditions have been determined for each submodule, their IV curve is combined with the other curves of the module, string, and finally MPPT input. This is done by adding the voltages of submodules in series to get the IV curves of the strings, and then adding the currents of the strings in parallel. The full shading losses can be split into a part proportional to the irradiance deficit part, named "linear shading losses" and the remaining "electrical shading losses".

In regular shed systems, since the shading conditions are horizontally uniform, it is possible to draw some general conclusions as to the resulting shading loss factors. One of our scenarios is for modules to be mounted in landscape orientation. In such a case, the submodules (typically 3) in each module will lie one above the other. Hence for a row of modules, 1/3, 2/3 or all submodules of the row will be shaded at once.

Figure 4 (already presented in [15]) shows the shading factor for one string, as a function of the number of submodules shaded. This is dependent on the number of strings connected to one MPPT input. We observe that for 3 strings in parallel or more, as soon as the bottom row of submodules (or cells) is shaded (i.e., 1/3 of submodules) the string becomes electrically inactive. This is due to the voltage mismatch between the strings. The losses are however lower for one (or possibly two) strings per MPPT input.

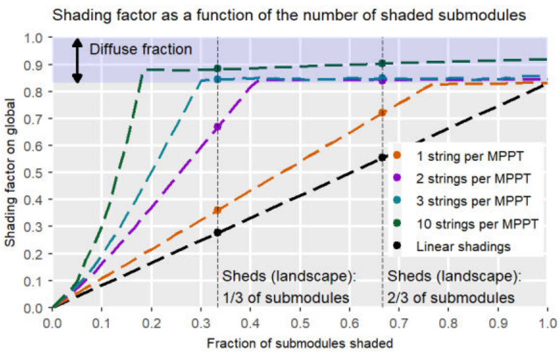

Figure 4: Electrical shading factor of a string for different numbers of strings per MPPT input. The more strings one adds per inverter input, the larger the electrical shading effect over the string. In the case of regular rows of landscape modules one shades 1/3 of the submodules at a time. For portrait oriented modules, one shades all the submodules at once.

In the case of portrait-sheds, since the submodules are arranged side-to-side, all submodules will be shaded at the same time. In this case, the shading loss factor will be maximal as soon as the bottom row of cells is shaded.

3.3 Simplified model for sheds

The simplified model takes advantage of the above observations. It is based on a partition in rectangles, each one representing a full string. As soon as the bottom of the rectangle (one cell width) is shaded, the full rectangle becomes inactive (electrically shaded). It can be applied with three different levels of sophistication in PVsyst.

The first step in the model is to determine the shading conditions on each of the string-rectangle partitions. This can be done in three ways. First, via a cross-sectional 2D unlimited sheds model (hereafter called the "2D simplified model"), allowing for analytical calculations. The partitioning in strings is configured by entering the number of modules in the height of the shed. Second, the string partitions can be defined in the 3D scene, with shading conditions interpolated from a pre-computed shading factor table. This model is called "fast 3D simplified model". Third, the same rectangles defined in the 3D scene can have their shading conditions computed hour-by-hour relative to the instantaneous sun position. We call this model the "slow 3D simplified model".

An advanced parameter in the simplified model is the fraction for electrical effect. It allows one to reduce the electrical shading losses by an overall factor. In this study we leave its default value, 100%.

Once the shading conditions of each rectangle have been computed, the simplified model bypasses the full IV-curve based calculation: the electrical shading losses are instead a simple step-like function of the shading conditions. Two factors are applied: a linear shading factor taking into account the irradiance deficit, and an electrical shading factor following the step-like function. Together these give the shading loss factor, which is applied to the beam irradiance component only. The function takes into account that if a part of the bottom cell is shaded, the current in the cell (and therefore in the submodule) is proportional to the shaded fraction of the cell. In the 2D case, the analytic calculation allows to evaluate this fraction. In the 3D case, we don't have the opportunity of applying a "partial loss" to the rectangle. Therefore, the shading on the first cell is considered null up to the middle of the cell, and complete when more than half of it is shaded. The errors should be averaged over all the hours of the simulation. The shading factors for the simplified model are represented in Figure 5.

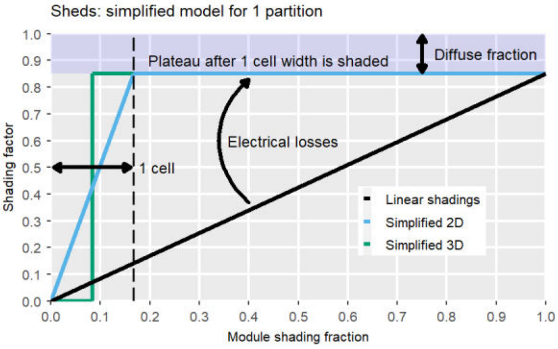

Figure 5: Simplified model for sheds, based on the behavior of the shading factor for 3 strings or more per MPPT input (see Figure 4).

In fact, the simplified model plateau behavior is based on the results for the module layout model, for landscape-oriented modules starting from 3 strings per MPPT, or for any string number of portrait-oriented modules. As a conclusion of this work, we will see that in the landscape case, for less than 3 strings per MPPT (typically for string inverters), it may be worthwhile to readjust the string-rectangle partitioning.

4 RESULTS AND DISCUSSION

Out of the one-year-long PVsyst simulations, it is possible to obtain, for a wide set of variables, both an hourly time-series and the yearly overall values. We use these two possibilities in respectively different ways: the detailed hourly results can be processed to assess the behavior of the models as a function of the shading conditions, which will vary hour by hour. Instead, we use the yearly results to benchmark the models against each other and determine which configurations should lead to lower overall electrical shading losses. As explained in Section 2, we use different setups for either hourly or yearly result evaluation. The more "realistic" setup is used to evaluate yearly results.

4.1 Detailed hourly results

The horizontally uniform shading conditions in shed systems make it possible to qualitatively characterize the shading conditions with a single variable, the beam linear shading fraction. This quantity corresponds to the shaded fraction of the active PV surface. In a perfectly regular array of sheds without module borders, this quantity is equal to the fraction of submodules heights shaded. It is thus interesting to compare the full shading factor (including the linear and the electrical shading losses) to the beam linear shading fraction. We plot these quantities for all the configurations of the study, which allows us to analyze the behavior of the models case-by-case and across the whole range of shading conditions.

In the complete model, the shading fraction always increases gradually by constant plateaus, while the simplified model exhibits slightly "curved" steps, a behavior due to the non-shaded beam fraction having been used to estimate the beam contribution to the array power. As confirmed in the next section, the simplified model is nonetheless very reliable in the case of shed systems, although it sometimes requires an adjusted rectangle partitioning.

The necessity for adjustments in the rectangle partitioning is well exemplified by the case 1L, shown alongside other cases xL in Figure 6. Instead of a single plateau, the complete model (shown in orange) increases in three well-defined constant steps corresponding to the three rows of submodules being shaded one after the other. In fact, this behavior could be anticipated already from Figure 4: in the case of 1 string per MPPT, when 1/3 of the submodules are shaded the maximum electrical shading factor has not yet been reached. To match this behavior with the simplified model (shown in blue), one should increase the number of partitions vertically.

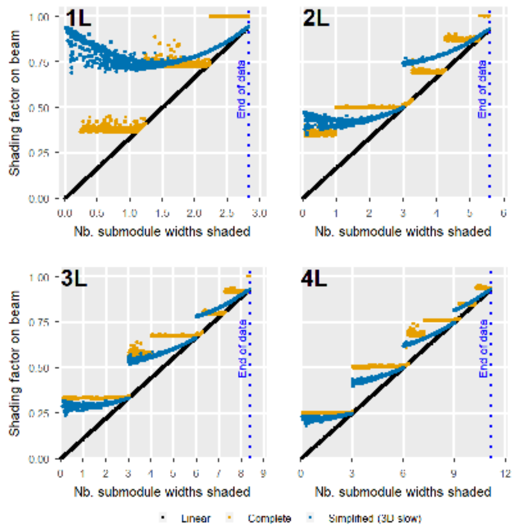

Figure 6: Full shading factor as a function of the number of submodules widths shaded, for all xL configurations. The simplified model (in blue) does not match the complete calculation (in orange) in the case 1L. In practice, the situation where only the first row of submodules is shaded has more weight on simulation results, since it occurs more frequently.

For the other cases xL, the more strings one adds to a single MPPT input, the faster the plateau of Figure 4 is reached, gradually leading to having a single plateau over the 3 first submodules shaded. This corresponds to 1 shaded row of modules—the first row is between 0 and 3 shaded submodules widths, the second between 3 and 6, and so forth. As the number of shaded rows increases beyond the first, the extra losses due to the current mismatch between strings will gradually decrease. When the last row is shaded, the behavior of the shading factor is qualitatively the same as in case 1L: there are three steps instead of a single plateau across the whole row width. Note that it is most important to accurately model electrical shadings on the first row. Indeed, shading over the first row happens more frequently, so that this situation will have more impact on simulation results.

In all cases xL except case 1L, the simplified model visibly succeeds in approximating the behavior of the detailed model. However, since the features of the detailed model are regular, it should be possible to improve the simplified model up to a much better agreement with the reference.

For the remainder of the cases, we will focus on those with 2 rows only (and always 2 strings per MPPT input), as they are representative for other number of rows (and allow us to discuss the “U-shape” connections as well). Cases 2P and 2T, presented in Figure 7, show a good agreement between the models. Both models follow the same behavior: as soon as one cell is shaded, the whole string is turned off. Still, some improvement in the form of a flatter plateau for the simplified model can be made. As discussed above, this could be done by estimating the beam fraction more accurately.

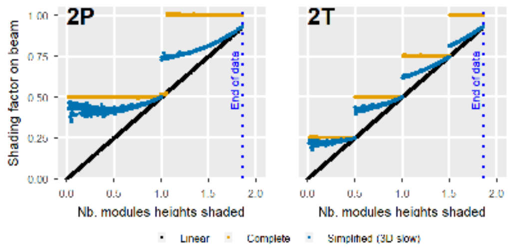

Figure 7: Full shading factor as a function of the number of submodules widths shaded, for the 2P and 2T configurations. The simplified model matches well with the complete calculation.

Instead, the U-shape cases (strings arranged vertically), exemplified in Figure 8, all need adjustments to the string-rectangle partitioning for the simplified model to match with the reference. This is because the U-shape configuration, without the constraint of a minimum inverter threshold, will simply mean that the operating point may still be chosen according to the MPP of the unshaded modules, and the electrical shading losses will be smaller. However, with a minimum voltage threshold, the inverter will more frequently select an operating point with the current limited by the shaded modules, thus leading to large electrical shading losses.

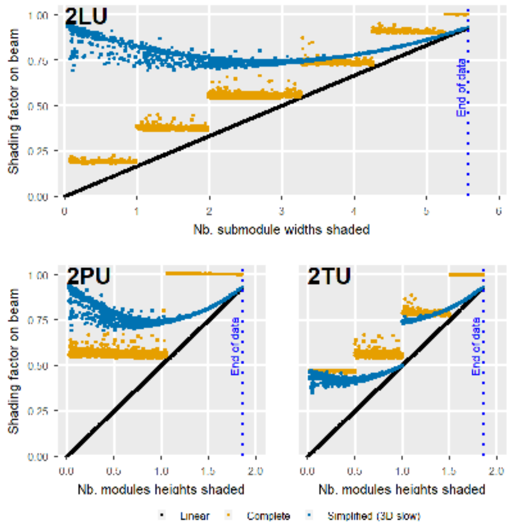

Figure 8: The case 2LU visibly needs an adjusted partitioning for the simplified model (in blue) to match with the complete calculation (in orange).

From these hourly results, it is possible to infer which configurations lead to the lower electrical shading losses. These observations will also be confirmed in the next section with the yearly results. With the understanding that the shading factor function behaves as a stepwise increasing function, having more steps, and lower ones, will mean having less electrical shading losses overall. For this reason,

a) increasing the number of rows per shed,

b) distributing the strings on the inverter inputs in terms of similar shading conditions, and

c) choosing landscape orientations for standard modules,

will ultimately decrease the electrical shading losses.

Note that throughout the section and Figs. 6-8 we have chosen to present only the slow 3D simplified model, since the results for the other simplified models are fully comparable both qualitatively and quantitatively.

4.2 Yearly results comparison

Yearly results are used to benchmark the simplified model against the reference model. Ideally, the simplified model should yield approximately the same (yearly) average electrical shading factor than the reference model. Some cases however lead up to an order-one difference, as we will see because of inappropriate string-rectangle partitioning. Typically, a difference of up to about 1% in the shading factor may be considered satisfactory.

In Figure 9 we show the electrical shading factors for the different models in the cases that are most common in actual projects. The string-rectangle partitioning is done as intended: delimiting the surface strings, or, in the case of twin half-cell modules, half strings.

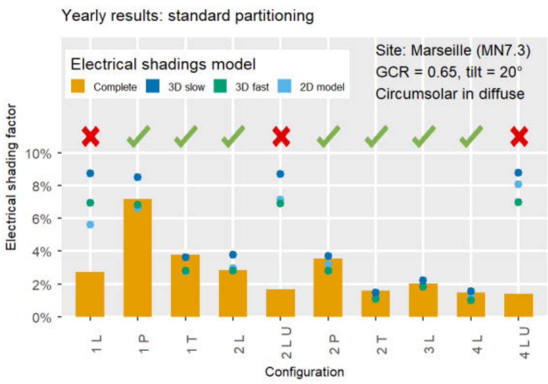

Figure 9: Yearly average electrical shading loss factor, across the most commonly used configurations. The complete calculation results (in orange) show that different configurations will lead to very different losses. The simplified models (in blue and green dots) do not always match the complete calculations, indicating that and adjusted partitioning might be needed.

For most cases, despite the small differences observed in the previous section, the yearly results show the different models matching well with each other. However, the case 1L as well as the cases with strings distributed on multiple rows (U-shape connections) do not match.

The reason behind the disparity in the cases 1L and xU can be understood from Figure 4 and from the perspective of the hourly results presented in previous section.

For the 1L case, the shading factor has a low value for 1/3 submodules shaded (around 38%, as seen in Figure 4). Since the first row of modules is more frequently shaded, this low value is the primary source of disparity. In Figure 6, this translates into a gradual increase in three steps instead of a single plateau as found by the simplified model. For the 2LU and 4LU cases, only 1/6 of the submodules are shaded at a time. In Figure 8 this translates into an increase of the shading factor over 6 steps instead of 1 for the simplified model. The most frequent shading situation is when only the lower 1/6 of the submodules are shaded, meaning that one looks at a very low value of the shading factor. Note that in Figure 4, one should look at the curve for 1 string per MPPT, because with strings in arranged vertically all of them have the same shading conditions.

To reduce the disparity for these problematic cases, we adjust the partitioning, to reflect the step-like behavior of the shading fraction. The resulting yearly shading factors are shown in Figure 10.

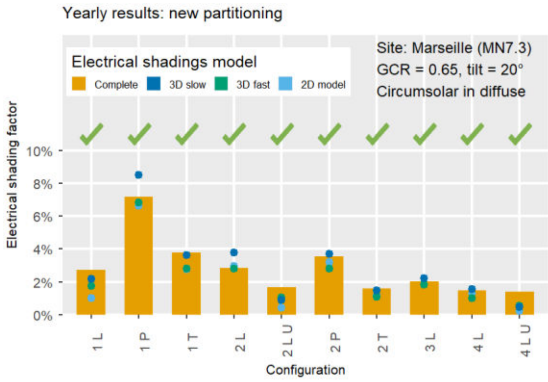

Figure 10: Idem to Figure 9, but with adjustments to the partitioning into string rectangles. The simplified model can thus match the complete calculations for all commonly used configurations.

The adjusted partitioning is shown in Table II.

Table II: Adjusted partitioning guidelines, directly applicable in the modelling in PVsyst, leading to the best match between simplified model and complete calculation. Partitionings with an (*) are the adjusted ones.

Case	Partitions in height	Case	Partitions in height
1L	2 partitions (*)	xPU	module layout (*)
xL	x partitions	xT	2x
xLU	3x partitions (*)	xTU	x (*)
xP	x partitions		

Although the most common cases can be made to match with the reference model, this is not the case for the case XPU. For example, in the 2PU case shown in Figure 8, one could think that two partitions would work best. However, since the shading factor is above 50% on the first step, the electrical shading losses end up being significatively underestimated.

Finally, it is possible to use these results to infer which configurations might produce less electrical losses. The general idea, repeated from the previous section is to:

a) increase the number of rows per shed,

b) distribute the strings on the inverter inputs in terms of similar shading conditions (alternatively reduce the number of strings per inverter input), and

c) choose landscape orientations for conventional modules.

The case xT gives approximately the same electrical shading factor as the (2x)L and the xLU case. Cases xPU and xTU are not interesting in terms of having a low electrical shading factor, and so U-shape connections are interesting only for landscape models.

4.3 Impact of inverter thresholds

A limitation for the applicability of the study happens at the level of the inverter. Indeed, inverters have upper and lower bounds on their voltage operating points. In the case of this study, a particularly important bound is the minimum inverter threshold. The different configurations lead to very different MPP voltages depending on the shading situation as shown in Figure 11 in the case of 2-row cases.

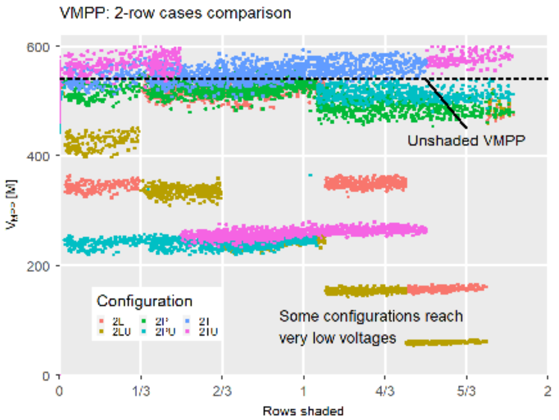

Figure 11: MPP voltage across different configurations for different shading conditions. Some situations lead to very low voltages, potentially below the inverter threshold. This will lead to extra losses.

Whenever the MPP voltage is below the inverter threshold, further losses are to be expected since the operating point of the inverter will be pushed away from the MPP. An explicit example is shown in Figure 12.

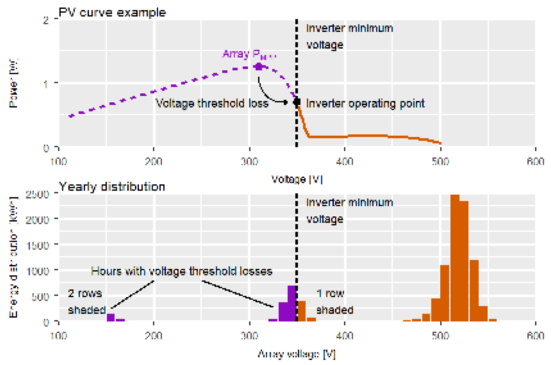

Figure 12: Example of a situation leading to extra losses due to the inverter minimum voltage threshold. Om this case hours with one or two rows shaded have an MPP voltage below the threshold.

5 CONCLUSION

To understand how the module and string arrangement in shed systems affects the electrical shading losses, we have simulated a set of different configurations in PVsyst. This also allowed us to benchmark the simplified models that are available in PVsyst in order to speed up calculations.

In general, to decrease the electrical shading losses, it is beneficial to increase the number of rows, have less strings per MPPT input, group strings by similar shading conditions, and use the landscape orientation with conventional (non-half-cell) modules. The U-shape connection may be interesting in the landscape case only.

These conclusions however hold only up to the inverter input. Once the inverter limitations are considered, some MPP with low voltages cannot be attained, and the operating point will be at a lower power, thus generating more losses. Furthermore, the losses from inverter limitations are only modellable using an IV curve approach, like the "module layout" tool of PVsyst. The losses further caused by the inverter limitations will be the subject of a future study.

We have found that in some cases, the partitioning of sheds into string-rectangles should be adjusted for the simplified model to match with the reference "module layout" model. This is the case for the 1L case that trivially has no mismatch between strings, but also for all the U-shape connection cases. We have included a table summarizing these adjusted partitioning guidelines.

A few examples of interesting extensions for this study are investigating the shading factor as a function of the GCR, as a function of the tilt, the study of tracking systems, as well as of other string or inverter layouts. A study with the circumsolar irradiance component taken into account together with the beam is expected to yield similar results.

Following this study, we plan to improve PVsyst with more options for electrical shading calculations and with a simplified model parameters ensuring a better match with the complete "module layout" calculation. In particular, we will implement a more accurate estimate of the beam contribution in the simplified model, allow more flexibility in the partitioning into rectangle-strings, as well as implement an extended "module layout" calculation, which would be applied on a subset of the system only, and then extrapolated to the whole system.

6 NOTES

This study is reproducible with PVsyst version 7.2.5. Contact the authors for additional details and results.

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