Progress and lessons learned in the development of the 3D energy yield calculation model

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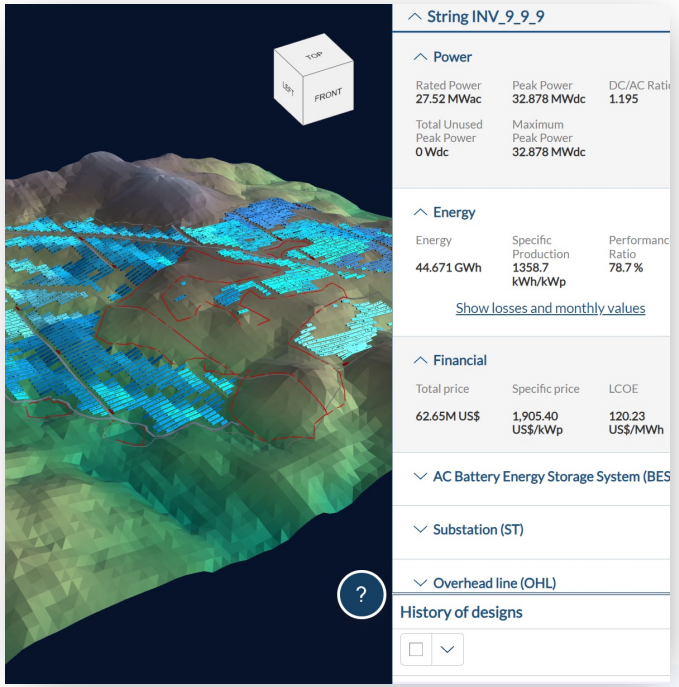
2024 PVPMC

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Introduction

The goal is to develop an energy yield calculation model which considers the effects of the terrain and the electrical losses due to partial shading.

- ➔ The development of a 3D energy yield model is a strategic priority for RatedPower. It is a long-term project which started in 2022.
- ➔ Previous developments lay the ground work for the feature, starting with the 2D energy yield calculation model and later on the 3D layout in RatedPower.
- ➔ The project is still in development, with no release date available yet. The methodology described in this presentation may change.



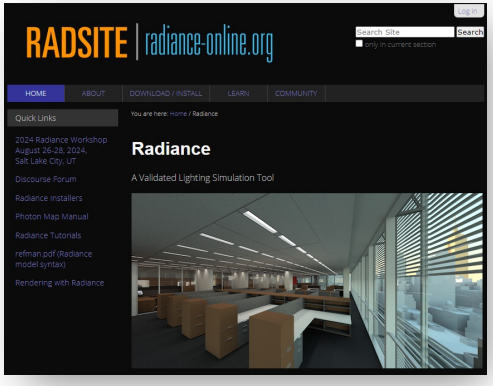
The irradiance calculation model

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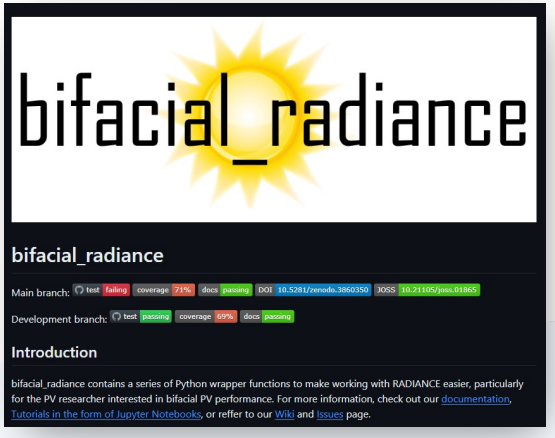
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Why Radiance?

The challenge: we want something which can calculate irradiance in a 3D scene, for the front and back face. And we do not want to implement it ourselves.



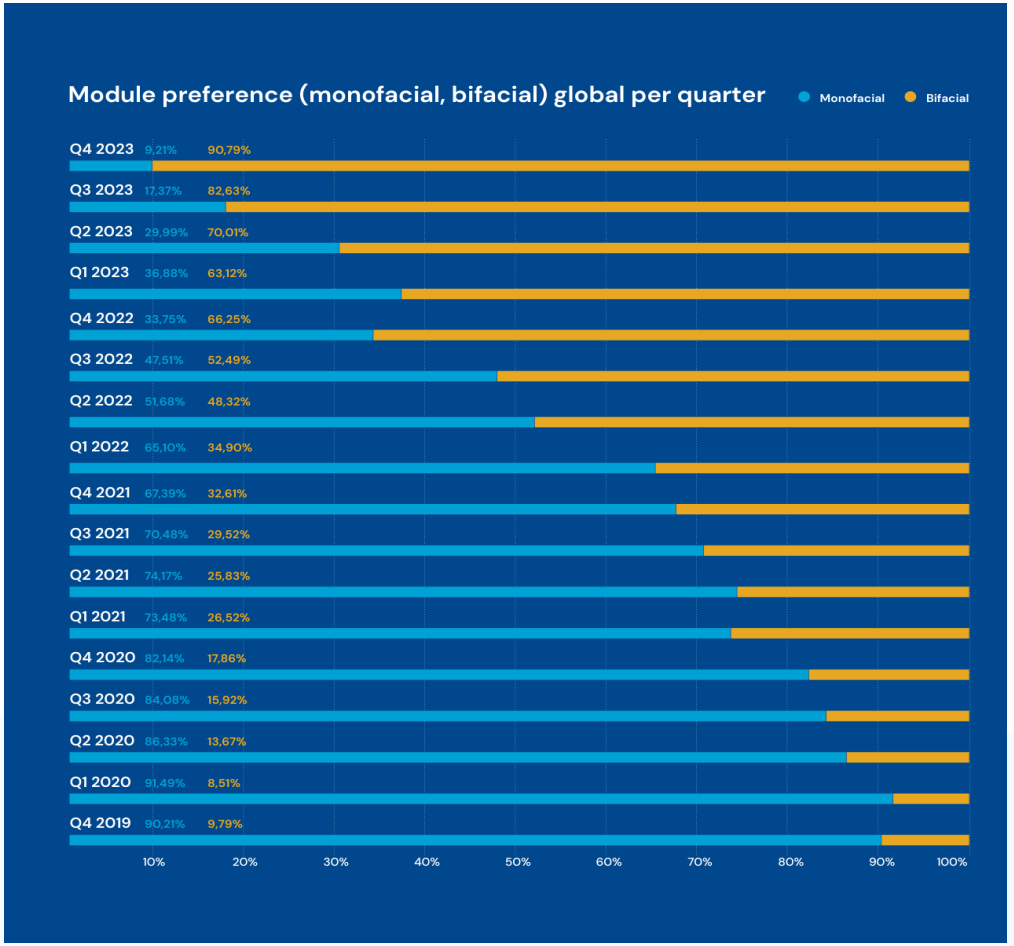
- ➔ We looked at several options at the beginning of the project.
- ➔ Radiance was chosen because it has accuracy as a goal and because it is well-known in the PV industry.
- ➔ The bifacial_radiance project was the basis to help us understand how Radiance works.
- ➔ Radiance is validated and is focused on photometrically correct rendering. It still is the best lighting simulation tool if accuracy is the main goal.



(1) Radiance — Radsite (radiance-online.org)
(2) NREL/bifacial_radiance: Toolkit for working with RADIANCE for the ray-trace modeling of Bifacial Photovoltaics (github.com)
(3) A comparison between Radiance and other rendering engines (thinkmoult.com)

Bifacial dominance

90% of all simulations in RatedPower use bifacial modules

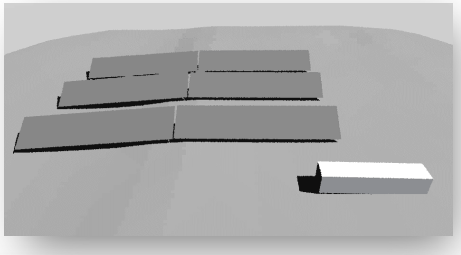


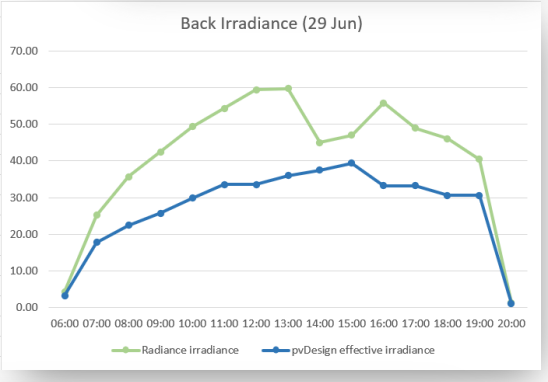
(1) RatedPower, 2024 Trends Report: Renewable Energy and Solar Research Report

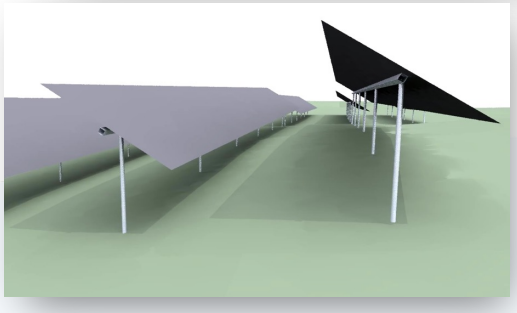
Why it matters

Pros and cons of using Radiance for utility-scale PV plants

- ➔ Ray tracing for the back face means we consider edge effects and the impact of terrain. The back face is a first-class citizen in this model.
- ➔ We can also model the effects of back face obstructions such as piles and torque beam with higher accuracy than before.
- ➔ We can easily include shading objects in the simulation, Radiance is agnostic to geometry.
- ➔ But including other losses, such as the horizon profile or the IAM loss, is more difficult.
- ➔ And it is orders of magnitude slower than other methods.

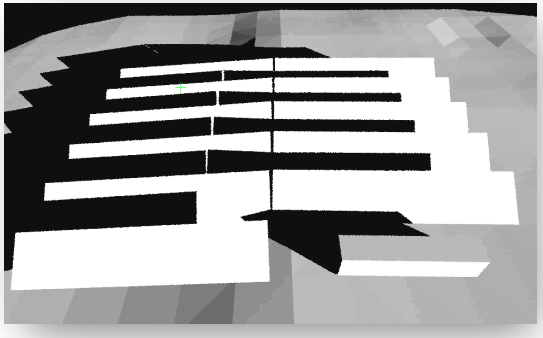




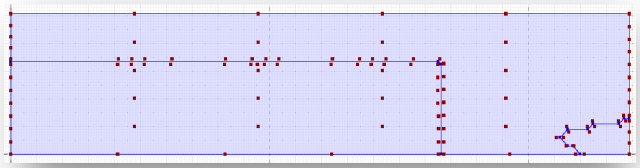


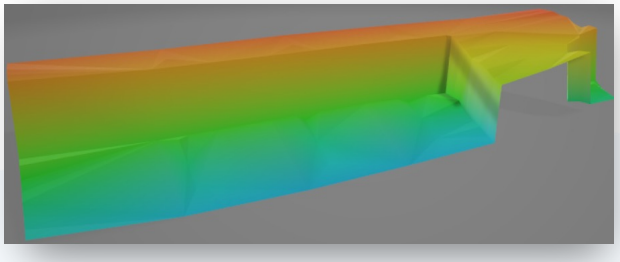
How we use Radiance

The starting point is the 3D model produced by RatedPower. We place sensors and measure irradiance values in the structures.



- We use a sensor positioning strategy which minimizes the number of sensors needed to model the distribution of irradiance on the table.
- We then build a surface using the results at each sensor, to calculate the irradiance in positions where we did not place a sensor.
- The surface is modeled as a triangular irregular network (TIN), where the sensor measurements are the vertices.
- Occlusion testing is used to determine which parts of the structure are shaded.

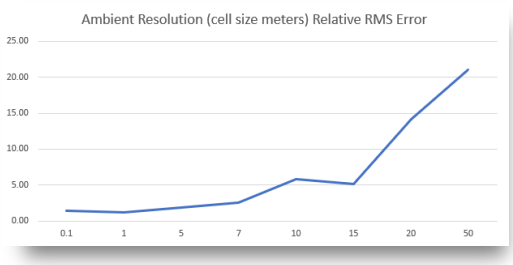


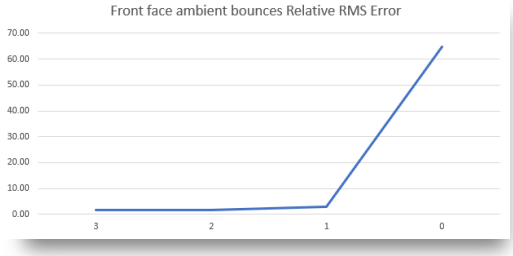


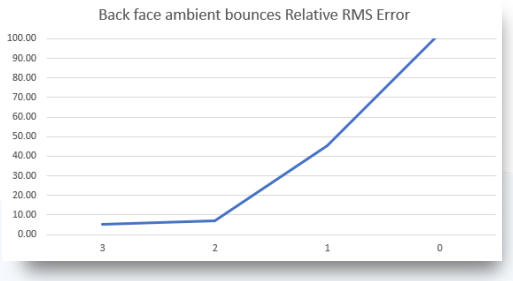
The challenge of Radiance parameters

Running a Radiance simulation of a PV plant is slow. We wanted to make it faster by tweaking the parameters of the rtrace command.

- ➔ A sensitivity study was needed to find which parameters have the highest impact on simulation time.
- ➔ We decided to use different parameters for the front and back face.
- ➔ Ambient bounces parameter is key for the back face.
- ➔ The ambient resolution should be adjusted depending on plant size.
- ➔ The Radiance cache (illuminance interpolation) can cause accuracy issues if the parameters are not correct.
- ➔ The parameters have a very significant impact on the results.







Electrical calculation model

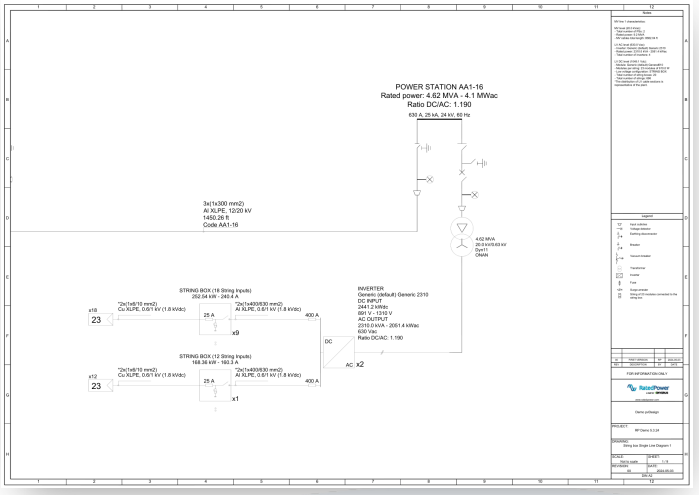
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Making the most out of Radiance

We want an electrical model which is up to the same level of detail as the irradiance calculation.

- ➔ For each module, we know how many PV cells are shaded, and the irradiance level at front and back face.
- ➔ Thanks to the RatedPower layout calculation model, we have a fully fledged electrical model with cables, combiners, MPPTs, inverters, transformers, and an MV network.
- ➔ We want to simulate as much of it as possible.
- ➔ These calculations will be time consuming, lots of optimizations required.



The challenges in implementing the electrical model

We ran into issues which we did not have before in the 2D model.

- ➔ We had to model PV modules at the substring level.
- ➔ Implemented a flexible DC array electrical model, with serial and parallel connections, to find the MPP.
- ➔ It soon became clear that a faster one diode model implementation was required (we were using a root finder).
- ➔ The Lambert W-function one diode model formulation gives us the required performance.
- ➔ We also had to simplify the DC array electrical topology. Too many series-parallel sequences negatively impacted performance.

4.1. Analytic and Numerical Solutions for Single Diode Equation

Eq. (1) cannot be solved for current (or voltage) explicitly using elementary functions. However, current can be expressed as a function of voltage $I = I(V)$ (or $V = V(I)$) by using the transcendental Lambert's W function [23] as presented by several authors ([24], [25]). Lambert's W function is the solution $W(x)$ of the equation $x = W(x)\exp[W(x)]$. Using this function we may write $I = I(V)$:

$$I = \frac{R_{SH}}{R_{SH}+R_S}(I_L + I_O) - \frac{V}{R_{SH}+R_S} - \frac{nV_{th}}{R_S} W\left(\frac{R_S I_O}{nV_{th}} \frac{R_{SH}}{R_{SH}+R_S} \exp\left(\frac{R_{SH}}{R_{SH}+R_S} \frac{R_S(I_L+I_O)+V}{nV_{th}}\right)\right) \quad (9)$$

or $V = V(I)$; see Appendix A for the derivations.

$$V = (I_L + I_O - I)R_{SH} - IR_S - nV_{th} W\left(\frac{I_O R_{SH}}{nV_{th}} \exp\left(\frac{(I_L + I_O - I)R_{SH}}{nV_{th}}\right)\right) \quad (10)$$

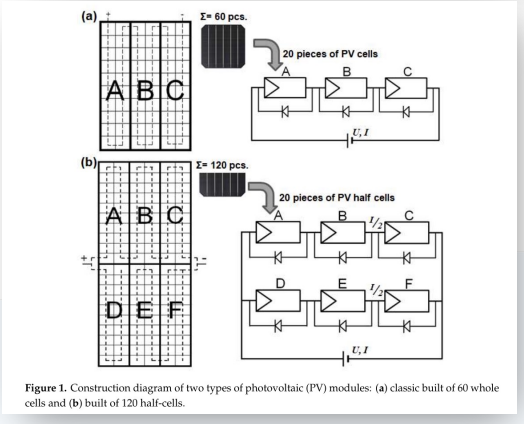


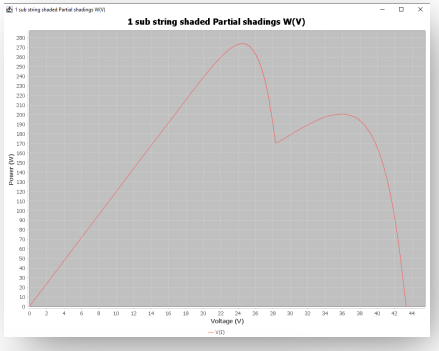
Figure 1. Construction diagram of two types of photovoltaic (PV) modules: (**a**) classic built of 60 whole cells and (**b**) built of 120 half-cells.

(1) Hansen, Clifford. Parameter Estimation for Single Diode Models of Photovoltaic Modules.
(2) Sarniak, Mariusz T. Modeling the Functioning of the Half-Cells Photovoltaic Module under Partial Shading in the Matlab Package

What we are modeling

In its current iteration, the electrical model can simulate the PV plant down to the module level. The implementation was a programming challenge.

- ➔ The irradiance level is measured for each module.
- ➔ Partially shaded modules have two measurements (one illuminated, one shaded), and we count the number of cells under each irradiance level.
- ➔ The cell temperature is modeled using the Faiman model.
- ➔ The cable resistance is modeled using the RatedPower layout cable sizing (we know the length and section of each cable).
- ➔ Starting at the inverter, we use the same models as in the regular 2D model (multi MPPT, clipping, efficiency model).



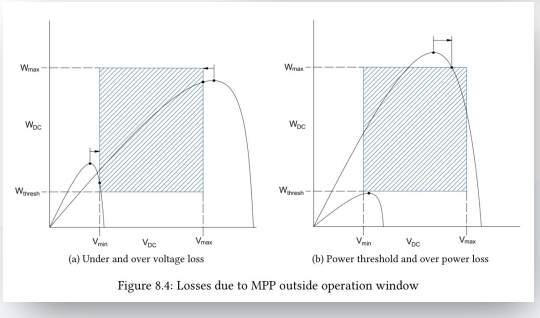
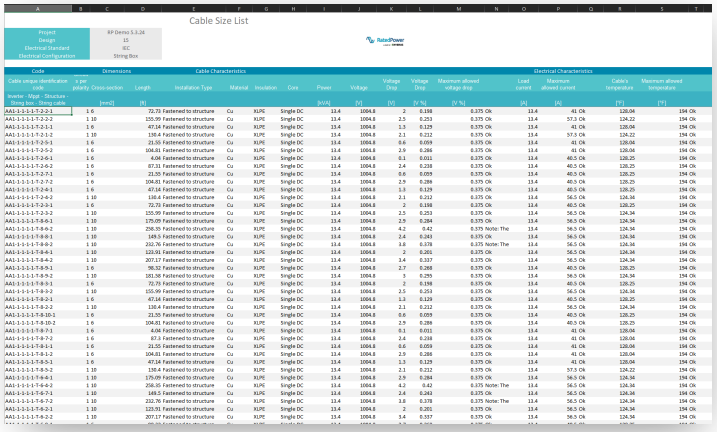


Figure 8.4: Losses due to MPP outside operation window

What we get out of the model

Modeling the electrical system at this level of detail can tell us a lot about the quality of the design

- ➔ We can compare the production of partially shaded modules to the output of unshaded modules, getting loss values for individual structures.
- ➔ It is possible to get the electrical losses of individual cables in the DC and AC systems.
- ➔ Individual inverters can be assessed in high levels of detail. Also, the MPPT configuration can be evaluated.
- ➔ All this information will help users improve their PV plant designs.
- ➔ We can not get the same level of details as before for shading losses (Radiance gives us effective irradiance, without intermediate steps).



Terrain-aware backtracking

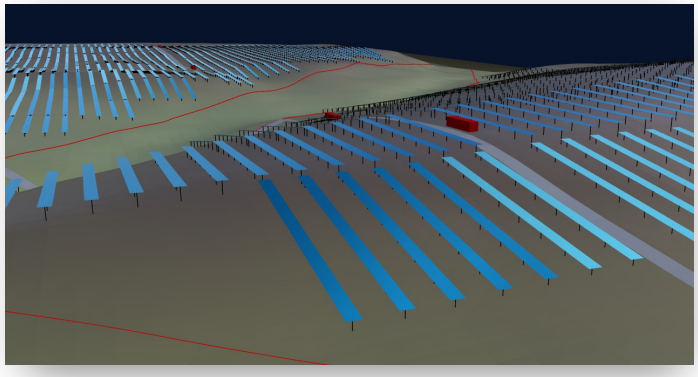
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Why it matters

For PV plants using SAT, a simulation with this level of detail does not make sense without terrain-aware backtracking.

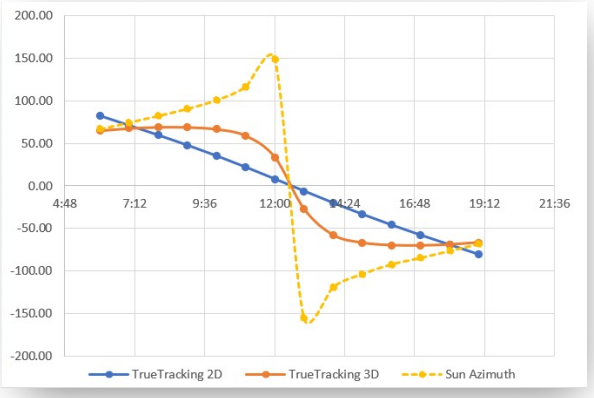
- ➔ The simulation using terrain-aware backtracking gives completely different results in complicated terrain, not just because of shading but also because of the incidence angle.
- ➔ With Radiance it is easy to model trackers with individualized tracking angles.
- ➔ So, the challenge is to implement the algorithm and validate it.
- ➔ We decided to implement the irradiance model first, and then use it to validate the terrain-aware backtracking algorithm.

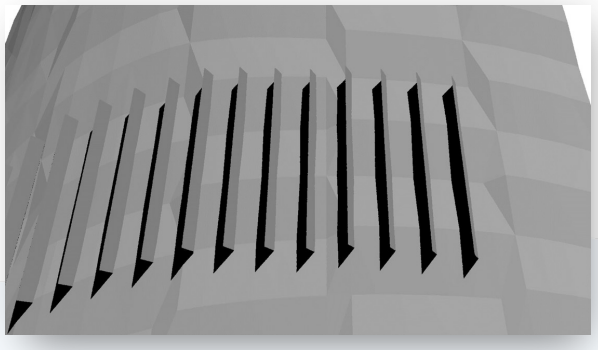


Terrain-aware backtracking implementation

There is not much literature about commercial solutions, or data we can use for validation.

- ➔ The starting point was the slope-aware backtracking formulation (1).
- ➔ It does not exactly match our use case, since the axis of trackers may be misaligned in complicated terrain. We decided to implement it anyway and evaluate the results; so far, we have not observed significant tracking errors. We plan on reformulating if necessary.
- ➔ We then had to figure out how to calculate the tracking angle considering all the trackers behind which may be affected, in a plant with arbitrary tracker placement.





(1) Anderson, K. and Mikofski, M. , Slope-Aware Backtracking for Single-Axis Trackers

Project status and next steps

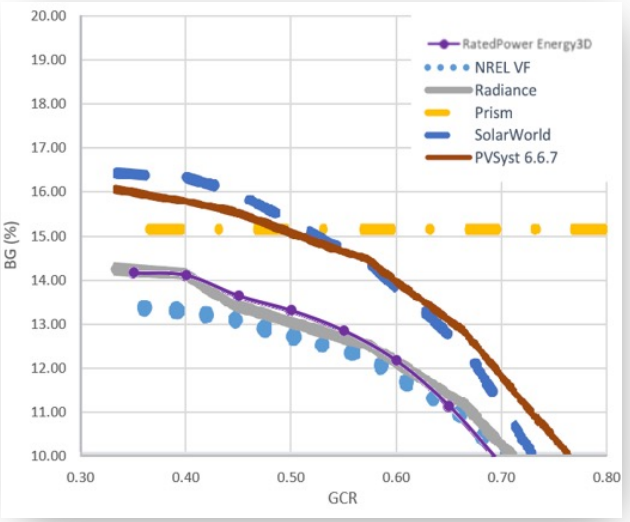
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What comes next?

Work in progress!

- ➔ As of May 2024, all the components of the calculation model have been integrated and we can run simulations.
- ➔ Work is ongoing in the cloud infrastructure.
- ➔ As we start running simulations, we will transition into a validation stage.
- ➔ We will start validating against the 2D model, and against other software. We will also do intensive internal validation using the model outputs. We would like to validate against real-life PV plant data, but it is challenging to do so.
- ➔ We will release an in-depth calculation methodology, in line with our current methodology document.



(1) S. A. Pelaez, C. Deline, S. M. MacAlpine, B. Marion, J. S. Stein and R. K. Kostuk, Comparison of Bifacial Solar Irradiance Model Predictions With Field Validation

Thank you!

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