Light and Shade – A hemicube approach for efficient shading calculations in utility-scale PV plants

Conference Paper · September 2023

DOI: 10.4229/EUPVSEC2023/4DO.1.2

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40th European Photovoltaic Solar Energy Conference and Exhibition

This presentation was selected by the Sc. Committee of the EU PVSEC 2023 for submission of a full paper to one of the EU PVSEC's collaborating peer-reviewed journals.

LIGHT AND SHADE – A HEMICUBE APPROACH FOR EFFICIENT SHADING CALCULATIONS IN UTILITY-SCALE PV PLANTS

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ABSTRACT: Accurate estimations of the energy production in the planning and design stage of photovoltaic (PV) plants require advanced models to simulate shading effects. This is particularly important for plants located in complex and irregular terrain, or plants that are affected by nearby shading obstacles. This paper presents a hemicube approach for calculating shading effects and assesses the model accuracy and performance for utility-scale PV plants. The validation of the model includes a sensitivity analysis of the model's computational efficiency and modelling accuracy for several fictitious power plants of diverse nominal capacities. The advanced shading model presented in this work can accurately estimate energy yield in PV plants in the pre-construction design and engineering stages to reduce financial risk for projects in locations with complex shading characteristics.
Keywords: modelling, shading, PV plant design

1 MOTIVATION

Utility-scale PV plants are being installed at locations where shading effects are becoming a significant driver for the layout design [1]. An accurate energy production assessment is utterly important to make financial decisions, where near shading effects considerations are made to evaluate the cost for civil terrain grading to reduce shading effects versus the energy production of the plant in more complex terrain without grading.

Simple models designed to estimate row-to-row shading in simple terrain are very fast, but not designed for modelling edge effects in PV plants and cannot consider complex shading effects for plants installed on complex terrain or shading from arbitrarily complex shading obstacles. In this work, we discuss the ability of a hemicube shading model to estimate shading effects and look at computational efficiency versus accuracy of a hemicube model when simulating utility-scale PV plants of diverse nominal capacities.

2 HEMICUBE MODEL

A hemicube can be used to represent a 360 ° view from a surface or point, here some specific target points on a PV module. For each target point we place an imaginary hemicube (half a cube) centred on the target point. For each face of the cube, we start with a white face and then render any object that can be broken down into triangles, like the terrain, complex 3D shading objects and racks with PV modules, into plain black silhouettes where the objects project on to the hemicube face. The hemicube reference system is defined by the orientation of the PV module so this can vary across a PV plant or even be time-dependent when modelling tracker systems. Each azimuth and zenith combination of the sun's position can be mapped to a pixel on one of the sides of the hemicube once the sun position is converted into the hemicube reference system. If the pixel is white, we can say the target point is not shaded, or if black it is shaded by an obstacle for a given sun position.

2.1 Rendering the hemicube sides

Four renderings (one for each of the side faces of the hemicube) are performed. Therefore, four camera positions are required – the camera's up vector for each face is pointing directly up the z-axis from the x-y plane. The camera's direction vectors point North, East, South and West from the target point for each of the four side faces.

Figure 1 shows the virtual hemicube (shown using dotted lines). The camera's viewport is shown with blue lines. The render surface is shown in red.

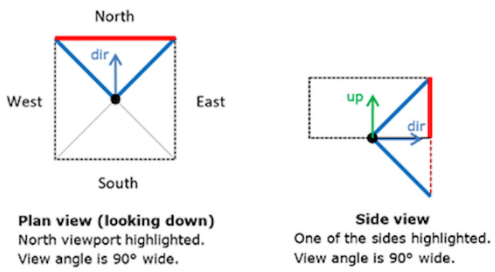

Figure 1: Sketch of hemicube for rendering the side face pointing North.

The view angle is 90 ° wide (45 ° to the left and right, 45 ° up and down). The render canvas is square. Only the top half (above the horizon) is used. This results in 4 black and white images, one for each side, as shown in Figure 2. These can be combined into a single side image.

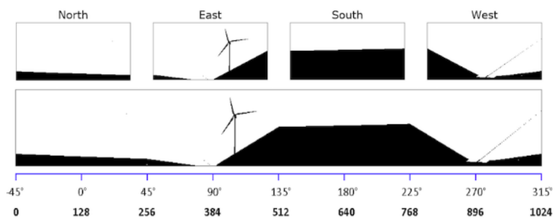

Figure 2: Images of rendered shading scene for hemicube sides and resulting side image.

For a given sun azimuth γ_z and zenith angle θ_z defined in the hemicube reference system, we can calculate an index into the side image for a fixed cube resolution *CubeRes*. The x_{side} of the image for azimuth values between -45 and +45 is calculated as:

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$$x_{side} = \frac{CubeRes}{2} + \left(\tan\gamma_s * \frac{CubeRes}{2}\right)$$

Then, depending on the quadrant's azimuth, the appropriate multiple of *CubeRes* is added to offset into the correct quadrant of the image.

The y_{side} of the image depends on both the θ_z and γ_z values and is calculated as:

$$y_{side} = \frac{CubeRes}{2} * \frac{\cot\theta_z}{\cos\gamma_s}$$

For certain combinations y_{side} will be greater than the height of the image, especially when θ_z gets below a certain angle (when the sun is higher in the sky). In this case we must index into the top face of the cube.

2.2 Rendering the hemicube top face

This time the camera is pointed directly upwards (perpendicular to the x-y plane) with a view angle of 90 ° as illustrated in Figure 3.

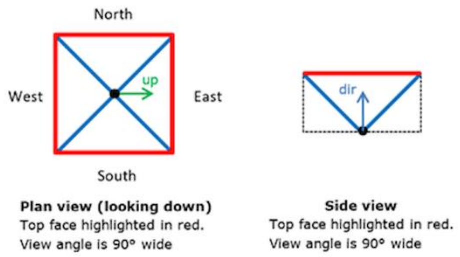

Figure 3: Sketch of hemicube for rendering the top face for cases when solar zenith angle is higher in the sky.

To index into the top image (of resolution *CubeRes* * *CubeRes*):

$$x_{top} = (\tan\theta_z \cos\gamma_s + 1) \times \frac{CubeRes}{2}$$

$$y_{top} = (\tan\theta_z \sin\gamma_s + 1) \times \frac{CubeRes}{2}$$

For all sun azimuth γ_z and zenith angle θ_z combinations, it is possible to index into the appropriate image (side or top) and extract the pixel value (black for shaded or white for unshaded) to estimate whether a target point is shaded.

2.3 Diffuse shading

The hemicube rendering used in the direct shading calculation above can also be used to determine the contribution by diffuse light from the sky for a target point. However, this needs to compensate for the hemicube's shape (the effect that perspective has on the areas of the pixels) and also take the angle that the light is falling on the module's surface into account. A weighting map is constructed that contains the appropriate weighting for each pixel in the hemicube, so they we can more accurately sum their contribution to the diffuse light shining on the target point, see Figure 4.

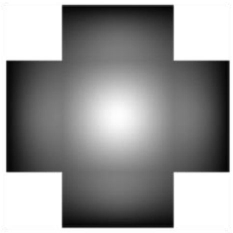

Figure 4: Weighting map for the diffuse light contribution for each pixel of the hemicube

For each target point we use the hemicube rendering used previously for the direct shading calculation. For each lit pixel (showing the white sky) in the hemicube we sum the corresponding weighting value from the weighting map. This results in a value between 0.0 and 1.0. This is the diffuse contribution for the target point.

2.4 Storing the results in a lookup table

The beam shading and diffuse values for each hemicube are compressed and stored in an efficient lookup table. Then, for the solar position of each timestamp of the energy calculation, a lookup is done for each target point for each timestamp to determine if it is shaded, rather than executing a complex shading calculation. This allows to easily handle multi-year and sub-hourly calculations without any additional shading calculations.

3 MODEL ACCURACY FOR BEAM SHADING

The most shaded cell in a PV submodule determines how much current can pass through the whole submodule as all the cells are connected in series. Therefore, the irradiance of the most shaded cell is needed to calculate I-V curves for all individual strings in a PV plant to estimate electrical mismatch and inverter losses; and so multiple hemicubes need to be placed on each submodule. To investigate the accuracy of the model to detect row-to-row shading cases, the proportion of a short row of modules directly shaded from a much longer row of modules in front has been compared to an infinite sheds model for a fixed-tilt site with monofacial modules in horizontal terrain for different resolutions of shading target points. The site details are summarised in Table 1.

Table 1: PV design characteristics of the test site.

Module	Number of cells	60
	Number of bypass diodes	3
	Orientation	Portrait
	Technology	Si-mono, monofacial
Rack system	Tilt	40 °
	Azimuth	180 °
	GCR	0.5

We have implemented the hemicube method in DNV's SolarFarmer software [2] and use this package to generate the results presented below. We compare the detection of row-to-row shading cases to an infinite sheds model [3], [4] where this is derived geometrically. The simulation period is 1 year and the time resolution is 1 hour. Additionally, the irradiance of the most shaded cell in the sub-modules is used in the comparison as this defines the

I-V curves going into the power calculation.

The number of hemicube shading target points used in the comparison is varied between 1 per module and 9 per cell. The location of the target points on a single module is shown in Figure 5.

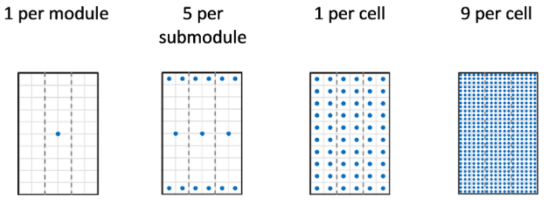

Figure 5: Location of shading target points on a single module.

The number of time stamps by time of day where shading of the direct irradiance is detected is shown in Figure 6 for the hemicube model with different shading target point resolutions and an infinite sheds model. Given the location of the target point in the module centre, the “1 per module” resolution can only detect shading cases where at least 50 % of the module is shaded. This results in no shading cases being detected in the morning where the average shaded proportion of the module is small according to the infinite sheds model. Adding target points in the corner cells of the submodule as in the “5 per submodule” or “1 per cell” resolutions improves the detection of the shading cases. However, given the location of the lowest target point at 5 % of the module height for a module with 60 cells, only cases where the shade line exceeds this proportion can be detected. This can be seen at 09:00 where the average shading proportion is only 4 % so both methods can only detect some of the shading cases. Using a “9 per cell” resolution allows to detect cases where less than 5 % of the module are shaded so this resolution gets close to the infinite sheds model.

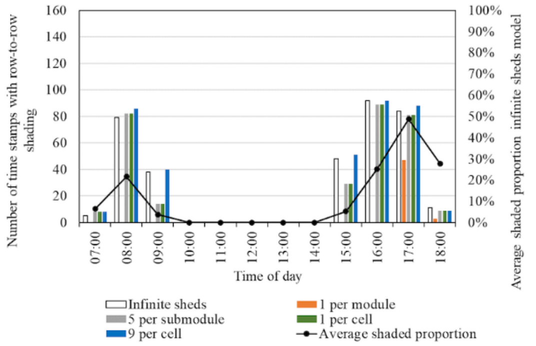

Figure 6: Number of row-to-row shading cases (bars) detected by hemicube model for different target point resolutions and infinite sheds model and average shaded proportion from infinite sheds model (line) by time of day.

The irradiance for the most shaded cell in a submodule is needed for correctly modelling the power output so the methods are compared for the irradiance of the most shaded cell in Figure 7. The most shaded cell irradiance considers shading of the direct and diffuse components so the hemicube model cannot be directly compared to the infinite sheds model as the shading for the diffuse irradiance is calculated differently. With the “1 per module” method not accurately detecting row-to-row shading cases, it tends to overpredict the irradiance while all other resolutions give almost the same results.

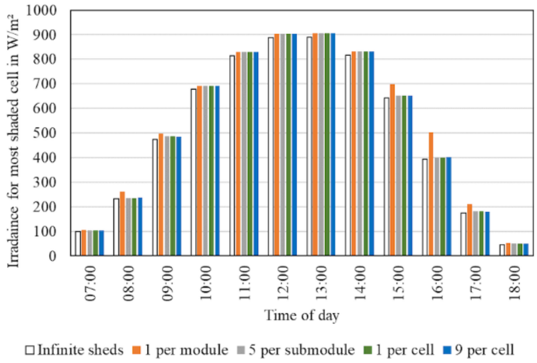

Figure 7: Irradiance for most shaded cell in back-row modules for infinite sheds model and hemicube model with different target point resolutions by time of day.

The detected number of row-to-row shading cases of the direct irradiance and the irradiance of the most shaded cell are summarised in Table 2 for all models and resolutions. The “1 per module” resolution detects only 14 % of the row-to-row shading cases for the direct irradiance compared to the infinite sheds model and overpredicts the irradiance for the most shaded cell by 3.5 % compared to the highest resolution. The additional use of the submodule corner points improves the detection of row-to-row shading cases and brings the modelled irradiance of the most shaded cell very close to the results of the “9 per cell” resolution. The hemicube model with “9 per cell” resolution detects slightly more shading cases than the infinite sheds model. This is caused by the chosen hemicube resolution.

Table 2: Number of detected direct shading cases and irradiance for most shaded cell for infinite sheds and hemicube model with different target point resolutions. The annual average global unshaded irradiance is 544.3 W/m².

Shading model	**Number of detected shading cases**	**Average irradiance for most shaded cell in W/m²**
Infinite sheds	357	511.9
Hemicube		
1 per module	50	540.4
5 per submodule	312	522.0
1 per cell	312	522.0
9 per cell	374	522.0

4 MODEL PERFORMANCE

We have run simulations for utility-scale test sites with SolarFarmer and measured the effect on the results for an annual energy yield estimation and the time to run the shading part of the simulation for different target point resolutions. The test sites are all theoretical sites in flat terrain without any shading obstacles. The site statistics are summarised in Table 3. The total number of shading target points ranges from 16,800 for the smallest site modelled with the “1 per module” resolution to

196,992,000 for the largest site modelled with the "9 per cell" resolution.

Table 3: Characteristics of tests sites used for performance testing

AC capacity in MW	5	20	100
Number of modules	16,800	73,440	364,800

The increase in the shading calculation time relative to fastest method with only 1 per module is shown in Figure 8. As expected, the simulation time scales directly with the number of shading target points and the number of modules in the PV plant.

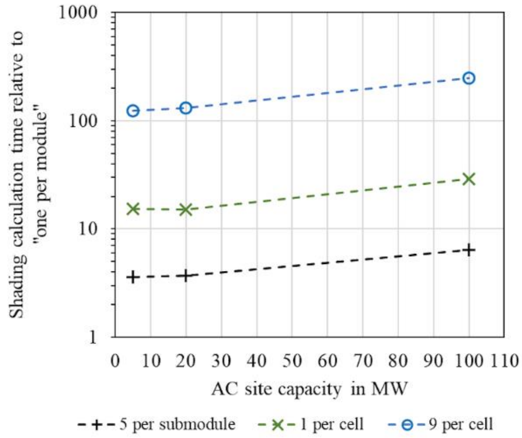

Figure 8: Increase in calculation time for different target point resolutions relative to the fastest "1 per module" method.

To assess the sensitivity of the modelled annual energy production depending on the shading target point resolution, the energy yield in kWh/kWp has been compared to the results using the highest resolution of 9 shading target points per cell as this is expected the most accurate. As shown in Figure 9, the "1 per module" resolution has the largest difference of 0.1 % to 0.2 % whereas the higher resolution methods show almost no difference compared to simulations with the "9 per cell" resolution.

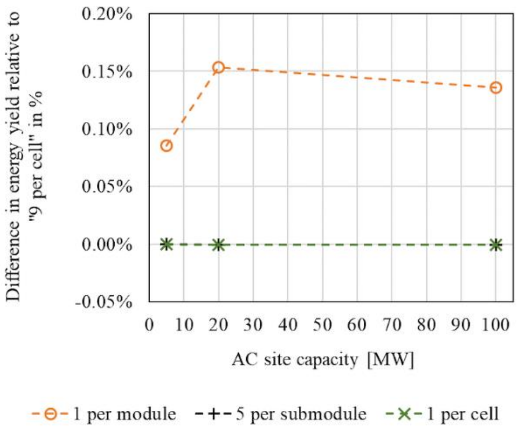

Figure 9: Difference in energy yield relative to "9 per cell" shading target point resolution.

5 CONCLUSIONS

The aim of this paper was to present a hemicube-based rendering model to account for near shading in fixed-tilt PV plants. The sensitivity of relevant parameters (e.g., target point resolution) of the proposed model was evaluated in terms of accuracy and computational performance as a function of PV project capacity. The results demonstrated that hemicube-based rendering models are suitable to estimate shading effects for utility-scale PV sites that are affected by row-to-row shading or shading caused by nearby terrain features or shading obstacles. Although such models can be computationally costly, a smart choice of shading target points helps to reduce simulation time while keeping an appropriate model accuracy to enable PV plant designers making the layout choice and reduce financial risk. It was found that using a shading target point resolution of "5 per submodule" represented a good compromise between accuracy and simulation time for energy assessments of utility-scale PV plants.

More information about the hemicube model, extended simulation results, and validation against operational data are available in [5].

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10.4229/EUPVSEC2023/4DO.1.2
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