

SPICE Simulation of Thin-Film Solar Cell Modules

User's Guide

Elliott Ivan Gurrola
Sourabh Dongaonkar

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Introduction

Gap between cell and module efficiencies is a significant hurdle in commercial success of thin film PV technologies. A key factor responsible for the reduction of large panel efficiency in comparison to small lab scale cells is parasitic shunt leakage phenomenon. These localized shunt paths vary significantly in magnitude from one cell to the other, and this magnitude follows a lognormal distribution. The performance of the panels is also determined crucially by the sheet resistance of the transparent contact materials.

In order to study the combined effect of series and shunt resistance a spice modeling framework is needed, which can include the cell characteristics and predict panel performance including series and shunt resistance effects. A typical thin film panel of size $L_{\text{panel}} \times W_{\text{panel}}$ has N_{series} cells are connected in series (Figure 1.1a). For simulating the panel we subdivide each cell into N_{parallel} subcells of width $W_{\text{panel}}/N_{\text{parallel}}$ and length $L_{\text{panel}}/N_{\text{series}}$. Each of these subcells is represented by the equivalent circuit in Figure 1b, and these are connected in series and parallel using the sheet resistance values.

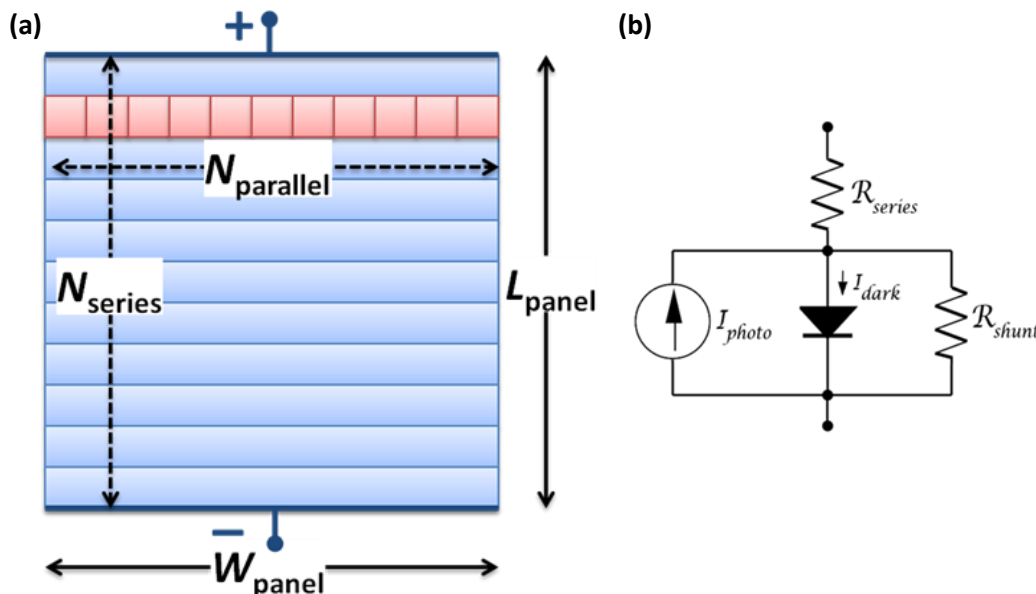


Figure 1.1: (a) Schematic of a thin film PV panel, showing the series and parallel connections of subcells. (b) Equivalent circuit used for each subcell showing the photo and dark current components and parasitic shunt and series resistances.

The full two dimensional network of cells is simulated, using Berkeley spice3 circuit simulator, to obtain the panel characteristics. The tool allows the user to vary shunt distributions, and provide different sheet resistance values, along with external factors like irradiance and ambient temperature, to evaluate the panel performance under different conditions. The outputs are displayed using the rappture interface and provide insight into panel operation and efficiency loss mechanisms. Moreover, all outputs of the spice simulations, as well as the spice input deck are available for download after the simulations for further processing or simulations.

Simulator Inputs

This simulator utilizes a user-friendly graphical user interface with several inputs that can be manipulated to analyzed different shunt current distributions and series resistance effects. This document will explain utilization of each of the given input parameters.

Section 1: Panel Configuration

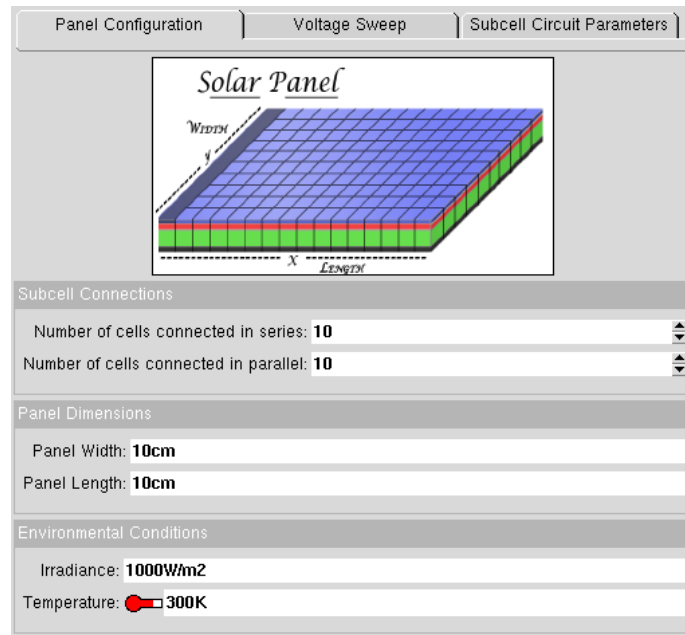


Figure 2.1: First input section found in this simulation tool

This section configures how will the given solar module will be subdivided and set the environmental conditions such as the temperature and the irradiance of the sun.

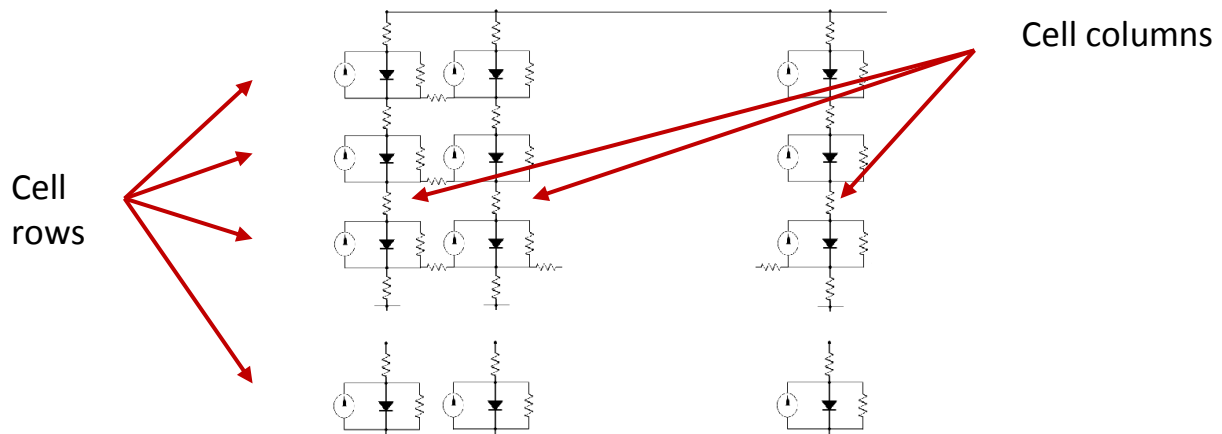


Figure 2.2: Row and column division on a solar module

Number of cells connected in series: As its name says, this parameter specifies the number of cells to be placed in a series. This determines the the voltage supplied by the module. Refer to figure 2 for a visualization of cell rows. A rough estimate of the panel open circuit voltage can be obtained by the value of this parameter, because the panel $V_{OC,panel} \sim N_{series} V_{OC,cell}$.

Number of cells connected in parallel: This parameter specifies the number of parallel subcells used for simulating a single cell. This will determine the resolution with which each large area cell is simulated in the system.

Panel Width: This parameter specifies the panel's width dimension. Typically in panels with a single row of cells, this will be equal to the width of each cell. The default units of this parameter are centimeters. However, Rapture can automatically convert other standard units of length into centimeters.

Panel Length: This parameter specifies the panel's length. It is measured in the same direction as the number of rows. This dimension along with the number of series connected cells will determine the length of each individual cell. The units of this parameter should be in centimeters.

Irradiance: Specifies the power per unit area that the solar module is receiving. This parameter is used to find the panel's efficiency, and might be changed according to local irradiance conditions, depending on time of day for example. The default value is set to 1000 W/m^2 for AM1.5G.

Temperature: Ambient temperature, this will change the behavior of the diodes used to simulate the solar cells. Resistive elements are not temperature dependent. The default value of this parameter is 300 K which occurs at room temperature. The user can also provide other units like degrees Celsius.

Section 2: Voltage Sweep

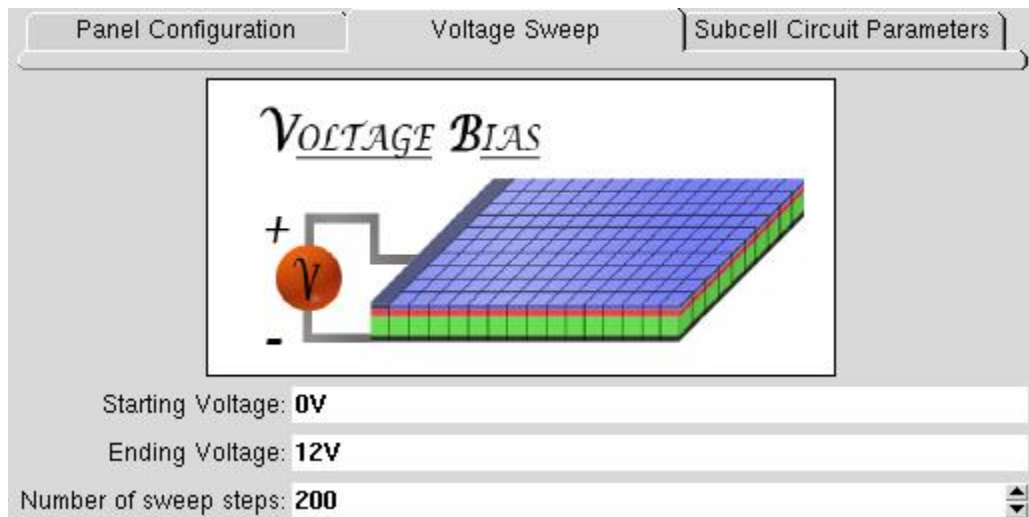


Figure 2.3: Voltage sweep input parameters

This section allows the user to set the proper voltage sweep at which the solar module will be simulated.

Starting Voltage: Minimum voltage for the I-V sweep. The input units are in volts. To ensure the proper calculation of all values select a value equal or smaller than 0 V. If this value is set higher than 0, then the short circuit current will not be calculated, and all values dependent on it will not be displayed such as the Fill factor.

Ending Voltage: Maximum voltage for the I-V sweep. The input units are in volts. If this value is too low, the open circuit voltage will not be reached and several calculations will not be performed. Also, the calculated maximum power / efficiency may not be correct for the given panel. This value should be greater than $N_{series}V_{OC,cell}$, to ensure that the module parameters are calculated properly.

Number of sweep steps: As its name implies, this number sets the number of points on the IV sweep. Internally, the program will calculate the step size based on the formula:

$$StepSize = \frac{EndingVoltage - StartingVoltage}{(NumberOfSteps - 1)}$$

A value between 100 and 200 is recommended. Increasing the number of steps will provide slightly better module parameters, at the cost of higher simulation time.

Section 3: Subcell Circuit Parameters

This section contains the different parameters of the typical lumped circuit elements used to model individual solar cells. It is divided into four sub sections, one for each element see Fig. 5 for reference. The photocurrent (I_{photo}) is determined by the by irradiance value, and the diode characteristics contain the material information. The parasitic components are shunt and series resistance which are varied for obtaining the module performance.

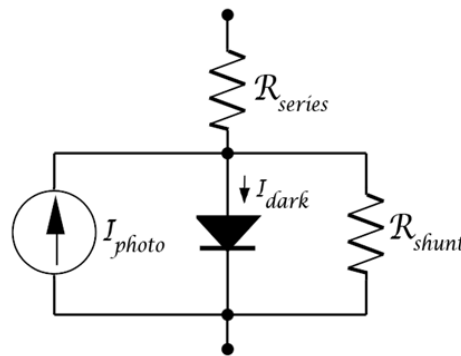


Figure 2.4: Equivalent solar cell circuit

Section 3.1: Photocurrent Value

Figure 2.5: Photocurrent parameters

The photocurrent corresponds to the current source in the equivalent circuit model.

Vary Photocurrent Values? This function allows the user to vary the amount of photocurrent generated by each current source. This variation would occur due to a misalignment of the solar panel or due to a degrading photocurrent generation. If this feature is set to **NO** the user will need to input a constant **Photocurrent Value** with units of A/cm². A typical value is to have a 0.010 A/cm². If this feature is activated, set to **YES**, the user will need to provide **Minimum and Maximum Value**. Internally, the code will do a linear increment of the current sources after calculating the step size. Current sources are increased from left to right, refer to figure 3.

Note: The ending value may be smaller than the starting value.

Number of shaded cells in parallel: In order to use the shading feature, the user must specify the number of columns and rows that should be shaded and specify the attenuating factor using the **Percentage Shading** option. This value sets the number of columns that will be shaded (starting on the left side of the module)

Number of shaded cells in series: Similar to the previous parameter, this value sets the number of rows that will be shaded (starting on the bottom of the module).

Note: Setting any of these configurations to zero will remove the shadowing effect.

*Note 2: The **Percentage Shading** option will proportionally reduce a current source's value by the specified percent:*

$$NewCurrent\ Value = InitialValue \left(1 - \frac{\%Shading}{100} \right)$$

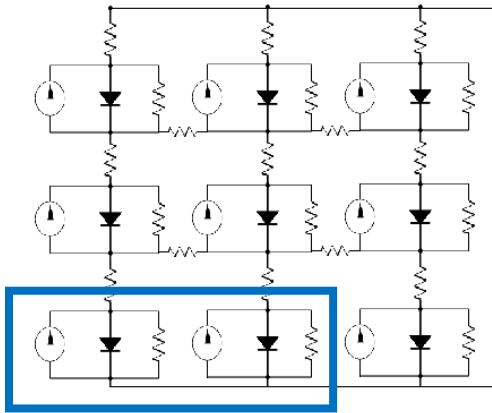


Figure 2.6: A 3 by 3 solar panel with two cells shaded in parallel and one cell shaded in series.

Section 3.2: Diode Parameters

Photocurrent Value	Diode Parameters	Sheet Resistance	Shunt Resistance
Saturation current density: 1e-14A/cm2			
Ideality Factor: 1.5			
Breakdown Voltage: 10			
Absorber Bandgap: 1.1			

Figure 2.7: Ideal diode parameters

This section customized the diodes used in the lumped equivalent circuit.

Saturation Current density: following Shockley's Diode equation:

$$I = AJ = AJ_s \left(e^{\frac{qV}{nkT}} - 1 \right)$$

The current flowing through the diode is determined by its saturation current density J_s , with units A/cm^2 . The code will internally calculate the area of an individual cell (from the number of series and parallel cells, and panel length and width) to obtain the diode current of each cell.

Ideality Factor: This is the n parameter found in the Shockley Diode equation above, and is determined by the nature of recombination inside the cell. For most cases the value should lie between 1 and 2.

Breakdown Voltage: In case of partial shadowing of a panel, the shaded cells can go into reverse bias. In order to simulate the cells under reverse bias, the code needs a reverse breakdown voltage for the technology, which should be few tens of volts for most materials.

Absorber Bandgap: The saturation current density J_s depends on the absorber bandgap as . In order to simulate the temperature effect on the module, correct bandgap of the absorber must be specified in eV. The default is set to 1.1eV for Si (or CIGS) based cells.

Note: the temperature parameter can be configured as shown in section 1.

Section 3.3: Sheet Resistance

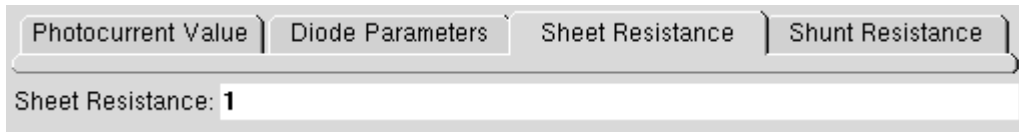


Figure 2.8: Sheet resistance

This simulator uses external contact sheet resistance to make the series and parallel connections in cells to form a panel. There are two internal sheet resistances, vertical and horizontal sheet resistance as shown in figure 9.

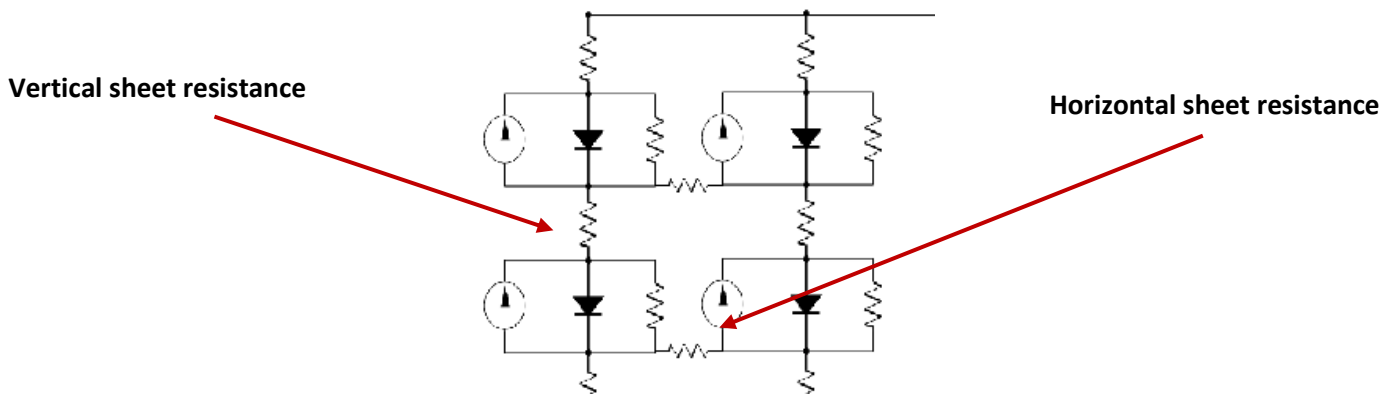


Figure 2.9: Vertical and horizontal sheet resistance

The values of each resistor are calculated from the resistivity formula

$$R = \rho \frac{L}{A} = \rho \frac{L}{WH} = R_{\square} \frac{L}{W}$$

where R_{\square} is the sheet resistance in ohm/square, L is the length, and W the width of the connecting cell area.

For vertical (for series connection) resistances:

$$R_v = R_{\square} \frac{CellWidth}{CellLength}$$

Since the length size of the contact is the calculated cell width, see section 1 for more details.

For the horizontal (for parallel connection) resistances:

$$R_h = R_{\square} \frac{CellLength}{CellWidth}$$

Cell length and width are internally calculated using the panel dimensions specified earlier.

Section 3.4: Shunt Resistance

Photocurrent Value | Diode Parameters | Sheet Resistance | Shunt Resistance

Shunt Resistance: 100kohm

Use randomly distributed shunt values?: yes

Shunt Random Sample Generator

Randomize All?: no

Number of Random Shunts: 1

Mean value: 100kohm

Standard Deviation: 15kohm

Figure 2.10: Shunt resistance parameters

This section contains the different parameters that can be adjusted for the parasitic shunt resistances. The shunt resistance can be kept constant or varied from cell to cell.

Shunt Resistance: values applied to every shunt resistor in the module. The units are expected to be in $k\Omega$.

Use randomly distributed shunt values? This feature enables MATLAB's random number generator in order to replace all/some of the existing shunt resistor values by a random generated value. Shunts will be randomly placed throughout the whole module and their values will be generated using a lognormal distribution.

Randomize All? This option automatically modifies all the shunt values in the module using the specifications in the next parameters.

Number of Random Shunts: This feature is only available when the Randomize All feature is disabled. This allows the user to manually decide how many shunts should occur in the module. The shunts are placed randomly. If the value is bigger than the number of solar cells, has the same effect as using the "Randomize All" feature above.

Mean and Standard Deviation: statistical variables for configuring the lognormal shunt distribution. These parameters will determine the variability of output performance in the module. A low mean and high variance will result in large output loss at the panel level. Combined with the sheet resistance parameter this determines the overall loss in efficiency in going from cell to panel level. The units are in $k\Omega$.

After specifying the correct input variables, hit the simulate button at the bottom to run the simulation. The interfacing script will create the spice input based on the specified parameters, run the spice simulation, and collect and process the output data to be displayed. The description of the output data and formats is given in the following sections.

Simulator Outputs

The simulator will output several plots, graphs, tables and logs which will be explained in this document. Refer to section one to learn about the inputs.

I - V Curve for the Solar Panel

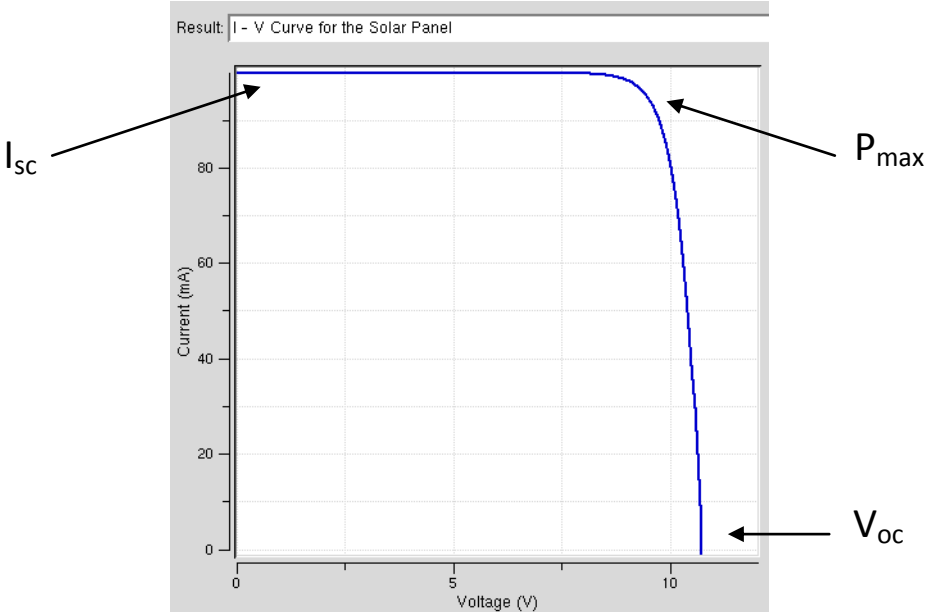


Figure 3.1: I-V Curve

The first output displayed is the characteristic I-V curve for the solar cell module. The output has been formatted so that the minimum current value is 0 A. If the negative values are of interest to the user, the axis settings can be modified by left clicking on the scale of the respective axis as shown in figure 3.2.

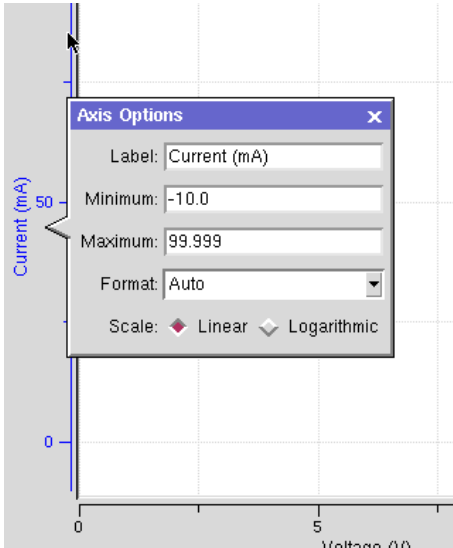


Figure 3.2: Modify the plot's default axis.

This plot is internally used to extract the open circuit voltage and short circuit current of the module. The user does not need to calculate any of the common parameters since they are already provided in the **Panel Calculations** log file.

P - V Curve for the Solar Panel

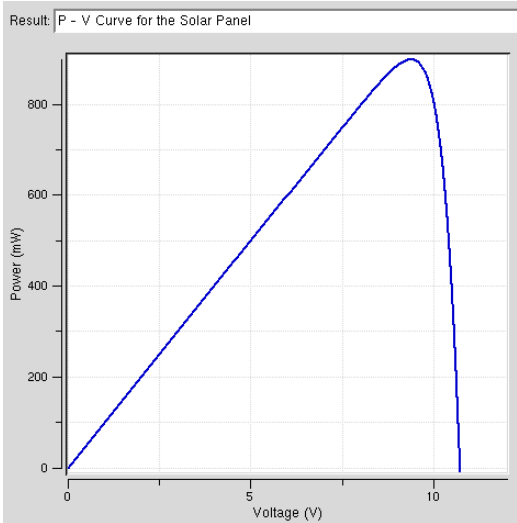


Figure 3. P-V Curve

This plot is similar to the I-V curve. This curve is used to calculate the maximum power output. The V_{mp} and the I_{mp} can be obtained once the coordinates of the maximum power have been calculated.

Note: The data in the IV and PV curves is available for download as a image as well as comma separated values for further analysis or plotting.

2D Node Voltage Drop

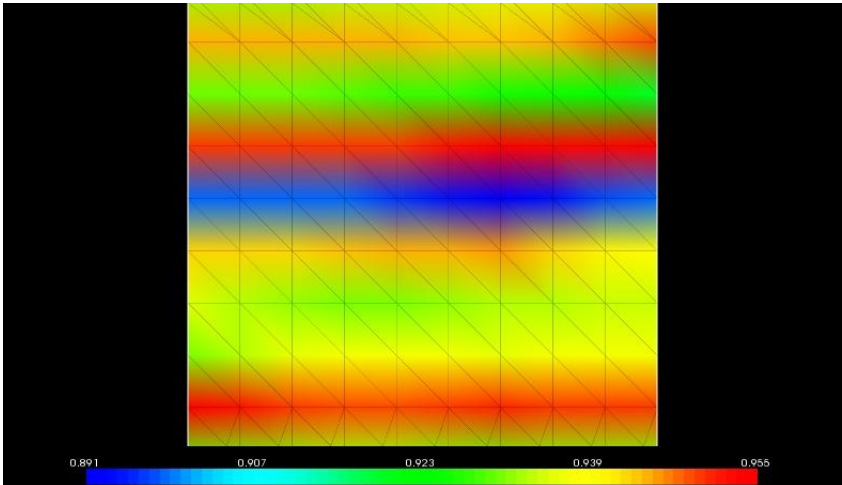


Figure 3.4: 2D Node voltage drop.

This plot shows the voltage drop across the individual cells in the whole module. The voltage drop is calculated across the terminals of all cells as shown in figure 3.4.

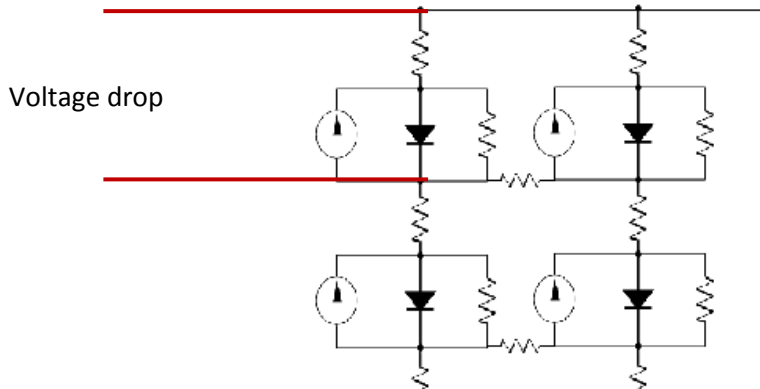


Figure 5. Voltage drop calculations

Whenever the user does not specify any variation (photocurrent or shunts) all cells should have the same voltage drop (and thus produce a plot one color). This graph will display the effects of shading/shunting a cell and how much area is affected by it. This feature is only available for modules bigger than 2 by 2.

2D Power Generation

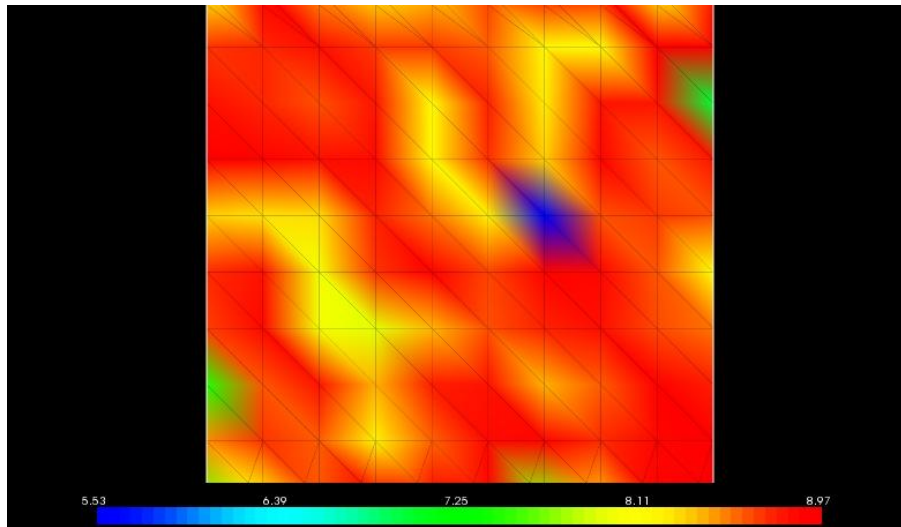


Figure 3.6: 2D power generation

This plot shows the amount of power generated by each individual cell (in mW). The power calculations are calculated as follows:

$$P_{cell} = P_{photo} + P_{diode} + P_{shunt} + P_{series}$$

The sign convention used assumes the generated power as positive and power dissipation to be negative. A defective cell will show lower values and the shaded cells may even show negative values (showing power dissipation). As we can see from figure 3.6, this graph will display the effects of shading/shunting a cell and how much area is affected by them.

Shunt resistances

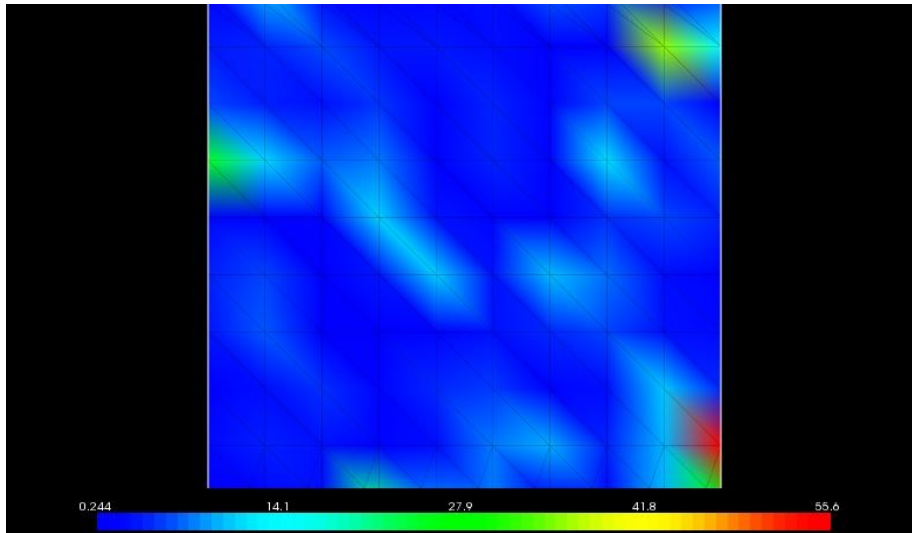


Figure 3.7: Locations and magnitudes of random shunts on the panel.

This plot shows the location of the randomly varying shunts and their values (in color), when randomization of shunt values is selected. This allows the user to correlate the small output power of the shunted cells and their shunt values. The scale at the bottom specifies the values in $k\Omega$.

Note: These two dimensional plots of voltage drop, output power, and shunt magnitude can only be downloaded as images from the rapture interface. Their values in downloadable text format is given separately in a log file.

Panel Calculations

```
Result: Panel Calculations
-----
SOLAR PANEL CALCULATIONS.
Light Irradiance: 1e+03 W/m2
Ambient temperature: 300 K

MODULE'S DESCRIPTION
Width: 10 cm
Length: 10 cm
Module area: 1e+02 cm2

Cells connected in series: 10
Cells connected in parallel: 10

CELL DESCRIPTION
Width: 1 cm
Length: 1 cm
Area: 1 cm2

CELL PARAMETERS
Photocurrent: 0.01 A
Diode Saturation Current: 1e-14 A
Diode ideality factor: 1.5
Vertical (Series) sheet resistance: 1 ohm
Horizontal (across) sheet resistance: 1 ohm
Shunt Resistance (min): 75.7 kohm
Shunt Resistance (max): 100 kohm
```

MODULE vs SINGLE CELL OUTPUT PERFORMANCE			
	MODULE	WORST CASE	BEST
Isc (mA)	99.999	10.000	
Voc (V)	10.704	1.085	
Pmax (mW)	899.205	8.967	
Vmp (V)	9.407	0.950	
Imp (mA)	95.589	9.439	
Fill Factor	84.011	82.649	
Efficiency (nu)	8.992	8.967	

Figure 3.8: Example Panel Calculations Log File

This log contains all the relevant calculations and user inputs used during the simulation. It also includes a module vs. cell comparison table in order to check the efficiency degradation due to the loss mechanisms found at module level. If a random shunt is introduced in the simulation, then this table will output a worst / best case calculation which represents the performance of the worst (lowest shunt resistance) and best (highest shunt resistance) solar cell present in the module.

Random cell parameters

Shunt resistances (Ohms)	Power Output (mW)	Voltage Drop (V)
5.7767e+03	8.845358	0.938619
1.1853e+04	8.927967	0.939369
1.2255e+03	8.287868	0.928900
6.9155e+03	8.874756	0.942087
5.1154e+03	8.822115	0.927144
2.0783e+03	8.580580	0.935625
3.3712e+03	8.742226	0.932354
5.1846e+03	8.834984	0.934153
3.1186e+04	8.968750	0.940739
1.9913e+04	8.951934	0.933740
2.0282e+03	8.570784	0.932636
2.3072e+04	8.960172	0.938770
6.4105e+03	8.863308	0.929977
4.1401e+03	8.785609	0.941689
6.3727e+03	8.849054	0.925703
3.8268e+03	8.775882	0.936173
4.0022e+03	8.783368	0.932230
9.7938e+03	8.913540	0.934157
9.2654e+03	8.903600	0.940709
9.4079e+03	8.903977	0.933686
6.2217e+03	8.863078	0.933012
2.1949e+03	8.600941	0.937790
6.3916e+03	8.855500	0.930880
1.0589e+04	8.913607	0.941709
5.6226e+03	8.827175	0.925860
7.6099e+03	8.881268	0.936950
6.4158e+03	8.864726	0.932177
3.6235e+03	8.754734	0.933968
5.0463e+03	8.899600	0.940894

Figure 3.9: Cell shunt and outputs values, downloadable as text.

This file lets the user download the cell shunt values and corresponding output power and voltage drops for further analysis and plotting.

LOG FILE: SPICE Input File

This file shows the input deck that was generated to perform the SPICE simulations. This file is provided in case the user wants to rerun the simulation and analyze the results on his or her own. The input deck will only calculate the operating point at the optimal operating bias. If the user wants to perform an I-V analysis the fifth and seventh lines should be uncommented (remove asterisk).

LOG FILE: SPICE Node Analysis:

This log file is the actual operating point analysis performed by SPICE. It contains the voltage at every node and the power dissipated by every element in the circuit.