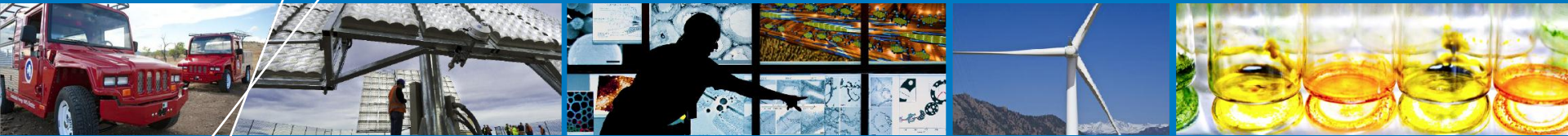


# Analytical Approximation of Inter-Row Shading in SAM



**SAM Virtual Conference**

**Chris Deline**

**7/23/13**

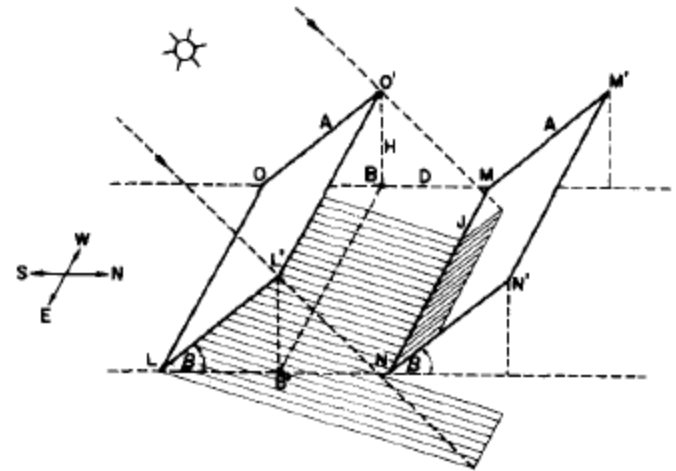
# Inter-row shading model in SAM

---

- How was the model developed
- How it works in SAM

# Inter-row shading

How much power is actually lost from inter-row shading?  
Can you improve kWh/m<sup>2</sup> or \$/kWh by closer row spacing?



Thakkar 2010

Applebaum 1979

# Shade model developed for SAM

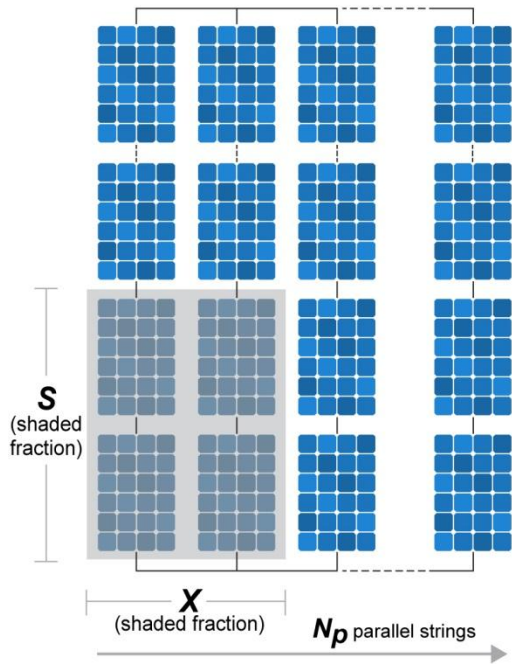
---

- **Requirements of SAM shading model**
  - Simple, fast (no significant increase in run time)
  - Widely applicable (many different module types)
  - Applies to large and small installations

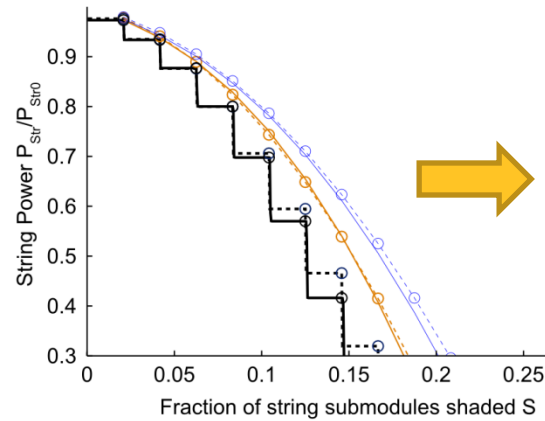
# Shade model developed for SAM

- **Requirements of SAM shading model**
  - Simple, fast (no significant increase in run time)
  - Widely applicable (many different module types)
  - Applies to large and small installations
- **Limitations of the model**
  - Only applies to uniform shading (inter-row shading, not obstruction shading)
  - Approximation, not a full simulation

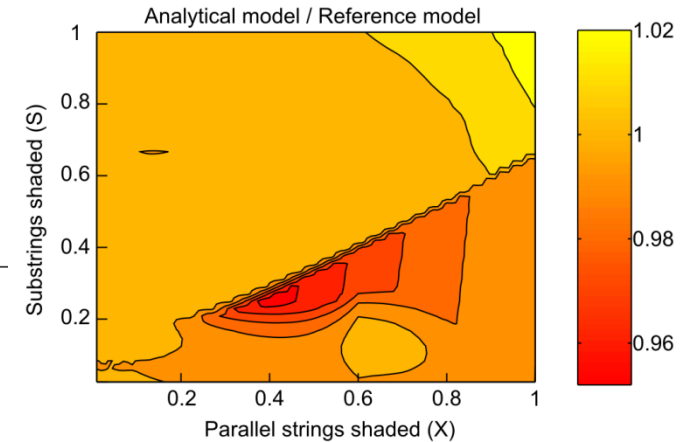
# Overview of inter-row shading model



Partial Shading  
definition



Empirical Model



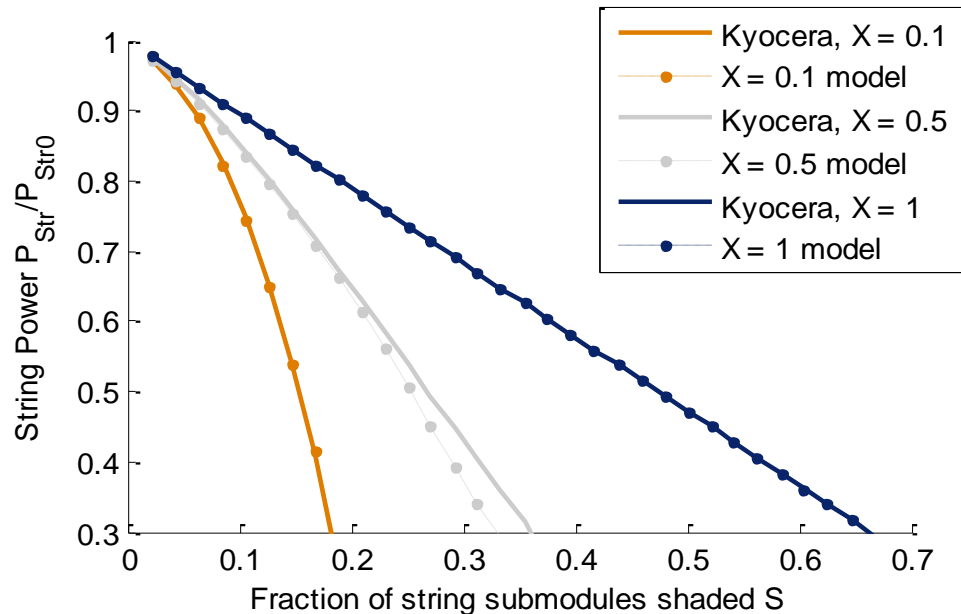
Model validation  
< 6% error

\*C. Deline et al., "A simplified model of uniform shading in large photovoltaic arrays,"  
Solar Energy (in press)

# Empirical shading model

- **Takes 4 inputs:**
  - Number of shaded modules per string  $S$
  - Number of shaded strings in the system  $X$
  - PV Module Fill Factor  $FF_0$
  - Shaded irradiance fraction  $E_e = G_d + G_r / G_{total}$
- **In SAM:**
  - Geometry of system defines hourly shading
  - Empirical model determines shading derate

# Example of empirical model output



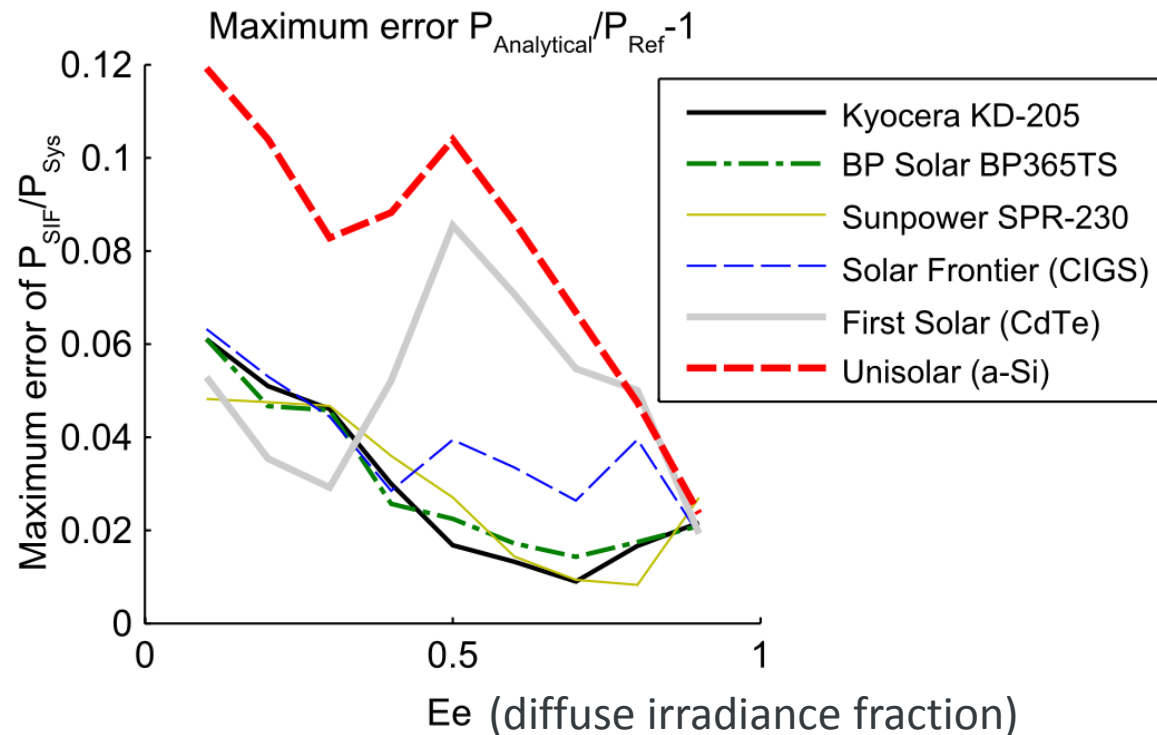
$X = 0.1$ : Only a few strings are shaded

$X = 1$ : All strings are shaded

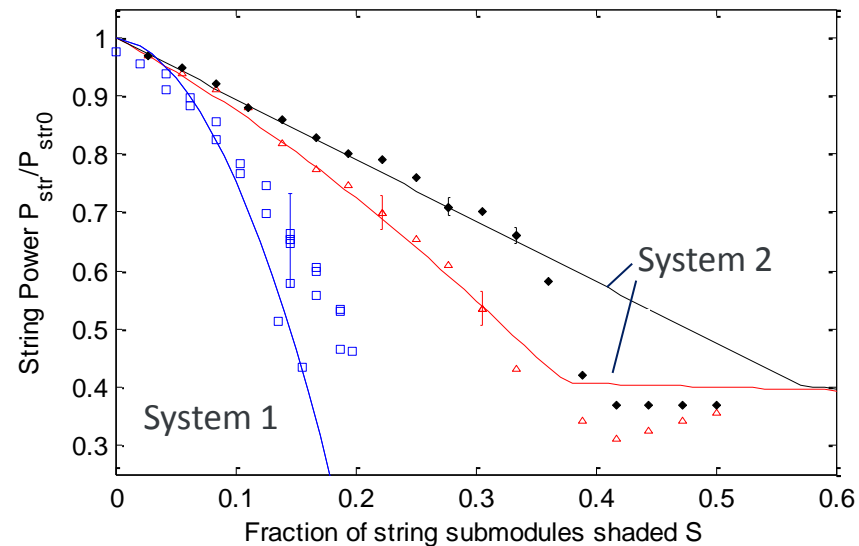


# Verification of model vs. full simulation

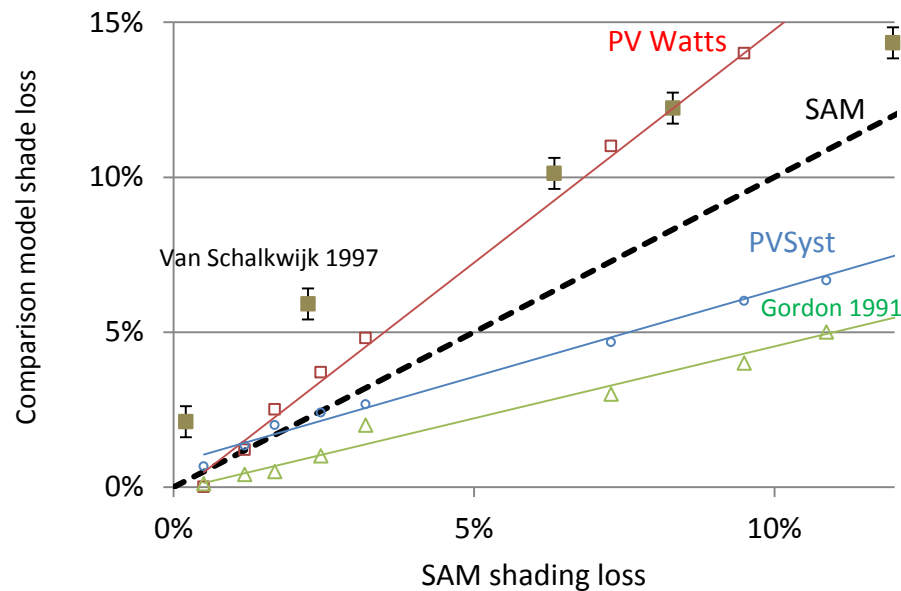
- Maximum model error, different panels types
  - Bigger error for thin-film, low diffuse fraction



# Experimental verification of model

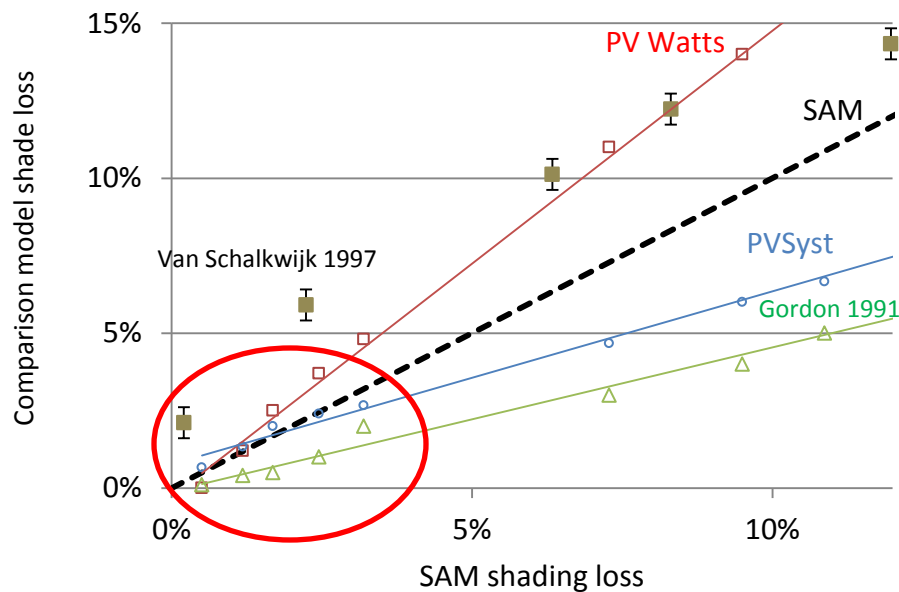


# Comparison with prior models



- Good agreement with PVSyst up to 4% loss, more conservative for higher loss
- Some experiments predict even higher losses from shading

# Comparison with prior models



- Good agreement with PVSyst up to 4% loss, more conservative for higher loss
- Some experiments predict even higher losses from shading

# Using inter-row shading in SAM

## Self Shading Calculator for Fixed Tilt Arrays

☒ Enable Self-Shading Calculator

### Module

Orientation **Landscape**

Length **1.848** m

Width **0.673** m

Number of Cells along Length **12**

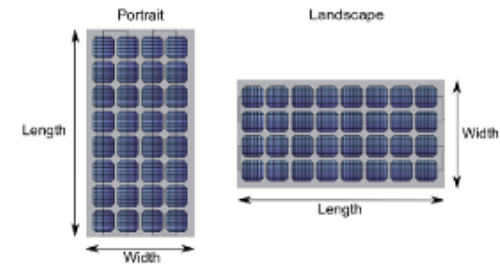
Number of Cells along Width **6**

Number of Bypass Diodes **3**

### Characteristics from Module Page

Area **1.244** m<sup>2</sup>

Number of cells **72**



### Array

String Wiring **Vertical**

Number of Strings along Bottom **1**

Side Length **2.019** m

Number of Modules along Bottom **2**

Row Spacing **5** m

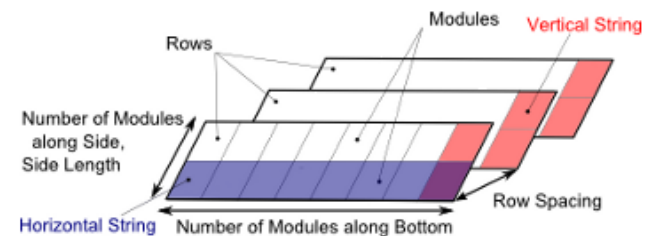
Number of Modules along Side **3**

Number of Rows **3**

### Layout from Array Page

Modules per String **9**

Strings in Parallel **2**



Enable the Self Shading option to model self shading of modules within the array.

The self shading model only works when you chose the CEC or Sandia model option on the Module page, and when you choose fixed tracking on the Array page.

The self-shading parameters must be consistent with the parameters you specify on the Module and Array pages. See Help for details.

The number of cells along the bottom must be an integer multiple of the number of diodes, or the number of diodes must be an integer multiple of the number of cells along the bottom.

# Step 1: Enter module details

Select Landscape or Portrait orientation

**Module**

Orientation: Landscape

Length: 1.848 m

Width: 0.673 m

Number of Cells along Length: 12

Number of Cells along Width: 6

Number of Bypass Diodes: 3

**Characteristics from Module Page**

Area: 1.244 m<sup>2</sup>      Number of cells: 72

Portrait      Landscape

Length      Width

Width      Length

User Adjustable

Details from SAM database

# Step 2: Enter layout details

**Array**

String Wiring:

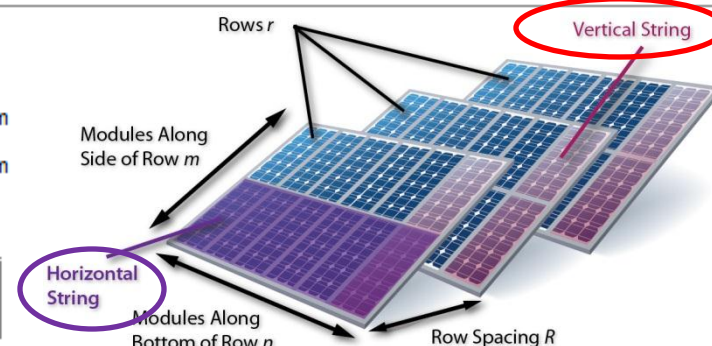
Number of Strings along Bottom:  Side Length:  m

Number of Modules along Bottom:  Row Spacing:  m

Number of Modules along Side:  Number of Rows:

**Layout from Array Page**

Modules per String:  Strings in Parallel:



The diagram illustrates a solar array layout with two rows, labeled 'Rows  $r$ ' and 'Rows  $n$ '. A 'Horizontal String' is highlighted with a purple circle and arrow, pointing to a string of modules along the bottom of a row. A 'Vertical String' is highlighted with a red circle and arrow, pointing to a string of modules along the side of a row. Labels include 'Modules Along Side of Row  $m$ ', 'Modules Along Bottom of Row  $n$ ', and 'Row Spacing  $R$ '.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Vertical strings: Not commonly used in practice

# Step 2: Enter layout details

**Array**

String Wiring:

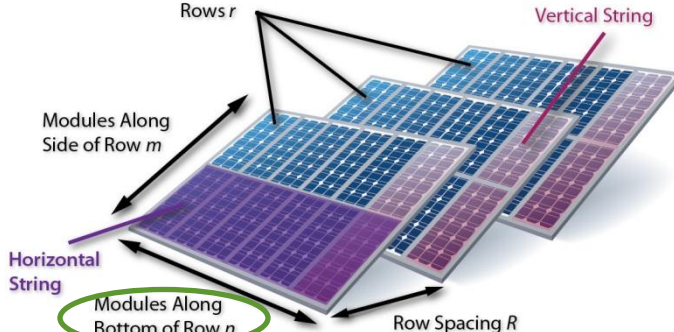
Number of Strings along Bottom:  Side Length:  m

Number of Modules along Bottom:  Row Spacing:  m

Number of Modules along Side:  Number of Rows:

**Layout from Array Page**

Modules per String:  Strings in Parallel:



The diagram illustrates a solar array layout with multiple rows of modules. Labels include 'Rows  $r$ ', 'Modules Along Side of Row  $m$ ', 'Vertical String', 'Horizontal String', 'Modules Along Bottom of Row  $n$ ', and 'Row Spacing  $R$ '. The 'Modules Along Bottom of Row  $n$ ' is circled in green, corresponding to the 'Number of Modules along Bottom' input field in the form above.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:
  - # Modules along bottom =



# Step 2: Enter layout details

**Array**

String Wiring:

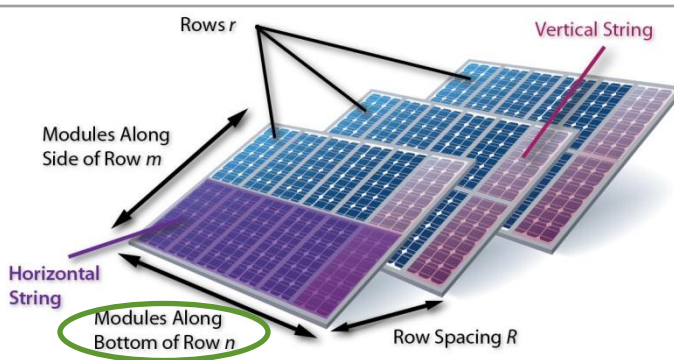
Number of Strings along Bottom:  Side Length:  m

Number of Modules along Bottom:  = Row Spacing:  m

Number of Modules along Side:  Number of Rows:

**Layout from Array Page**

Modules per String:  Strings in Parallel:



The diagram illustrates a solar array layout with multiple rows of modules. Labels include 'Rows r', 'Modules Along Side of Row m', 'Vertical String', 'Horizontal String', 'Modules Along Bottom of Row n', and 'Row Spacing R'. The array is shown as a grid of modules, with rows and columns clearly defined. The 'Horizontal String' and 'Vertical String' labels point to the respective wiring paths. The 'Modules Along Bottom of Row n' label points to a specific row of modules.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:
  - # Modules along bottom = Modules / String \*

# Step 2: Enter layout details

**Array**

String Wiring:

Number of Strings along Bottom:  ←

Number of Modules along Bottom:  =

Number of Modules along Side:  ←

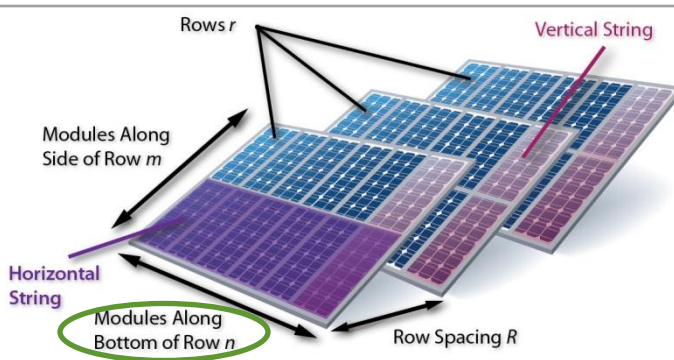
Side Length:  m

Row Spacing:  m

Number of Rows:

**Layout from Array Page**

Modules per String:  \* Strings in Parallel:



The diagram illustrates a solar array layout with multiple rows of modules. Labels include 'Rows r', 'Modules Along Side of Row m', 'Horizontal String', 'Vertical String', 'Modules Along Bottom of Row n', and 'Row Spacing R'. A blue arrow points from the 'Number of Modules along Bottom' input field to the 'Modules per String' input field in the 'Layout from Array Page' section.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:

- $\# \text{ Modules along bottom} = \text{Modules} / \text{String} * \text{Strings along Bottom}$

# Step 2: Enter layout details

**Array**

String Wiring:

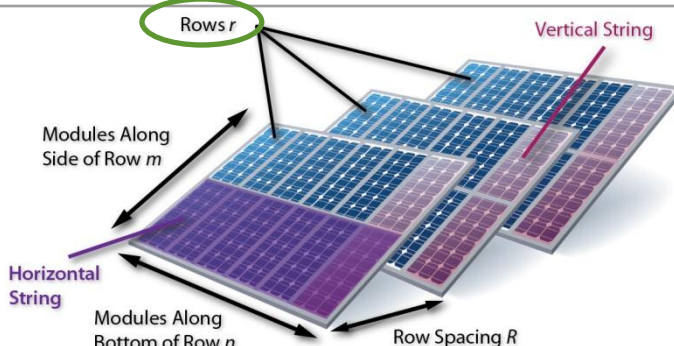
Number of Strings along Bottom:  Side Length:  m

Number of Modules along Bottom:  Row Spacing:  m

Number of Modules along Side:  Number of Rows:

**Layout from Array Page**

Modules per String:  Strings in Parallel:



The diagram illustrates a 3D perspective of a solar array layout. It shows multiple rows of solar modules. A green circle highlights the text 'Rows r' with arrows pointing to the rows. A red line points to a 'Vertical String' within a row. A purple line points to a 'Horizontal String' within a row. Labels include 'Modules Along Side of Row m', 'Modules Along Bottom of Row n', and 'Row Spacing R'.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:
  - # Modules along bottom = Modules / String \* Strings along Bottom
  - Number of Rows =

# Step 2: Enter layout details

**Array**

String Wiring:

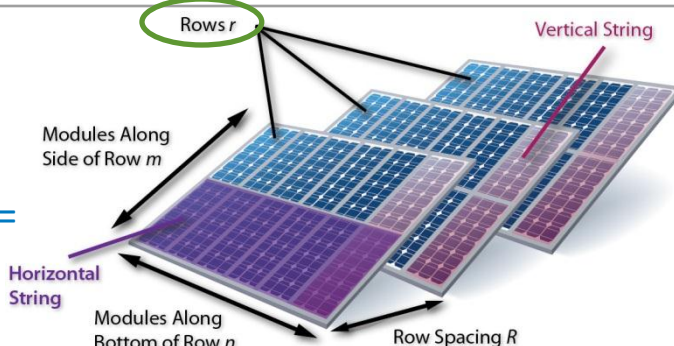
Number of Strings along Bottom:  Side Length:  m

Number of Modules along Bottom:  Row Spacing:  m

Number of Modules along Side:  Number of Rows:  =

**Layout from Array Page**

Modules per String:  Strings in Parallel:



The diagram illustrates a solar array layout with two rows of modules. The top row is labeled 'Rows r' and the bottom row is labeled 'Row n'. A 'Horizontal String' is shown running across the bottom of the array, and a 'Vertical String' is shown running down the side. Labels indicate 'Modules Along Side of Row m' and 'Modules Along Bottom of Row n'. The 'Row Spacing R' is also indicated.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:
  - # Modules along bottom = Modules / String \* Strings along Bottom
  - Number of Rows = Strings in Parallel /

# Step 2: Enter layout details

**Array**

String Wiring:

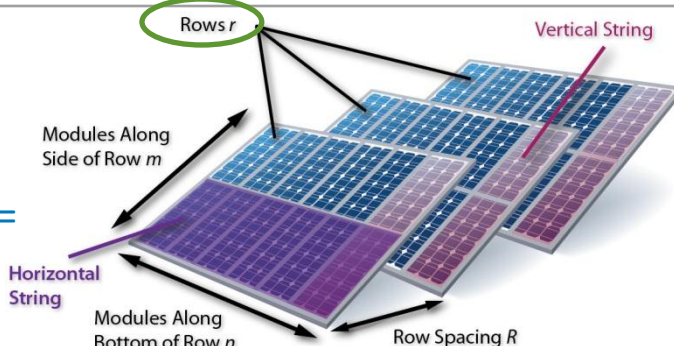
Number of Strings along Bottom:       Side Length:  m

Number of Modules along Bottom:       Row Spacing:  m

Number of Modules along Side:       Number of Rows:  =

**Layout from Array Page**

Modules per String:       Strings in Parallel:  /



The diagram illustrates a 3D perspective of a solar array layout. It shows multiple rows of solar modules. A green circle highlights 'Rows r' with arrows pointing to individual rows. A red line indicates a 'Vertical String' running through the modules. A purple line indicates a 'Horizontal String' running along the bottom of a row. Labels include 'Modules Along Side of Row m' and 'Modules Along Bottom of Row n'. The 'Row Spacing R' is also indicated between the rows.

Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:

- $\# \text{ Modules along bottom} = \text{Modules} / \text{String} * \text{Strings along Bottom}$
- $\text{Number of Rows} = \text{Strings in Parallel} / \text{Strings along bottom} /$

# Step 2: Enter layout details

**Array**

String Wiring:

Number of Strings along Bottom:  /

Number of Modules along Bottom:

Number of Modules along Side:

Side Length:  m

Row Spacing:  m

Number of Rows:  =

**Layout from Array Page**

Modules per String:

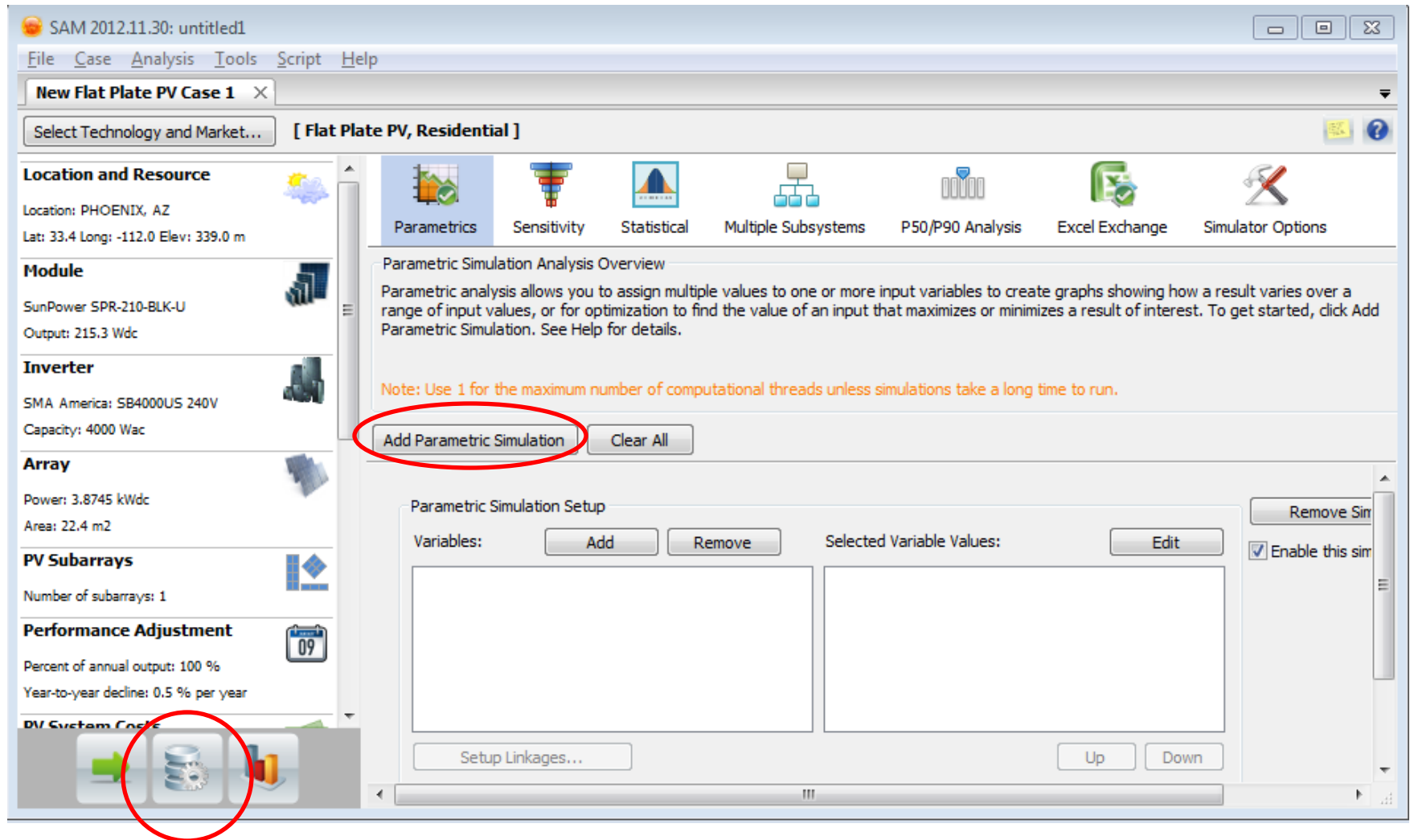
Strings in Parallel:  /

The diagram illustrates a 2x9 grid of solar modules. A green circle highlights 'Rows r' with an arrow pointing to the two rows. A red line indicates a 'Vertical String' running down the side. A purple line indicates a 'Horizontal String' running across the bottom. Arrows point to 'Modules Along Side of Row m' and 'Modules Along Bottom of Row n'. The 'Row Spacing R' is indicated between the two rows.

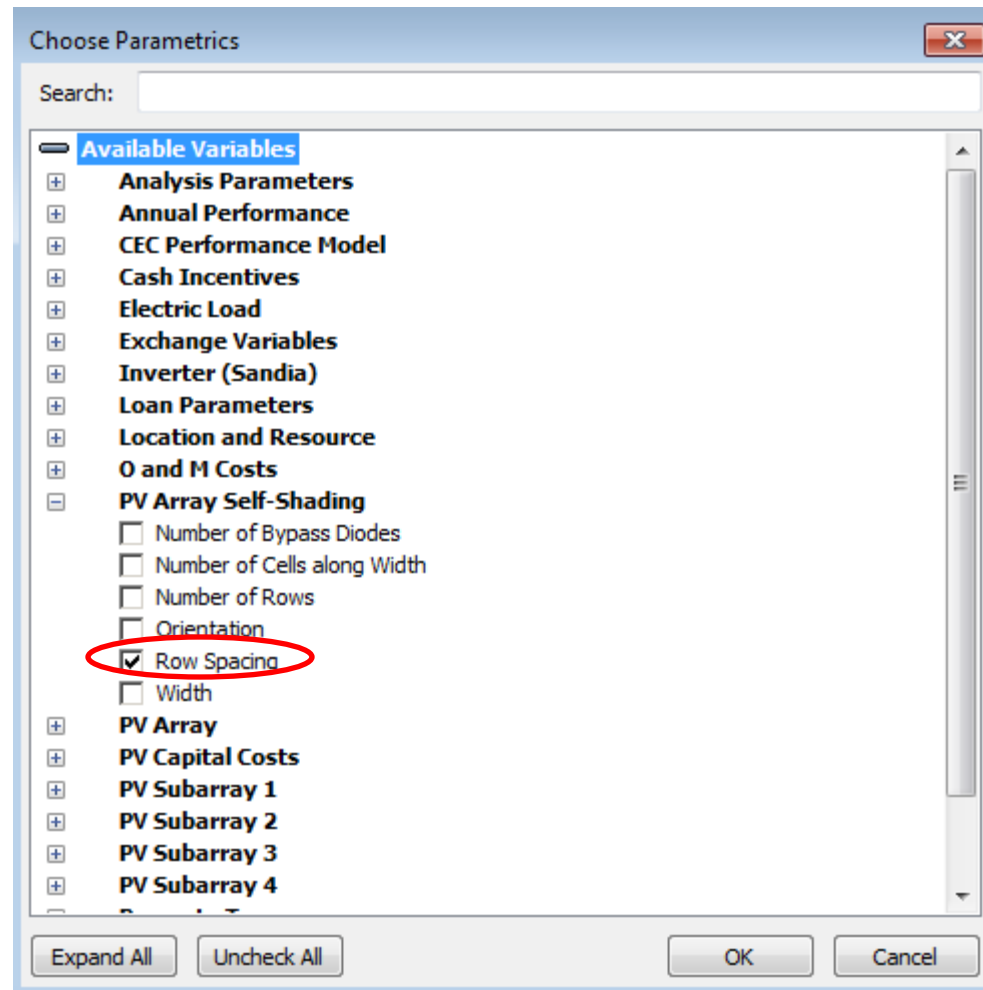
Only 2 layouts are currently allowed: Horizontal and Vertical strings

- Horizontal strings:
  - # Modules along bottom = Modules / String \* Strings along Bottom
  - Number of Rows = Strings in Parallel / Strings along bottom / Modules along Side

# Setting up a Parametric Simulation



# Parametric Simulation: select 'Row spacing'





# Define array of Row Spacing values

SAM 2012.11.30: untitled1

File Case Analysis Tools Script Help

New Flat Plate PV Case 1 X

Select Technology and Market... [ Flat Plate PV, Residential ]

**Location and Resource**

Location: PHOENIX, AZ  
Lat: 33.4 Long: -112.0 Elev: 339.0 m

**Module**

SunPower SPR-210-BLK-U  
Output: 215.3 Wdc

**Inverter**

SMA America: SB4000US 240V  
Capacity: 4000 Wac

**Array**

Power: 3.8745 kWdc  
Area: 22.4 m2

**PV Subarrays**

Number of subarrays: 1

**Performance Adjustment**

Percent of annual output: 100 %  
Year-to-year decline: 0.5 % per year

**PV System Costs**

Parametric Simulation Analysis Overview

Parametric analysis allows you to assign multiple values over a range of input values, or for optimization to find the best values. See Help for details.

Note: Use 1 for the maximum number of computations.

Add Parametric Simulation Clear All

**Edit Parametric Values for 'Row Spacing (m)'**

Variable Values

2  
3  
4  
5

Define Range

Start Value: 2  
End Value: 5  
Increment: 1

Update

Add After... Add Before...  
Up Down Remove

Help... OK Cancel

**Parametric Simulation Setup**

Variables: Add Remove

PV Array Self-Shading/Row Spacing (m)

Selected Variable Values: Edit

5

Setup Linkages... Up Down

Remove Simulation Enable this simulation

# View results of Parametric simulation

SAM 2012.11.30: untitled1

File Case Analysis Tools Script Help

New Flat Plate PV Case 1 X

Select Technology and Market... [ Flat Plate PV, Residential ]

**Location and Resource**

Location: PHOENIX, AZ  
Lat: 33.4 Long: -112.0 Elev: 339.0 m

**Module**

SunPower SPR-210-BLK-U  
Output: 215.3 Wdc

**Inverter**

SMA America: SB4000US 240V  
Capacity: 4000 Wac

**View and export data:** Graphs **Tables** Cash Flows Time Series Loss Diagram

Choose Simulation: Parametric Set 1 Copy to clipboard Save as CSV... Send to Excel

**Output Variables**

**Metrics**

- ☒ Annual Energy
- ☐ LCOE Nominal
- ☐ LCOE Real
- ☐ Total revenue without system
- ☐ Total revenue with system
- ☐ First Year Net Revenue
- ☐ Net present value (\$)
- ☐ Payback (years)
- ☐ Capacity Factor
- ☐ First year kWhac/kWdc
- ☐ System performance factor
- ☐ Total Land Area

**Single Values**

**Monthly Data**

**Data: 25 values**

**Annual Data**

**Metric Base**

Annual Energy	6,854 kWh
LCOE Nominal	20.96 ¢/kWh
LCOE Real	16.99 ¢/kWh
Total revenue without system (\$)	\$ 0.00
Total revenue with system (\$)	\$ 822.50
First Year Net Revenue	\$ 822.50
Net present value (\$)	\$ -3,709.00
Payback (years)	17.687
Capacity Factor	20.2 %
First year kWhac/kWdc	1,769
System performance factor (%)	0.79
Total Land Area	0.01 ac

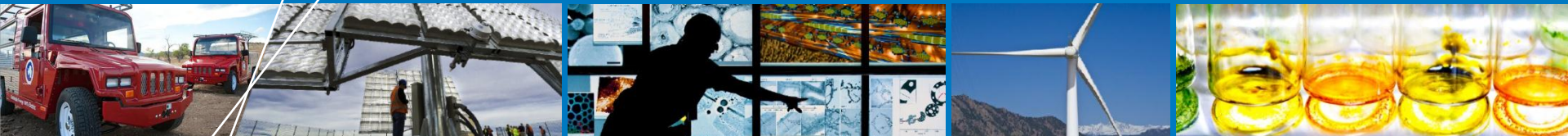
	Annual Energy Row Spacing=1	Annual Energy Row Spacing=2	Annual Energy Row Spacing=3	Annual Energy Row Spacing=4	Annual Energy Row Spacing=5
1	6625.35	6844.71	6851.56	6853.65	6854.48

Clear all

# Questions?

---

Download a preprint of the paper  
at [sam.nrel.gov/webfm\\_send/373](https://sam.nrel.gov/webfm_send/373)  
or email me at [chris.deline@nrel.gov](mailto:chris.deline@nrel.gov) for a copy.



# The End