NATIONAL RENEWABLE ENERGY LABORATORY

CHARACTERIZING SHADING LOSSES ON PARTIALLY SHADED PV SYSTEMS

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PV Performance Modeling Workshop

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Overview

Introduction: Shading on PV systems

Theory: Shaded PV power loss

Practical issues with modeling shaded PV

- Shade Estimation
- IV curve analysis

Methods of implementing partially shaded PV modeling

Some experimental results

Current and future work

Introduction – Shading on PV systems

Shading and mismatch occur on all types of PV installations.

- Nearby shade obstructions like trees and telephone poles
- Horizon shading from faraway structures
- Self-shading from adjacent rows
- I_{mp} mismatch from orientation, manufacturing tolerance, differential aging or soiling

Some types of shading are easier to quantify and model than others.

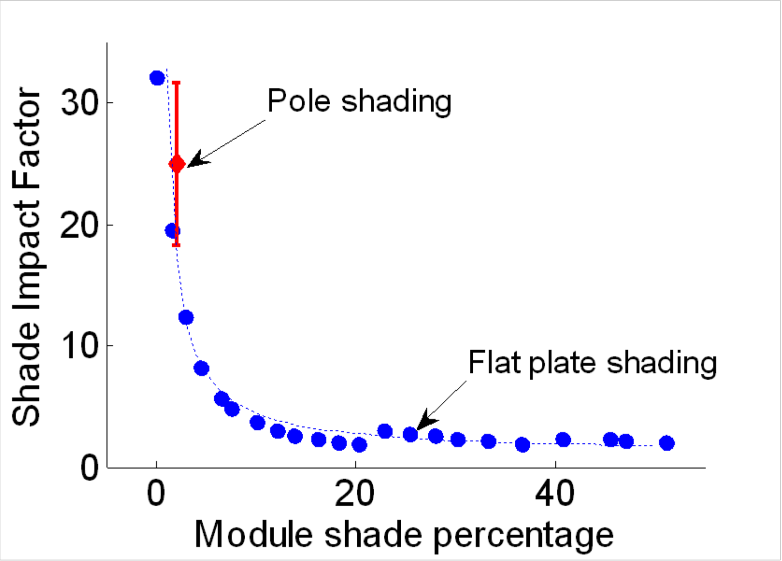
1: Lakewood, CO. 2: Maumee, OH. 3: Arlington, VA

Introduction – Impact of Shade

Shade impact depends on e.g. module type (fill factor, bypass diode placement), severity of shade, and string configuration.

Power loss occurs from shade, also current mismatch within a PV string and voltage mismatch between parallel strings.

Power lost is greater than proportional to the amount of shade on the system



'Shade Impact Factor' (ratio of power lost to area of shade) for a single module in a single string PV system [1]

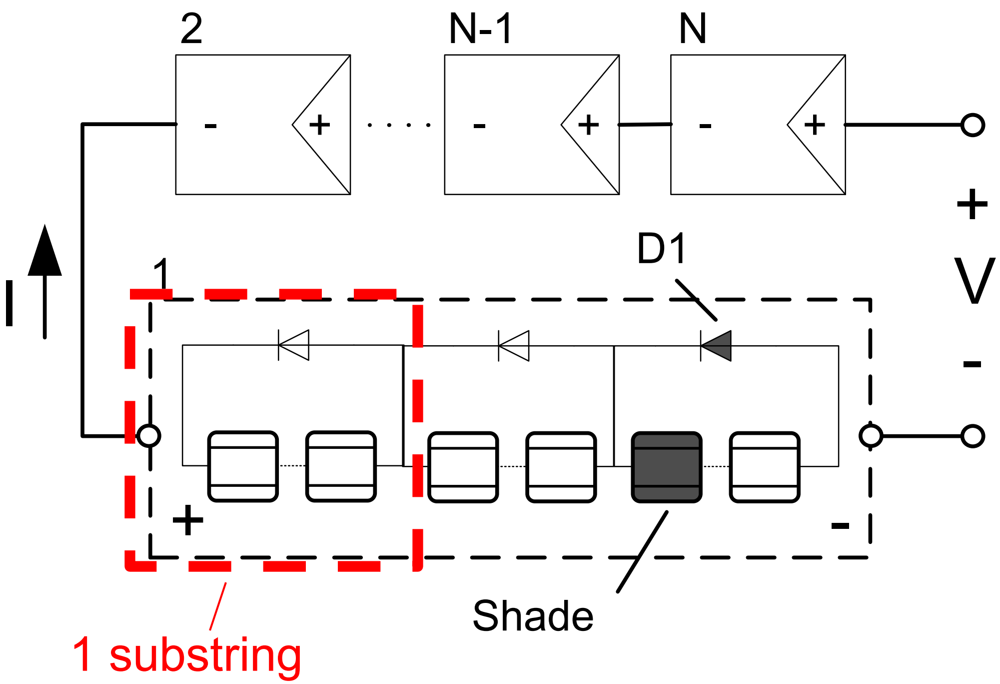
[1] C. Deline, IEEE PVSC, 2009

Bypass diode operation in most modules

Bypass diodes typically protect substrings of 15-20 cells. Shade on one of these cells can cause the diode to turn on, removing those cells electrically from the string.

Current is continuous in the PV string; a small amount of shade can greatly reduce output power.

On typical Si modules, reducing 1 cell's irradiance by 25% can lead to bypass diode turn-on.

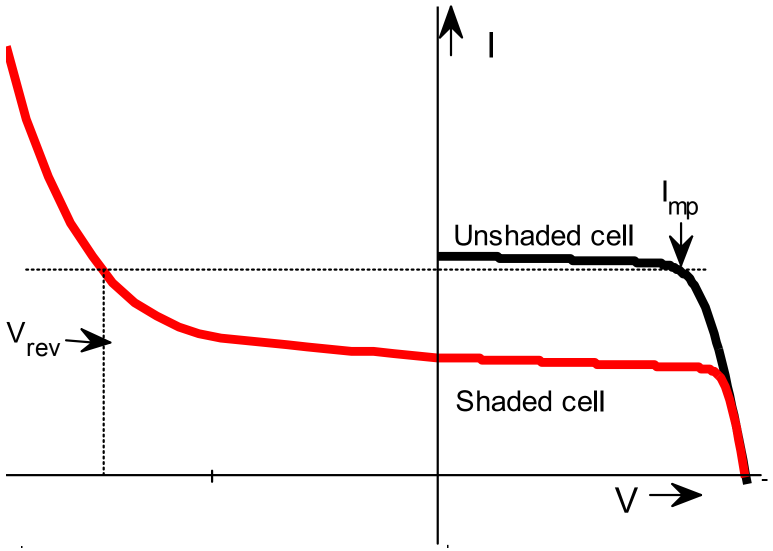


Theory – Partially shaded substring of cells

A shaded cell has reduced I_{sc}. In order to pass the string current I_{mp} the cell will operate in reverse bias. The total substring voltage is a sum of the various operating voltages including the reverse biased cell.

If the total substring voltage < 0, the bypass diode turns on and the shaded cell will operate near $V_{rev.}$

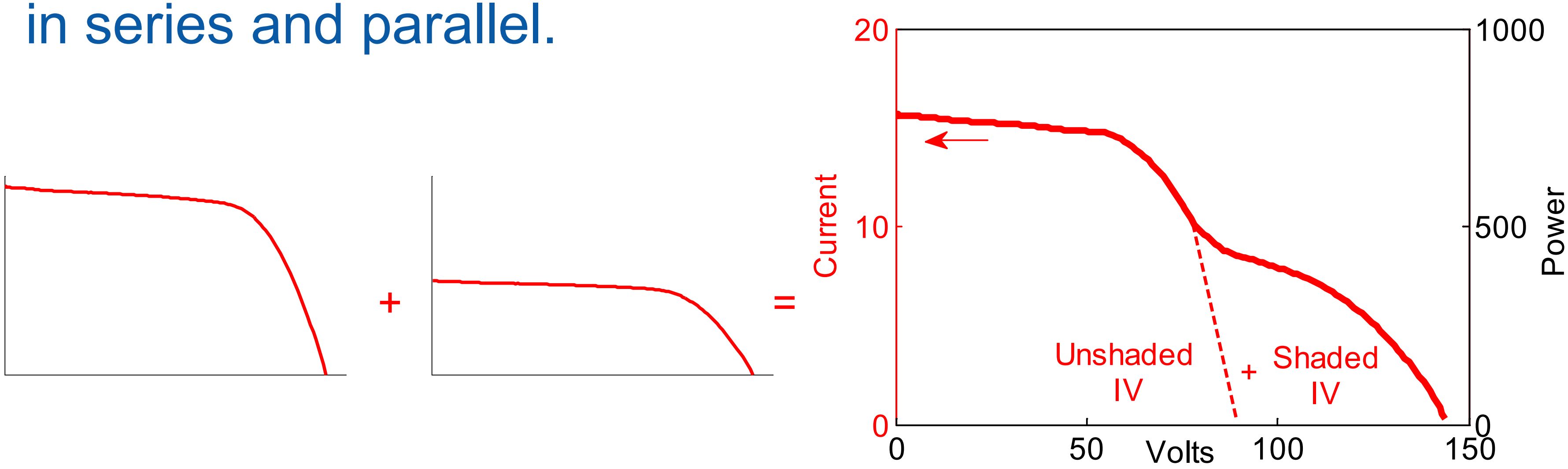
Variability exists in the reverse-bias characteristics of different cells – the same shading could result in different outcomes.



Full I-V curve of a partially shaded cell. Current continuity requires the shaded cell to operate in reverse bias to pass the Imp current of the rest of the substring.

Theory – system level IV curve

System IV curve is built from individual substring IV curves in series and parallel.

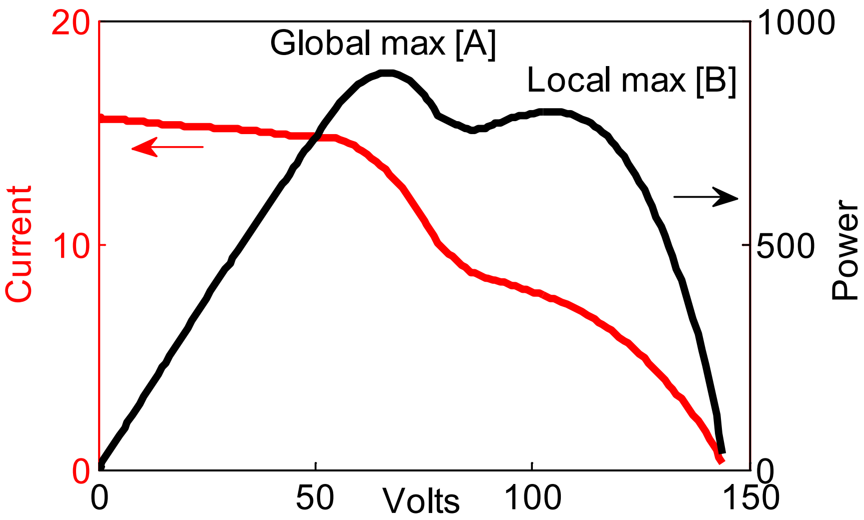


Theory – system level IV curve

System IV curve is built from individual substring IV curves in series and parallel.

Partial shading can lead to Local [B] and Global [A] maxima.

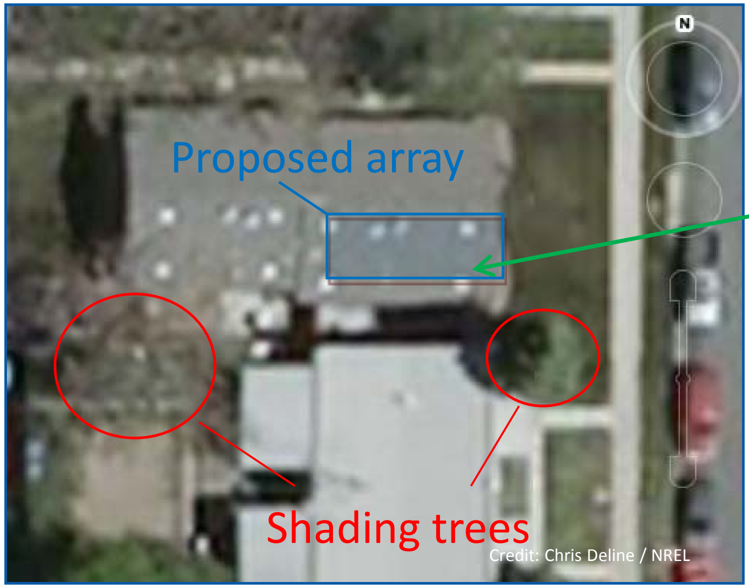
Bypass diode turn-on depends on the peak power point chosen. For instance, operating at point [A] requires shaded bypass diode turn-on while point [B] does not.



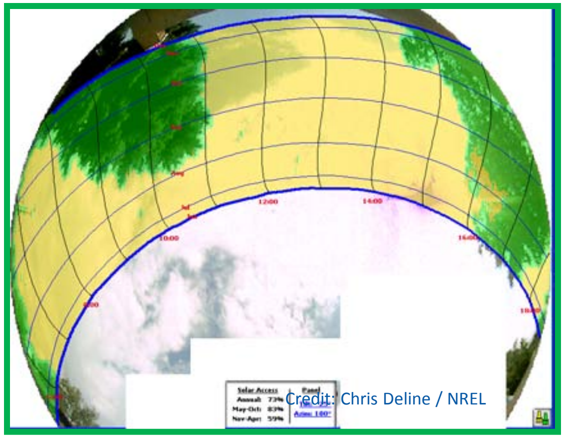
Practical matters – shade estimation

Shading site survey typically relies on aerial imagery and fisheye shade analysis e.g. SunEye™, or Solar Pathfinder™.

Some issues include: foliage changes throughout the year, spatial resolution requires multiple pictures, shading objects are considered 100% opaque, nearby objects have more position uncertainty, 3D CAD modeling is time intensive.



Rooftop survey



Methods of modeling substring IV curves

Full 5-parameter IV curve

- High accuracy, but slow (when calculated 1000's of times)

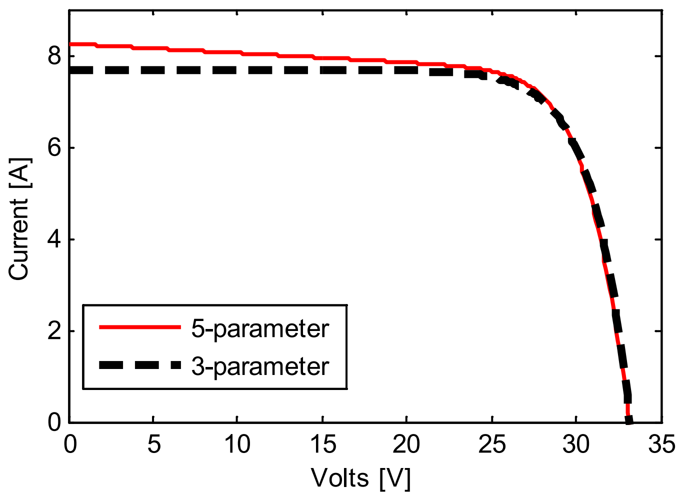
$$I = I_{ph} - I_0\left[\exp\left(\frac{V+I\,R_s}{a}\right) - 1\right] - \frac{V+I\,R_s}{R_{sh}}$$

Simplified IV curve (3-parameter)

- Computationally less intense, reduced accuracy for V < Vmp.
- $I = C_1 - C_2 \exp(C_3 * V)$

Empirical 'Shade impact factor'

- System-specific lookup table, based on shade % and diffuse / global ratio.



Comparison of full 5-parameter IV curve with a simplified 3-parameter IV curve for an Evergreen ES-200 PV module. Accuracy is better for V > Vmp .

Real-world application of shade modeling

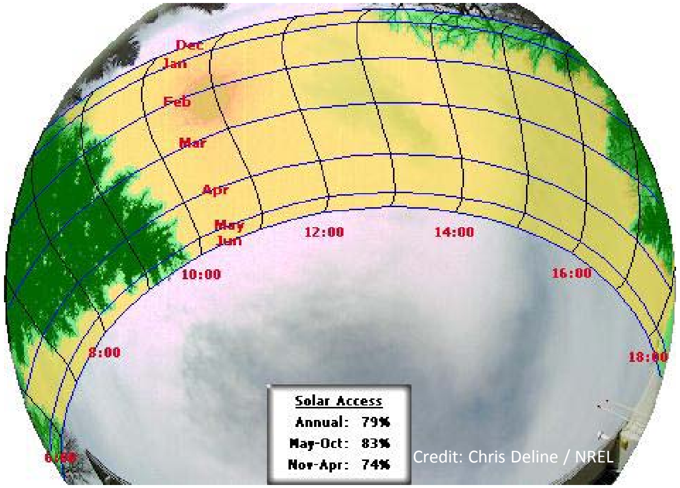
Site survey conducted on a 'typical residential installation'[3]

- Most shade from 6-10am, 2-6pm
- ~21% annual irradiance loss
- 2 strings of 7 mSi modules @ 3kW

Site survey picture taken at each PV module substring

- 3 images per module = 42 total
- Provides # of shaded substrings for a given hour and date

'Typical residential installation'. 2x7 mSi panels



Site survey:~20% irradiance loss due to shade

[3] R. Levinson, Solar Energy **83,** 2009

Numerical shade simulation

Simulation uses PVWatts with additional shade derating[4]

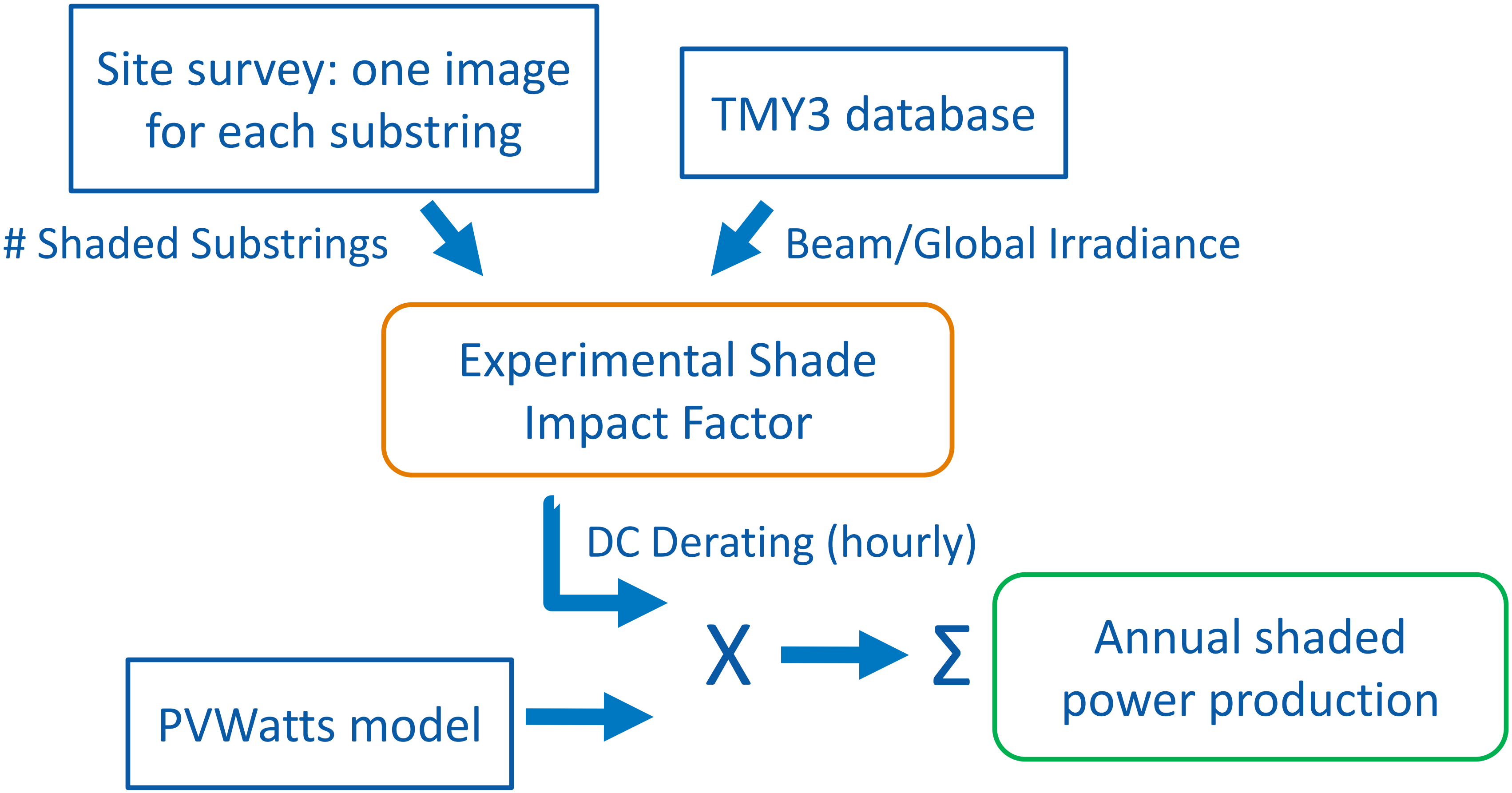
- Derating based on empirical relationships between shade extent and power loss, as determined in a scale experiment at NREL.
- TMY3 weather data and the default PVWatts AC to DC factor (0.77)

Two shade conditions are simulated: 1) both strings are shaded as per the survey, and 2) one string is entirely unshaded

- Two-string shading is more realistic, but some installations may have more limited shading.

[4] C. Deline, IEEE PVSC, 2010

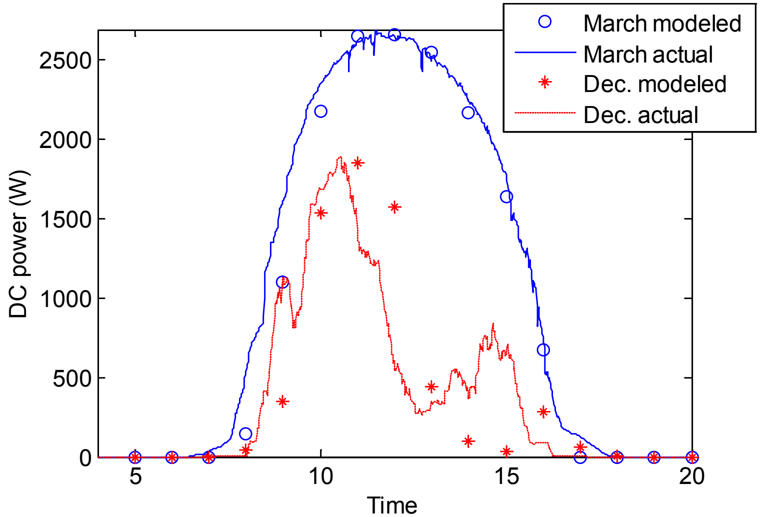
Simulation method - overview



Simulation results

Modeled results compare favorably with measured data on representative sunny days.

Annual results show close agreement with site survey's 'solar resource fraction' (but this is not always the case)



Modeled results (dots) and measured data (lines) for two representative sunny dates

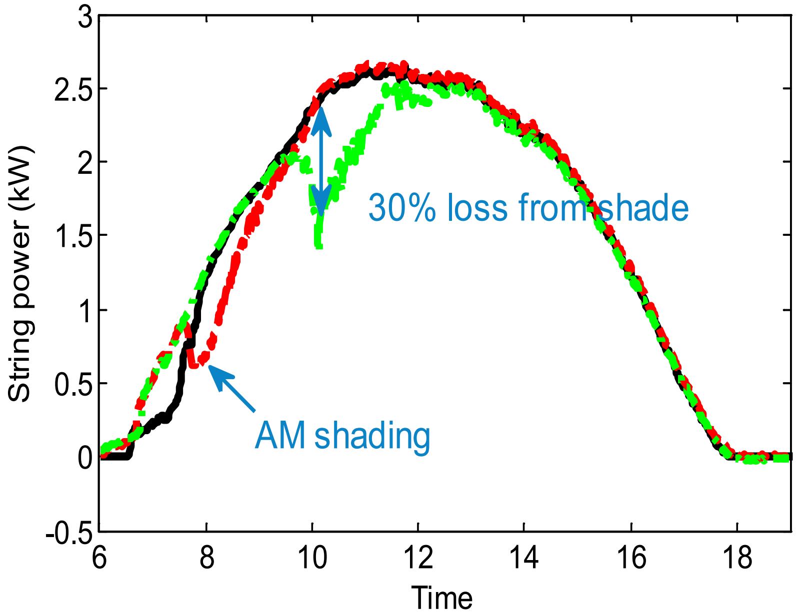
	Annual power produced	Power lost to shade
Unshaded baseline	4.4 MWh	0
Site survey estimate		-21%
2 strings shaded	3.5 MWh	-22%
1 string shaded	3.7 MWh	-17%

PVWatts simulation results using site survey data for a two-string PV system.

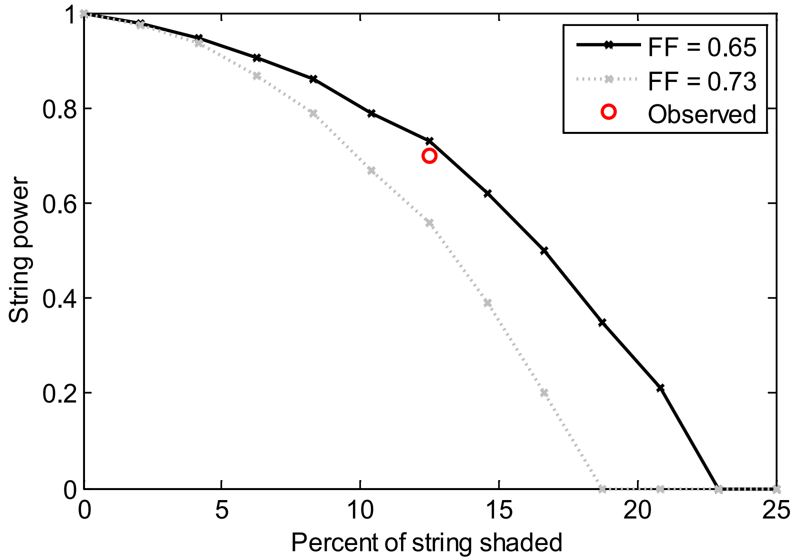
Large commercial installation

This 1MW installation has 16 PV modules per string. Periodic shading occurs from nearby light poles.

Morning power loss is monitored with DC current transducers. 30% loss is coincident with 12.5% string shading



Modeled shade impact for large parallel systems. Note that higher FF is more sensitive to shade.



Current / Future work at NREL

- Shade simulation feature going into Solar Advisor Model, specifically for inter-row shading of large utility-scale systems.
- Further work on developing and validating shaded PV models
- Test & Evaluation of DC-DC converter devices and micro-inverters to determine the performance improvement

Questions / Comments?

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Backup slides

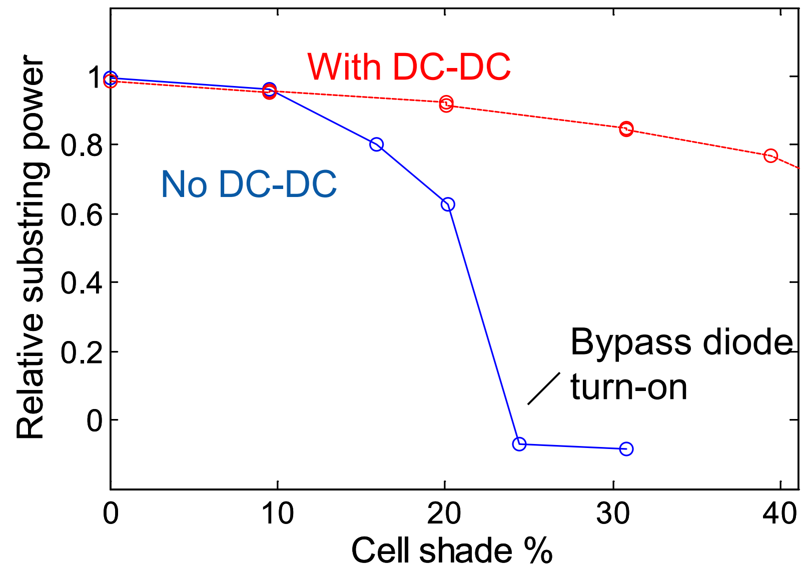
Results – single module shading

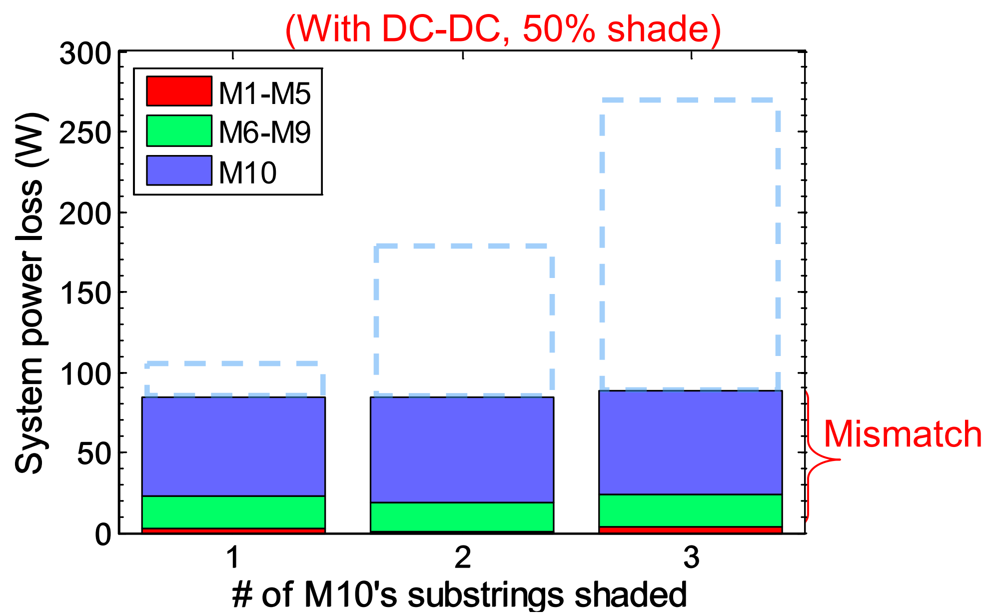
Without DC-DC devices:

- Single-cell shading of 25% causes bypass diode turn-on
- Mismatch loss accounts for ~40% of the total shade loss

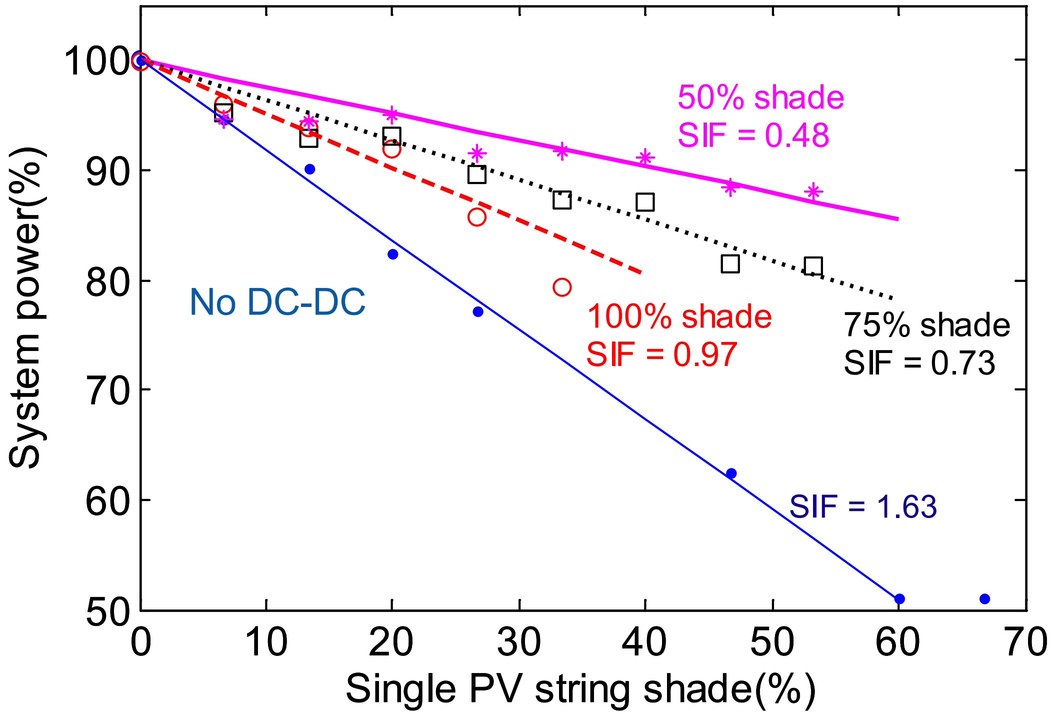
With DC-DC devices:

- Bypass diode turn-on can be delayed
- Mismatch losses reduced
- Shaded module output proportional to shade opacity





Results – Shade Impact Factor



Shade Impact Factor without DC-DC= 1.63
With DC-DC, SIF = shade opacity