Shade Matters

Peter Hoberg
Solmetric Corporation
Shade Matters

- Shade’s impact on PV production
  - Cell, module, string, array
  - Example measurements

- Characterizing shade
  - Why measure shade?
  - Shade measurement strategies
  - Dealing with shade

- Predicting energy production
  - Ballpark estimates
  - Analytical tools

- Resources, Questions and Answers
Basic PV System

Source: http://www.eere.energy.gov/consumer/your_home/electricity/index.cfm/mytopic=10720
Shading: a little bit goes a long way

Business Card covering half of one cell
Disproportional Impact of Mismatches


<table>
<thead>
<tr>
<th>Shade</th>
<th>Power loss Series connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15%</td>
<td>3.7%</td>
</tr>
<tr>
<td>2.6%</td>
<td>16.7%</td>
</tr>
<tr>
<td>11.1%</td>
<td>36.5%</td>
</tr>
</tbody>
</table>

Nine (multi-crystalline) Photowatt PW1650 (4 bypass diodes) connected in series to a SMA Sunny Boy SB1100 inverter

Slide courtesy of:
Solar Cell

- Charge generation
- Charge separation
- Charge collection

Photon
I-V Curves

Diode:
- Forward conduction
- Power dissipation
- Reverse breakdown

Solar cell:
- Reverse breakdown
- Power production

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Maximum Power Point

Contours of constant power generation $I \times V$

Max power

$Imp \times Vmp$

$+ 0.6 \, V$

$Vmp$

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Cells in Series & Parallel

Max power point

I-V curve of the array
Bypass Diodes

- **Cell without bypass diode**
  - Point A
  - Wasted power
- **Cell with bypass diode**
  - Point B
  - Max Power

- **Partially shaded cell**
  - Unshaded cell
  - Partially shaded cell

- **Max Power**

- **I** vs. **V**

- **-12 V** to **+0.6 V**

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How Cells Become Reverse Biased

Vreverse = (N-1) x Vnew – N x Vpmax = N x (Vnew – Vpmax) - Vnew

N = # of cells
Inverter dynamics
Max Power Point Tracking (MPPT) Methods

- ‘Perturb & observe’ or ‘hill climbing’
- $\Delta P/\Delta V$
- Fraction of $V_{oc}$ or $I_{sc}$
- Fuzzy logic
- Neural network
- Ripple correlation
- Current sweep
- Load current or load voltage maximization
- $dP/dI$ or $dP/dV$ feedback control

From “Comparison of PV array maximum power point tracking techniques,” Esram & Chapman, 2007
Max Power Point Tracking (MPPT)
Perturb & Observe method

$P_{\text{max}}$

$V$

$V + \Delta V$

$P$

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The Challenge of Partial Shading

Contours of constant power generation ($I \times V$)
Strings in Parallel

String I-V curves

String max power points

Note: Shaded strings can be further penalized by operating below MPP
Shading Demonstration

Shading conditions:

1. No shade
2. Shade ½ of one module
3. Shade 1 cell
4. Place credit card on one cell

West string  →  East string

2 strings of 12 BP SX120 modules
PV Array Performance Analyzer

Copyright Solmetric Corporation, 2009
I-V Curve of Un-shaded String

1 string of 12 BP SX120 modules (864 cells in series)
½ of One Module Shaded

1 string of 12 BP SX120 modules (864 cells in series)

Copyright Solmetric Corporation, 2009
One Cell Shaded

1 string of 12 BP SX120 modules (864 cells in series)
Credit Card Placed on One Cell

1 string of 12 BP SX120 modules (864 cells in series)
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• Resources, Questions and Answers
Insolation for fixed plane (San Diego)

Annual Insolation as a Function of Panel Orientation
Location: SAN DIEGO LINDBERGH FI, CA  Optimal Tilt=32°, Azimuth=191°, Insolation=2143 kWh/m²
Station ID: 722900, Latitude: N 32.73, Longitude: W 117.17

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Insolation for fixed plane (Honolulu)

Annual Insolation as a Function of Panel Orientation
Location: HONOLULU INTL ARPT, HI  Optimal Tilt=24°, Azimuth=143°, Insolation=2060 kWh/m²
Station ID: 911820, Latitude: N 21.32, Longitude: W 157.93

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Why measure shade?

• Choose optimum location for panels
• Identify issues early in the process
• Ensure sufficient energy production
• Ensure optimum state rebate

Remember: Shading can have disproportionate impact on energy production
Shade through a fisheye lens
Steps for measuring solar access

1. Point south
2. Hold Level
3. Press the button
Shade measurement strategies

• Take multiple point readings
  – Spacing between readings
• Look for worst case
  – Array corners
  – Points closest to obstructions
• Average solar access readings
• Obstruction elevation angles

Note: Be sure you meet the requirements of your state program and rebate calculators
Dealing with Shade

- Optimize Shade-Free production
  - Avoid shade whenever possible
  - Find the best location for the desired season/time-of-day

- Tree removal
  - Reduce shade
  - Minimize debris

- Module Level MPP
  - Incorporate new technologies that mitigate shade impact
The SolarMagic™ Power Optimizer

**SolarMagic™ Input**
- High speed MPPT algorithms maximize panel energy harvest
- Wide-input range accommodates almost all panel types

**SolarMagic™ Output**
- Automatically scales output current and voltage to optimize power of the entire string.
- Wide output range maximizes flexibility
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PV energy production

Sun Az/El, panel tilt/Az
Insolation, temp., wind speed

Module-level shading
Module parameters
Inverter parameters, MPP behavior

AC kWh
Predicting energy production

• Solar Calculators:
  – PVWatts by NREL
  – Vendor web sites
  – State rebate calculators
    • CSI Incentive Calculator (EPBB Calculator)
    • NSHP Calculator
  – Commercial software products
    • PV*SOL, PV-Syst, Laplace, Maui
    • On-grid, CPF Tools, Clean Power Estimator
    • Etc.
### Station Identification

<table>
<thead>
<tr>
<th>Cell ID</th>
<th>0175345</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>California</td>
</tr>
<tr>
<td>Latitude</td>
<td>38.5 ° N</td>
</tr>
<tr>
<td>Longitude</td>
<td>122.6 ° W</td>
</tr>
</tbody>
</table>

### PV System Specifications

<table>
<thead>
<tr>
<th>DC Rating</th>
<th>4.00 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC to AC Derate Factor</td>
<td>0.770</td>
</tr>
<tr>
<td>AC Rating</td>
<td>3.08 kW</td>
</tr>
<tr>
<td>Array Type</td>
<td>Fixed Tilt</td>
</tr>
<tr>
<td>Array Tilt</td>
<td>38.5 °</td>
</tr>
<tr>
<td>Array Azimuth</td>
<td>180.0 °</td>
</tr>
</tbody>
</table>

### Energy Specifications

| Cost of Electricity | 12.7 ¢/kWh |

### Calculator for Overall DC to AC Derate Factor

<table>
<thead>
<tr>
<th>Component Derate Factors</th>
<th>Component Derate Values</th>
<th>Range of Acceptable Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module nameplate DC rating</td>
<td>0.95</td>
<td>0.80 - 1.05</td>
</tr>
<tr>
<td>Inverter and Transformer</td>
<td>0.92</td>
<td>0.88 - 0.95</td>
</tr>
<tr>
<td>Mismatch</td>
<td>0.98</td>
<td>0.97 - 0.96</td>
</tr>
<tr>
<td>Diodes and connections</td>
<td>0.995</td>
<td>0.99 - 0.997</td>
</tr>
<tr>
<td>DC wiring</td>
<td>0.98</td>
<td>0.97 - 0.99</td>
</tr>
<tr>
<td>AC wiring</td>
<td>0.99</td>
<td>0.98 - 0.993</td>
</tr>
<tr>
<td>Soiling</td>
<td>0.95</td>
<td>0.30 - 0.995</td>
</tr>
<tr>
<td>System availability</td>
<td>0.98</td>
<td>0.00 - 0.995</td>
</tr>
<tr>
<td>Shading</td>
<td>1.00</td>
<td>0.00 - 1.00</td>
</tr>
<tr>
<td>Sun-tracking</td>
<td>1.00</td>
<td>0.95 - 1.00</td>
</tr>
<tr>
<td>Age</td>
<td>1.00</td>
<td>0.70 - 1.00</td>
</tr>
</tbody>
</table>

**Overall DC to AC derate factor**

0.77  

*(PVWATTS Default)*
**Calculation Type**
- Standard PV
- Other Solar Generating Technologies
- MASH

**Documentation**
- What's New
- PV User Guide
- Other Solar Generating Technologies User Guide

Get Adobe Reader
Calculator Source Code

**Links & Resources**
- PG&E
- SCE
- CSSE
- Go Solar California

**Site Specifications:**
- Project Name: Hoberg
- ZIP Code: 95403
- Utility: PG&E
- Customer Type: Residential
- Incentive Type: EPBB

**PV System Specifications:**
- PV Module: Evergreen Solar ES-B 200-fb1
  200W Glass-EVA-Tedlar Construction with MC Connectors (177.90W PTC)
- Number of Modules: 20
- Mounting Method: >1" to 3" average standoff
- Inverter: SMA America: SB4000US (208V)
  4kW, 208Vac Sunny Boy Utility Interactive Inverter with display (95.5% efficiency)
- Number of Inverters: 1
- Shading:
  - [ ] Minimal Shading

**Shading Derate Factors (%)**
- January: 100
- February: 100
- March: 100
- April: 100
- May: 100
- June: 100
- July: 100
- August: 100
Solmetric PV Designer
Some References

- Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques (Esram and Chapman)
- On-site Measurements of photovoltaic systems for detection of failure modules (Oozeki, Yamada, and Kato)
- MATLAB-Based Modeling to Study the Effects of Partial Shading on PV Array Characteristics (Patel Agarwal)
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Questions?

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