Shading Effects on Photo-Voltaic Arrays

The impact of partial shading of your PhotoVoltaic system

on System Energy Yield

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Abstract

The effects of partial shading on photovoltaic modules is modeled and the impact on energy production for various conditions is shown. Methods of mitigating losses and economic impacts are discussed. Examples and qualitative results are shown.

Outline

• Solar Irradiance	• 1 slide	
• Typical Solar Cell	• 1 slide	
• Typical Solar Module	• 2 slides	
• Typical Solar Array	• 3 slides	3 mins.
• Silicon cell equivalent circuit model.	• 6 slides	
• Definition of terms		
• Datasheets		10 mins?
• Model Details	• 3 slides	3 mins
• Test/verification details	• 2 Slides	2 min.

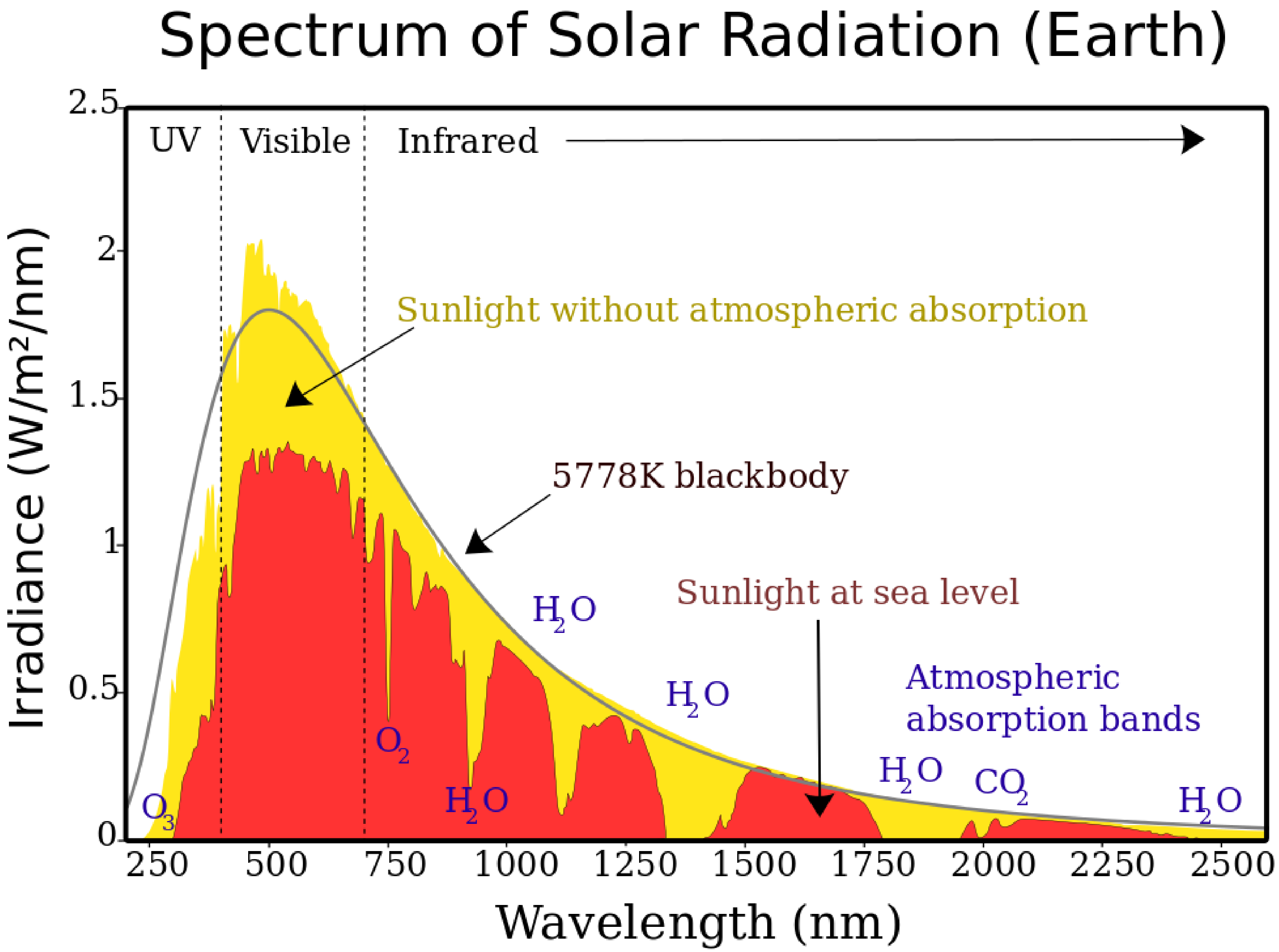
Outline

• Module level Model results	• 3 slides	2 mins.
• Shading Considerations	• 2 slides	3 mins.
• Reverse Voltage	• 3 slides	2 mins
• Cell mismatch effect	• 3 slides	2 mins
• Quiz #1	• 2 slides	2 mins
• Shading Effects on String & Array yield	• 1 slide	
• Module MPP, String MPP	• 2 slide	3 mins
• Mitigation method: Bypass Diodes		
• Module MPP, String MPP, Array MPP	• 3 slides	3 mins
• Site Survey importance	• 2 slides	mention

Outline

• Quiz #2	• 2 slides	2 mins
• Actual test results		
• Effects of snow cover	• 5 slides	3 mins
• Model correlation	• 3 slides	3 mins
• Mitigation method: Module Optimizers	• 1 slide	
• Performance example	• 2 slides	
• ROI calculations	• 2 slides	
• Quiz #3	• 2 slides	1 mins
• Reference material & footnotes	• 2 slides	0 min

Solar Irradiance



Typical Hi-η Solar Cell

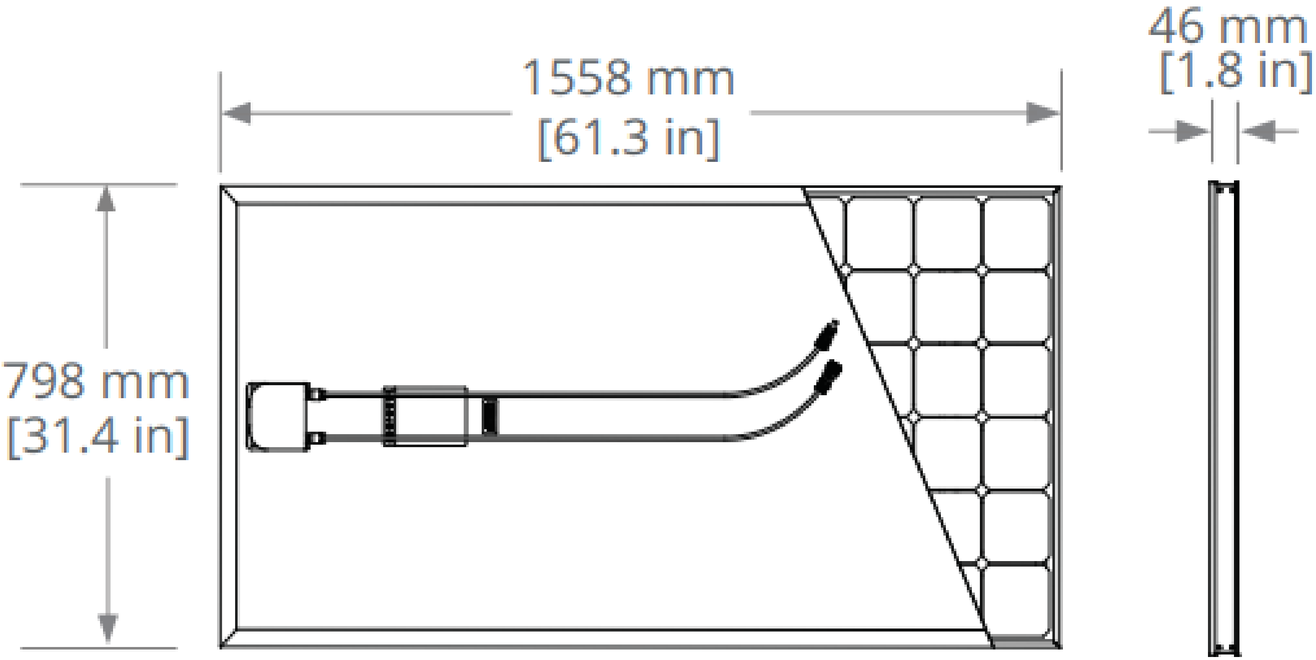
SunPower Maxeon High-efficiency monocrystalline cell

Backside Metalization, Frontside active area, 124 mm square

Typical Solar Module

“Panels” are referred to as Modules.

Dimensions for SPR E20-245 modules on my roof:



Typically 60, 72 or 96 series-connected cells per Module

- A “72s1p” module, 1.28 m^2, in this case

Typical Solar Module [4]

Wiring:

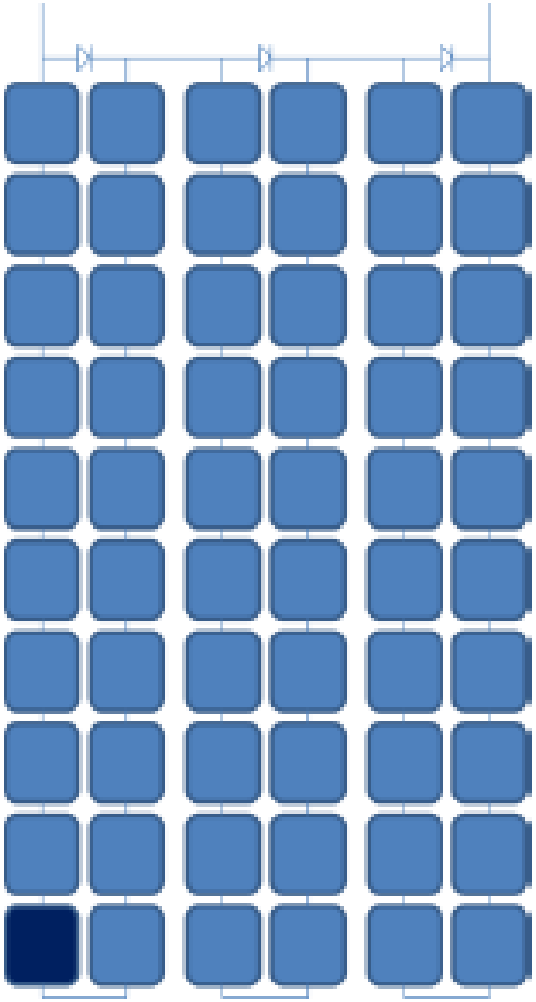
- Series-connected strings
- Typically three sub-strings, with
- Three Bypass Diodes

60, 72 or 96 series-connected cells per Module

- A “60s1p” module, in this illustration, with
- (3) 20s substrings

Bypass Diodes – what for?

- Cell Vf typ. 0.5V ~ 0.6V (can be calculated from any module datasheet)
- Cell Vr: -2.5V ~-20V (NOT typically reported on module datasheets)



Typical Solar Array

Modules assembled into Array

A view of the modules on my roof: East Array, facing South

9 plus 7 SPR-245 E19 modules, wired 8S-2P

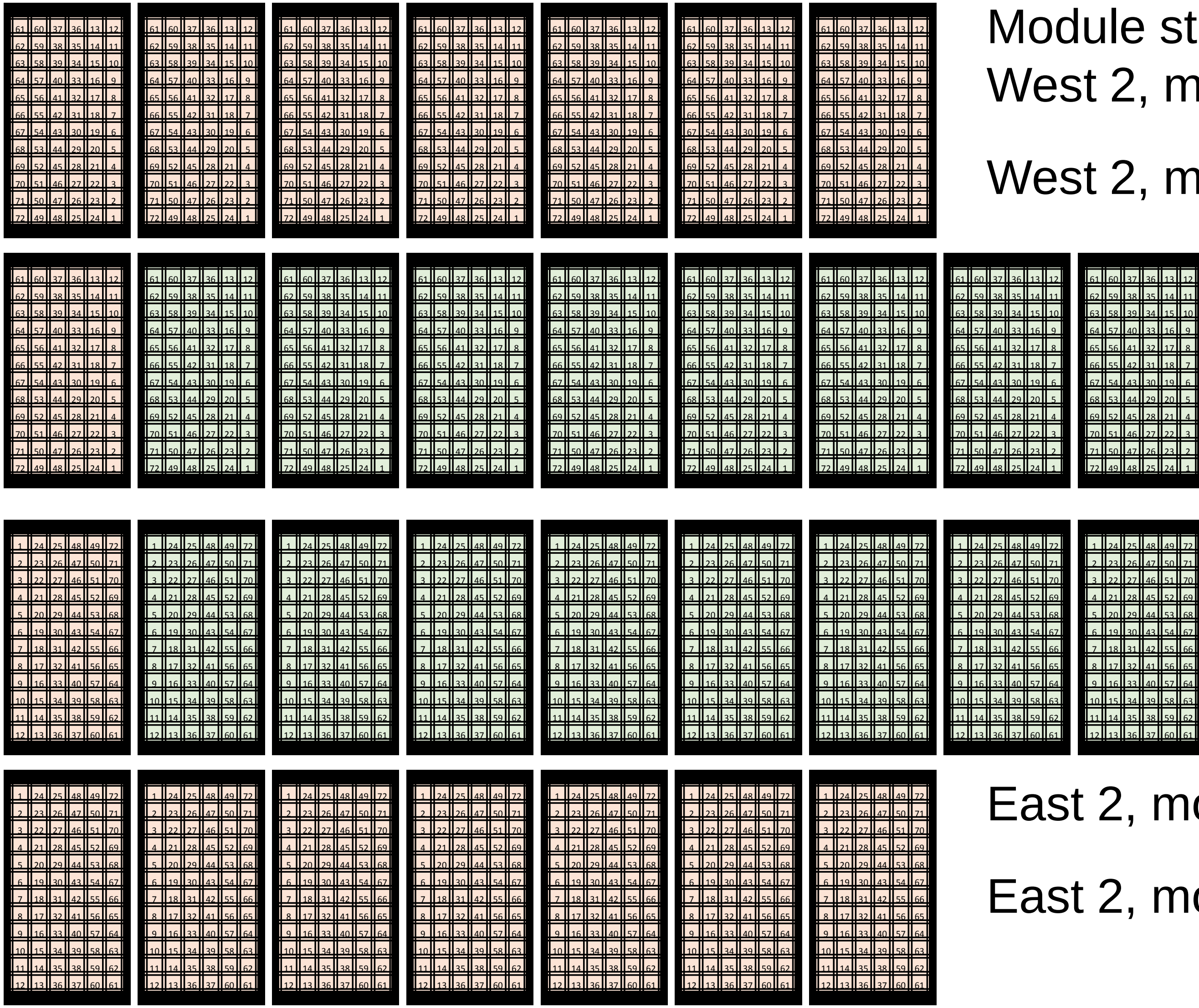
Typical Solar Array

A view of the modules on my roof: West Array, facing South East

9 plus 7 SPR-245 E19 modules, wired 8S-2P

Total : 2 Arrays, 8S-2P, feeding Grid-Tied Inverter with Dual MPP (Maximum Power Point) tracking.

Typical Solar Array



Module strings, Top – bottom:
West 2, mod 2-8

West 2, mod 1, West 1, mod 1-8

East 2, mod 1, East 1, mod 1-8

East 2, mod 2-8

Silicon cell equivalent circuit model

- Some definitions & terms
  - V_{oc} (Open-circuit Voltage):
    - Output voltage, no load (zero power delivery)
  - I_{sc} (Short-circuit current):
    - Output current, terminals shorted (zero power delivery)
  - MPP (Maximum Power Point) curve
    - Point on the I-V output curve that I*V (power output) is maximum
  - STC (Standard Test Condition) : 25°C, 1000 W/m^2 Irradiance, AM1.5 SSID
    - SSID = Solar Spectral Irradiance Distribution
  - NOCT (Nominal Operating Cell temperature)
    - 800W/m^2, 20°C amb. Temp., 1m/s wind speed

Silicon cell equivalent circuit model

- Used on the data sheet

PLATFORM ELECTRICAL DATA

STC Values

		At Standard Test Conditions						
Module	Platform (Number of cells)	Nominal Power	Power Tolerance (%)	Rated Voltage Vmp (V)	Rated Current Imp (A)	Open Circuit Voltage Voc (V)	Short Circuit Current, Isc (A)
SPR-E20-327	96	327	+5/-0	54.7	5.98	64.9	6.46
SPR-E19-320	96	320	+5/-0	54.7	5.86	64.8	6.24
SPR-E20-245	72	245	+5/-0	40.5	6.05	48.8	6.43
SPR-E19-235	72	235	+5/-0	40.5	5.80	48.4	6.18

Silicon cell equivalent circuit model

- Definitions & terms cont'd
  - Voltage & Power Temperature coefficients
    - For c-Si: Voc & Pwr TCs are negative,
      Isc TC slightly positive

TEMPERATURE COEFFICIENTS & EFFICIENCY REFERENCES

	At Standard Test Conditions		Basic Temperature Data				Efficiency Numbers		
Module	Nominal Power	Avg Power	Current (Isc) Temp. Coeff. (mA/ºC)	Voltage (Voc) Temp. Coeff. (mV/ºC)	Power Temp. Coeff. (%/ºC)	NOCT @ 20ºC (Value +/- 2ºC)	Average Power Efficiency (%)	Nominal Peak Power per Unit Area (W/m²)	N
SPR-E20-327	327	333	2.6	-176.6	-0.35%	45.0	20.4%	204.2	
SPR-E19-320	320	324	2.6	-176.6	-0.35%	45.0	19.9%	198.6	
SPR-E20-245	245	249	2.6	-132.5	-0.35%	45.0	20.0%	200.2	
SPR-E19-235	235	240	2.6	-132.5	-0.35%	45.0	19.3%	192.9	

Silicon cell equivalent circuit model

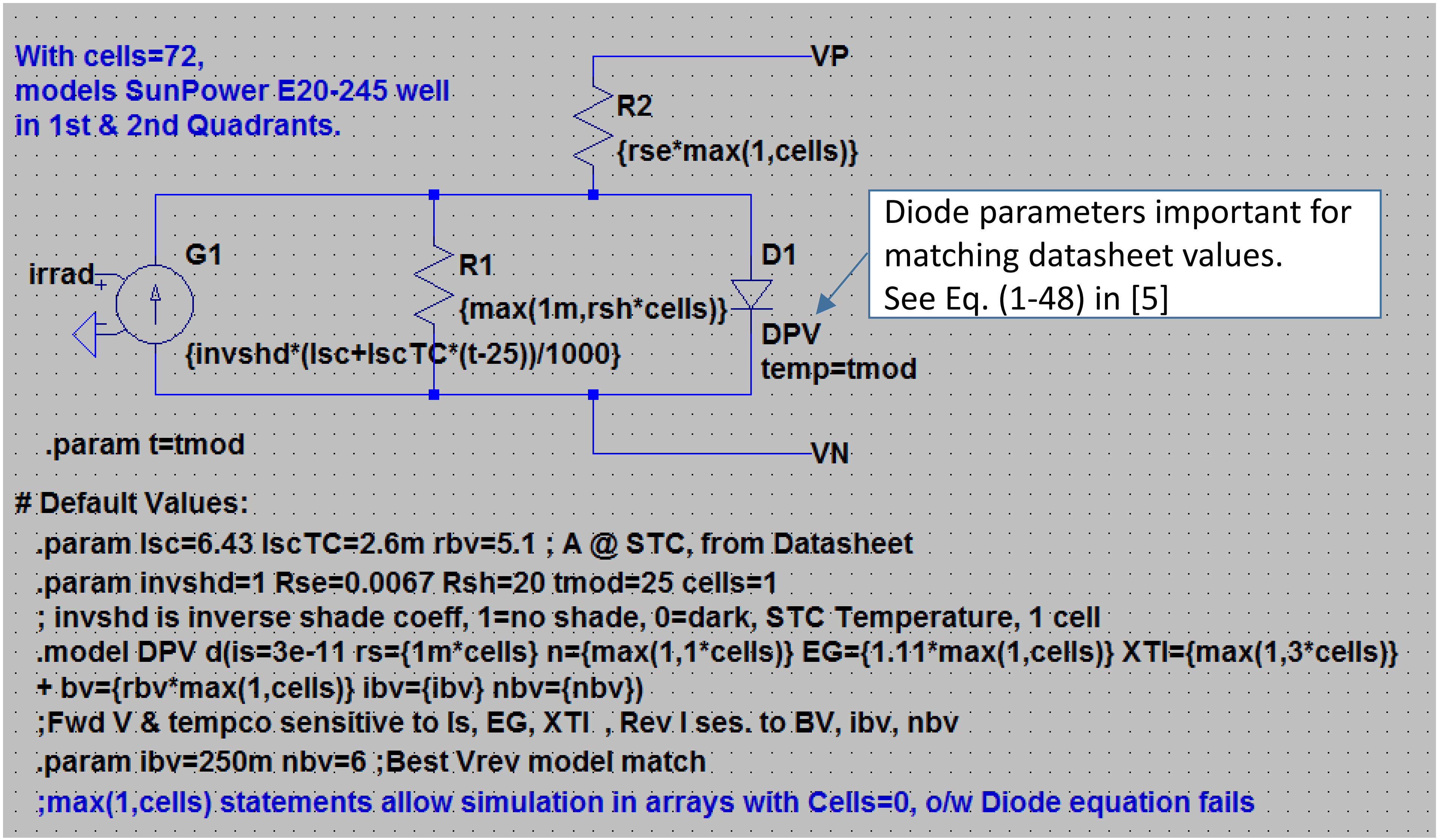
- Definitions & terms cont'd
- STC (Standard Test Condition) : 25°C, 1000 W/m^2 Irradiance, AM1.5 SSID
- SSID = Solar Spectral Irradiance Distribution
  - See earlier Irradiance slide
- NOCT (Nominal Operating Cell temperature)
  - 800W/m^2, 20°C amb. Temp., 1m/s wind speed

PLATFORM PERFORMANCE AT NOCT

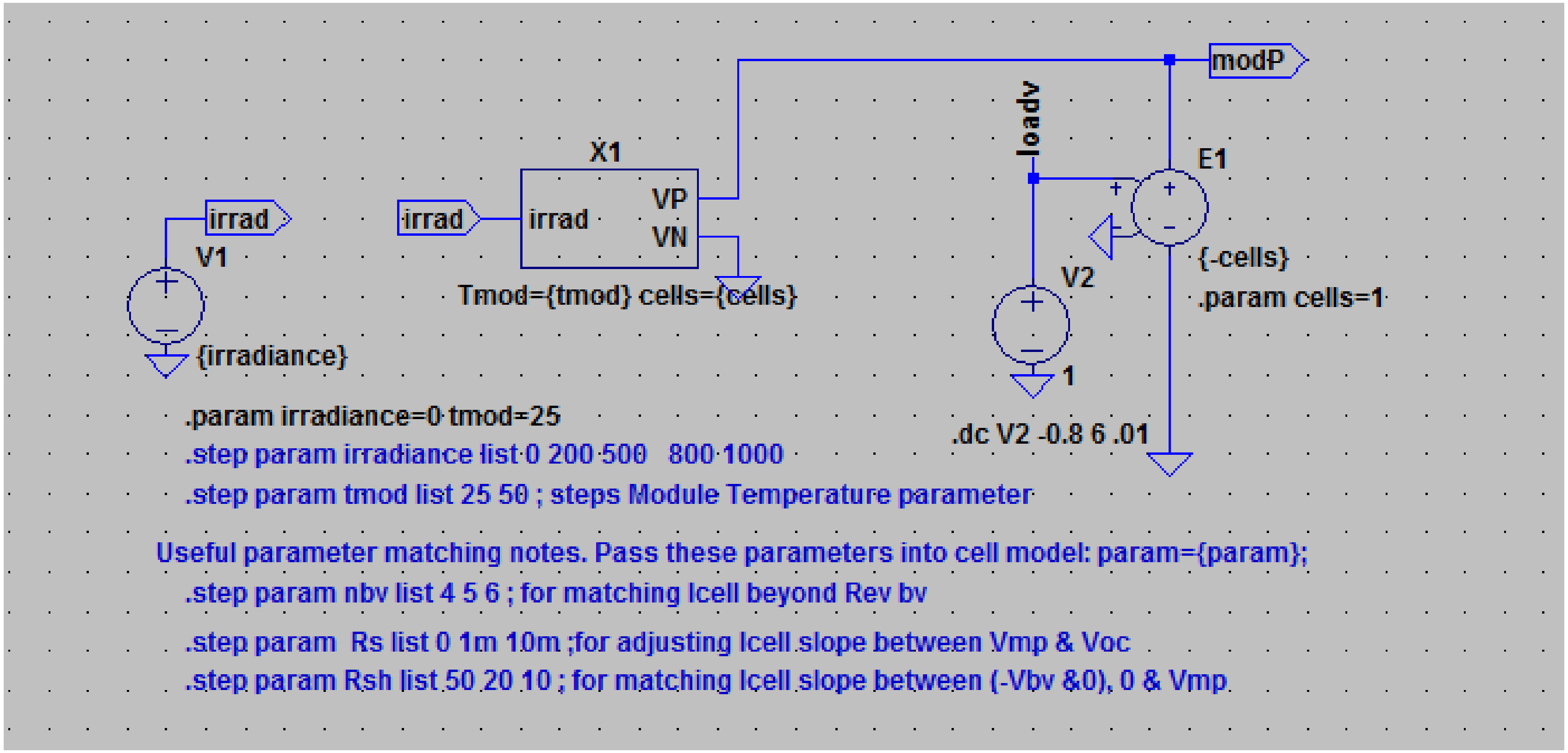
(800 W/m^2, 20°C ambient, 1 m/s wind speed)

	At STC	Nominal Electrical data at NOCT (NOCT : 800W/m^2, 20°C amb. Temp., 1m/s wind speed)					
Module	Nominal Power	NOCT Pnom	NOCT Vmpp	NOCT Impp	NOCT Voc	NOCT Isc	NOCT % of rated
SPR-E20-327	327	246	51.5	4.82	60.8	5.22	75.2%
SPR-E19-320	320	243	51.5	4.72	60.7	5.04	75.9%
SPR-E20-245	245	182	37.4	4.88	45.7	5.20	74.4%
SPR-E19-235	235	175	37.4	4.68	45.3	5.00	74.4%

Silicon cell equivalent circuit model



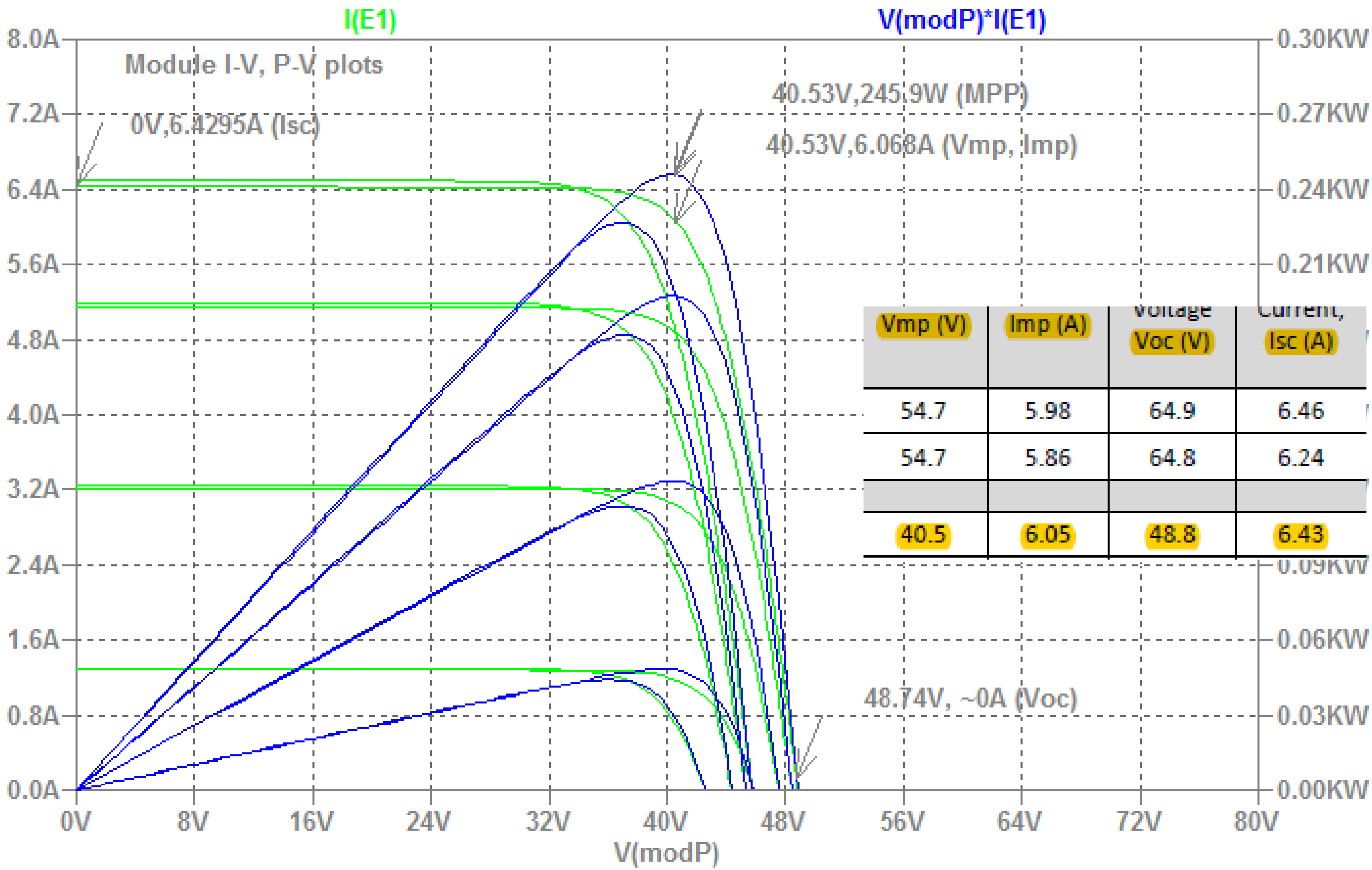
Silicon cell eq ckt & string test file



- Includes notes on parameter stepping

  Shows parameters to adjust to match I-V curve to measured values

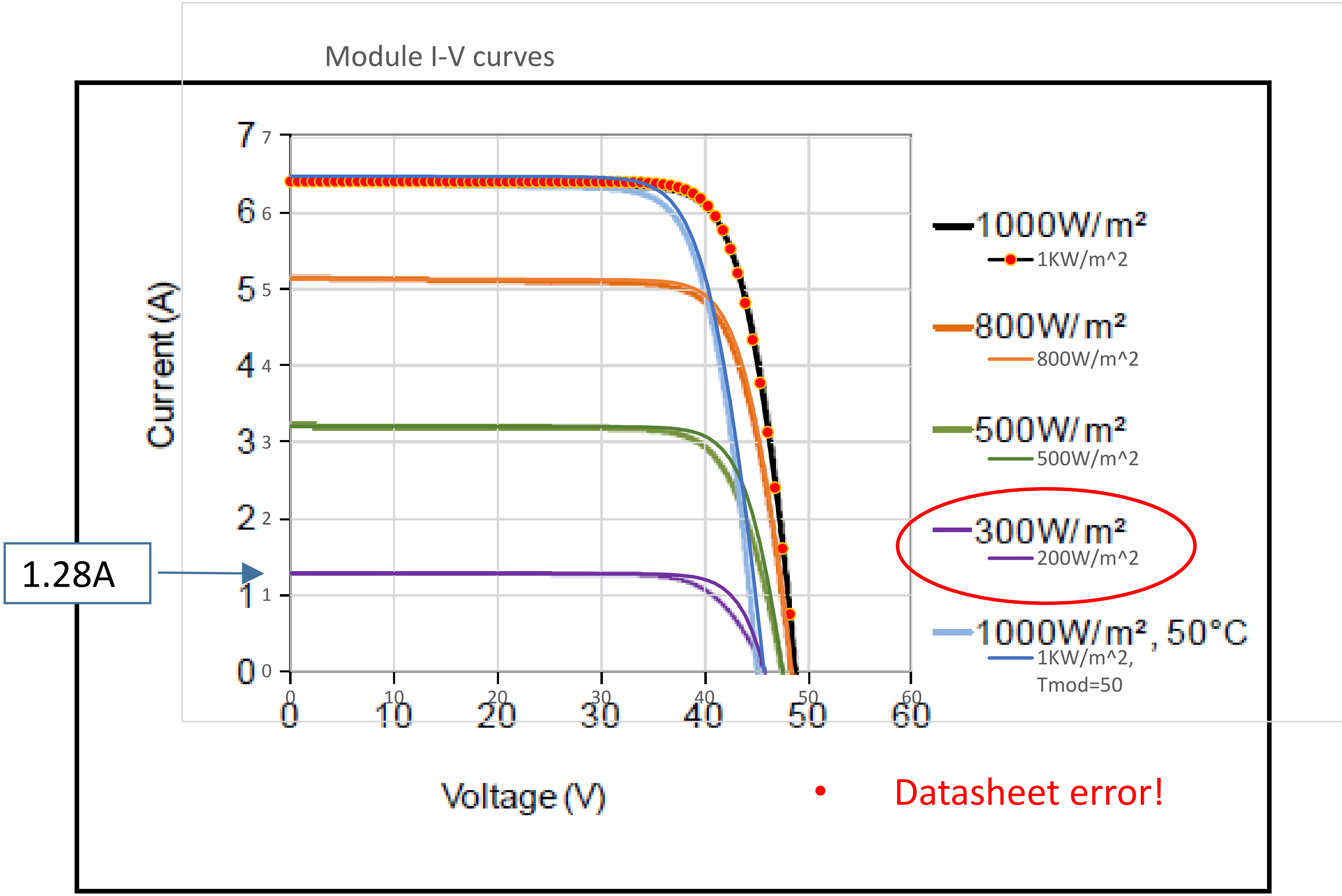
Module – level results



Vmp (V)	Imp (A)	Voltage Voc (V)	Current, Isc (A)
54.7	5.98	64.9	6.46
54.7	5.86	64.8	6.24
40.5	6.05	48.8	6.43

Module – level results

SPR-E20-245



- Datasheet error!

Module – level results

- Datasheet error? (!)
  - ds curve 300 W/m^2 matches
    sim curve@ 200W/m^2
  - Simulation reasonably matches Low Irradiance data

PLATFORM PERFORMANCE AT LOW IRRADIANCE

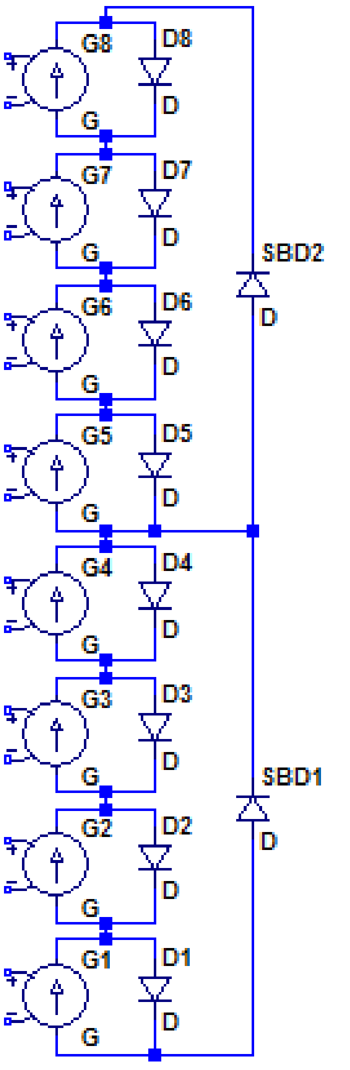
(200 W/m^2, 25°C cell temperature, air mass 1.5 SSID*)

	At STC	Irradiance vs. Power at Low Irradiance (200W/m^2 and @25°C (SNL coefficients))			
Module	Nominal Power	Low irradiance Pmpp (W)	Low irradiance Vmpp (V)	Low irradiance Impp (A)	Pctg. of nominal power
SPR-E20-327	327	62.8	52.0	1.21	19.2%
SPR-E19-320	320	61.5	52.0	1.18	19.2%
SPR-E20-245	245	47.0	38.5	1.22	19.2%
SPR-E19-235	235	45.1	38.5	1.17	19.2%

*SSID = Solar Spectral Irradiance Distribution

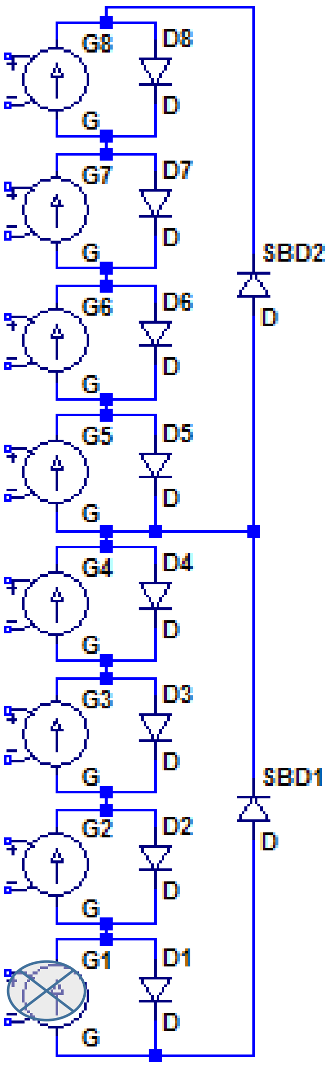
Shading consideration

- Module panels are series-connected photodiode cells
- Modeled as irradiation-dependent current sources with a maximum Voc.
- All cells in a string must be closely matched in terms of generated current vs. irradiance.
- If shading reduces irradiance on one or more cells in a string, current generated by those cells decreases



Shading consideration

- MPP Tracker may drive Cell into reverse voltage “Zener” characteristic
- Reverse voltage & shaded cell power dissipation limited by using bypass diodes
- Typical bypass diode arrangement is three per module
- Cell designs that have a lower reverse “Zener” voltage would have lower shaded power dissipation



Reverse Voltage characteristic

- From SunPower [1], cell I-V characteristics are shown for Gen II (E-Series) and Gen III (X-Series) cells

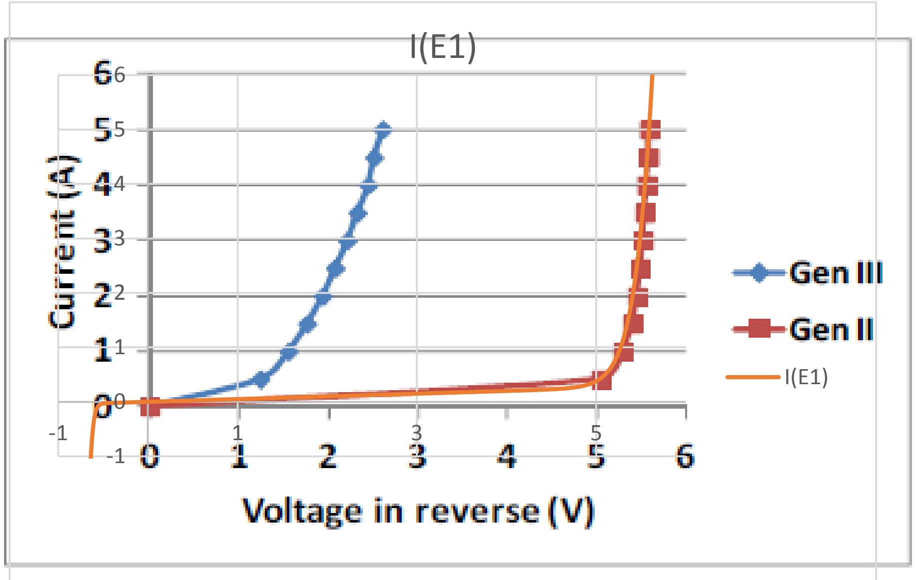
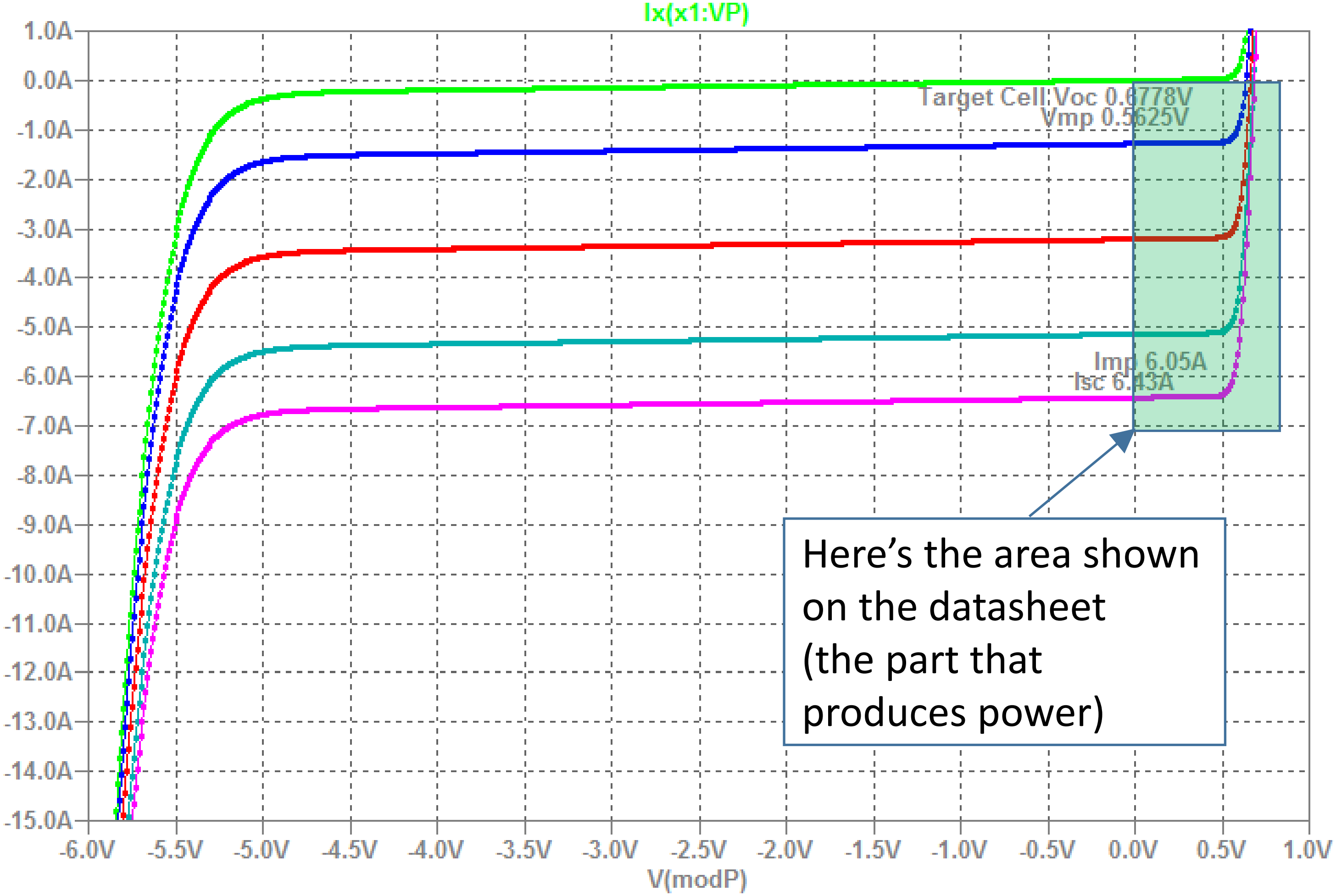


Fig. 6. Reverse current-voltage characteristic of Maxeon Gen III cells.

- These values not typically disclosed on datasheets

Cell 2-quadrant I-V char.

- Sign convention: (+I) flows into (VP) terminal



Cell 2-quadrant I-V char.

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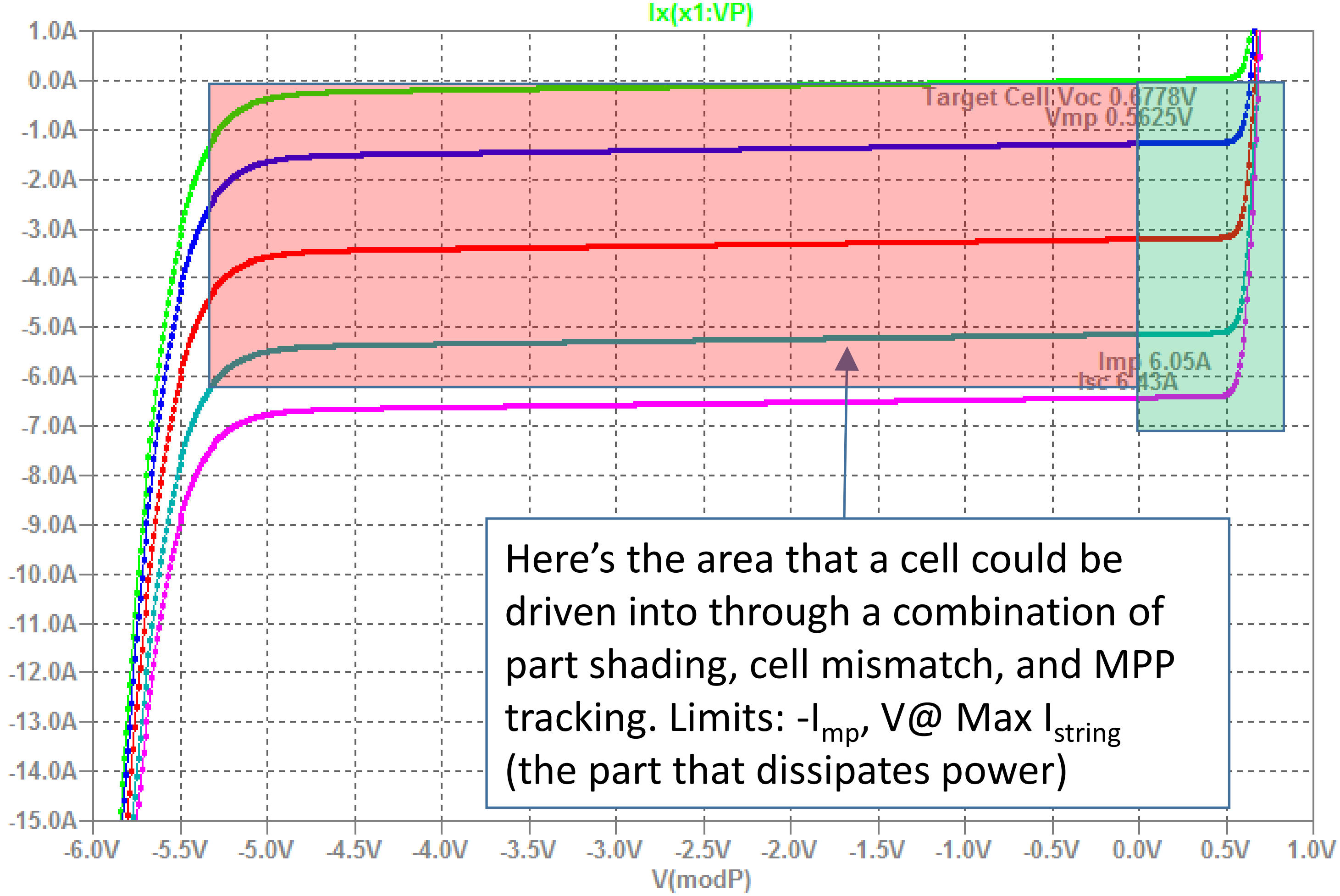
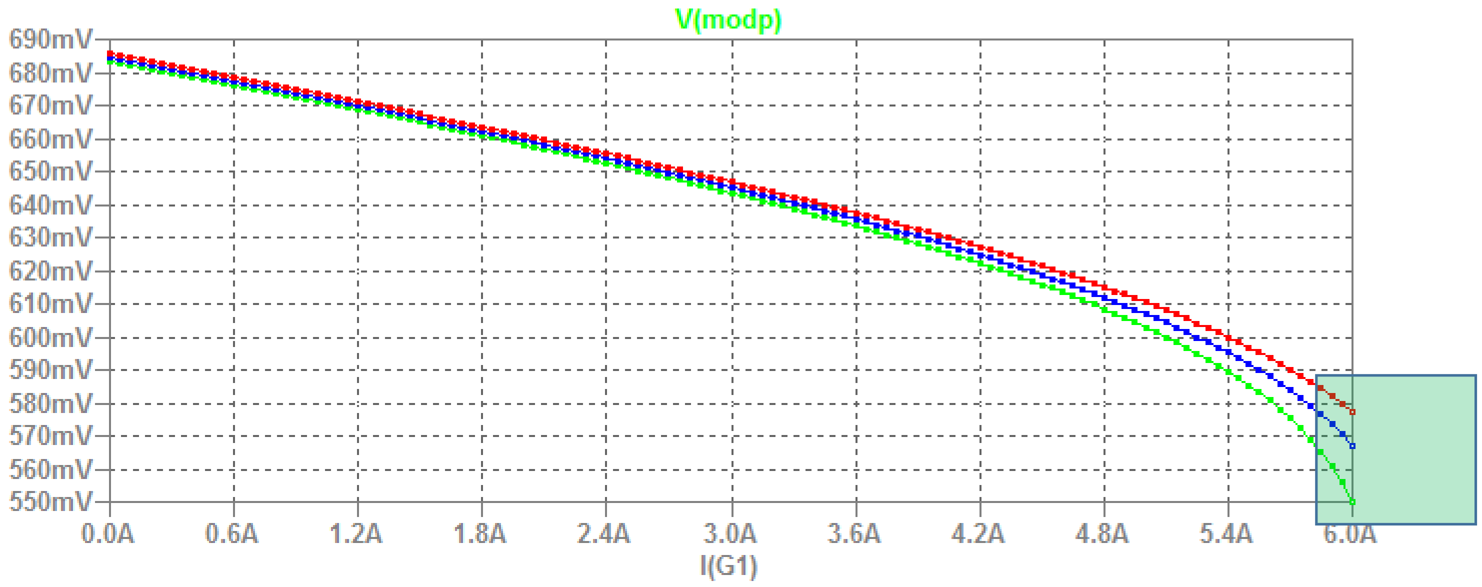


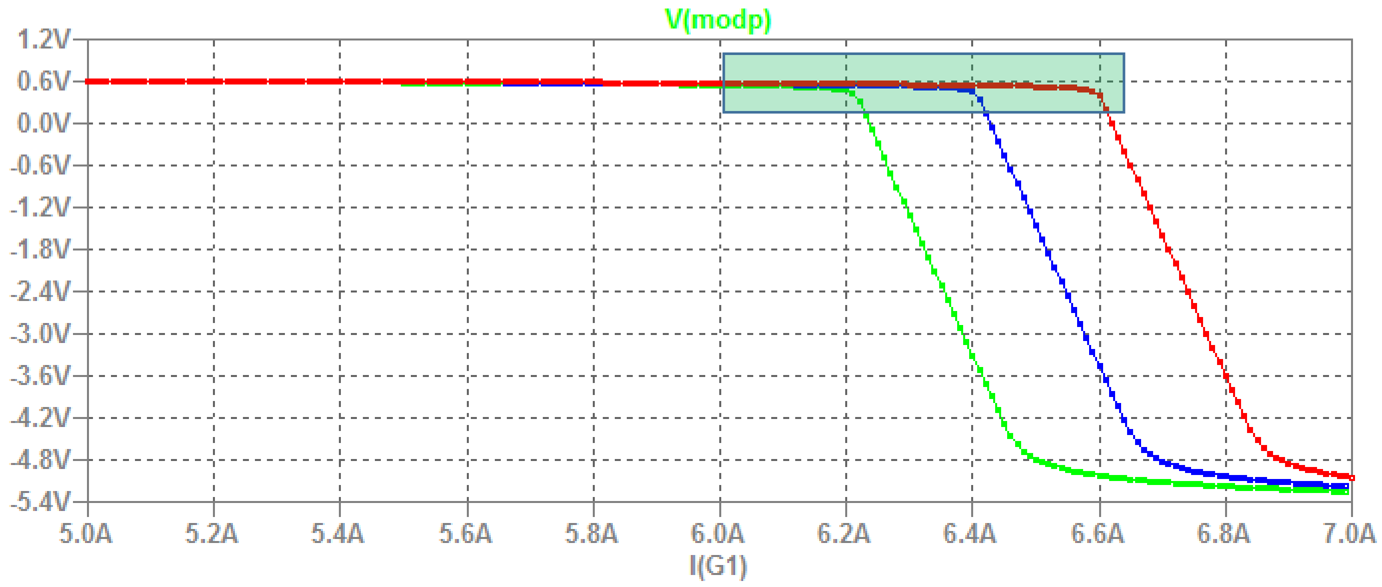
Cell mismatch I-V char.

- Vary Cells' (irradiance gain), +/-3% mismatch
- Sweep Cell Iout (as an MPP tracker would)



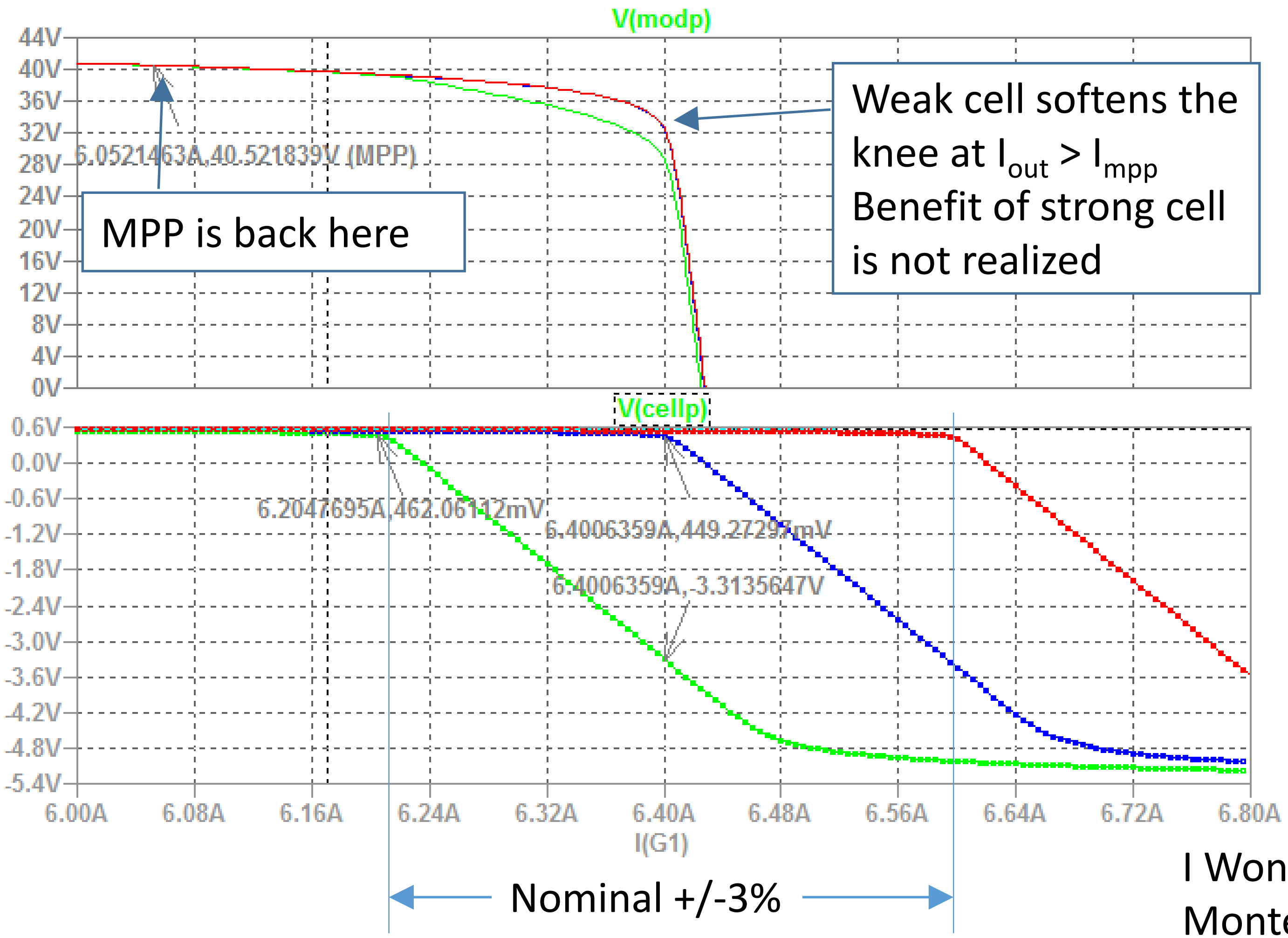
Cell mismatch I-V char.

- Three Cells, +/-3% (irradiance gain) mismatch
- Sweep Cell Iout (as an MPP tracker would)



Cell mismatch I-V char.

- One Cell, +/-3%, 71 cells nominal



I Wonder what a 3% Monte-Carlo run would look like…

Quiz #1 Questions

1. Cells in solar modules produce (x) in proportion to Irradiance, and are connected in (y) circuit configuration?
   a. (Current), and (parallel) connected
   b. (Voltage), and (parallel) connected
   c. (Current), and (series) connected
   d. (Voltage), and (series) connected

2. Silicon photovoltaic cells have temperature coefficients that are:
   a. (Small Negative) Voltage, (Small Negative) Current
   b. (Small Negative) Voltage, (Small Negative) Current
   c. (Moderate Negative) Voltage, (Small Positive) Current
   d. (Moderate Positive) Voltage, (Small Positive) Current

Quiz #1 Answers

1. Cells in solar modules produce (x) in proportion to Irradiance, and are connected in (y) circuit configuration?

   a. (Current), and (parallel) connected
   b. (Voltage), and (parallel) connected
   c. (Current), and (series) connected
   d. (Voltage), and (series) connected

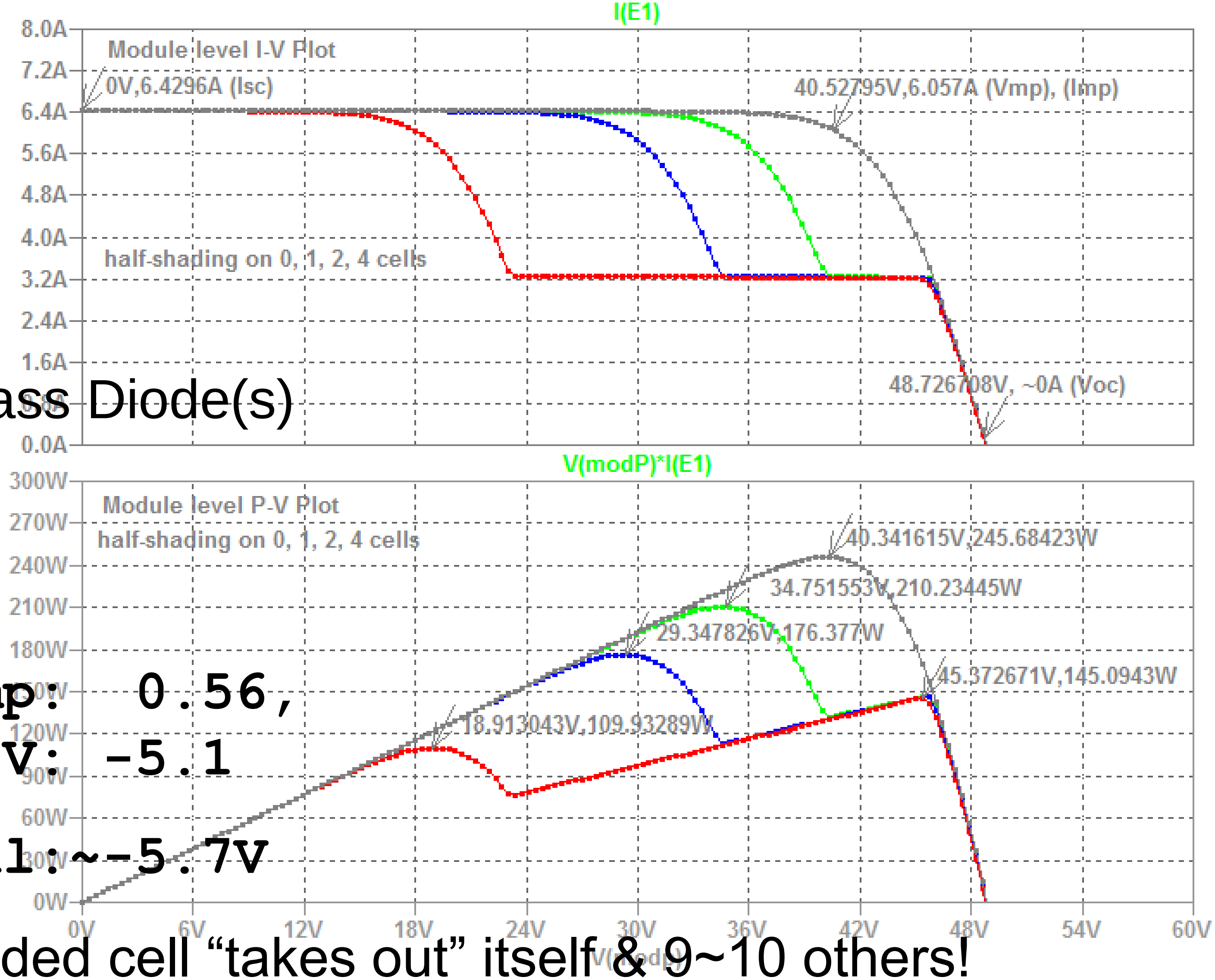
2. Silicon photovoltaic cells have temperature coefficients that are:

   a. (Small Negative) Voltage, (Small Negative) Current
   b. (Small Negative) Voltage, (Small Negative) Current
   c. (Moderate Negative) Voltage, (Small Positive) Current
   d. (Moderate Positive) Voltage, (Small Positive) Current

Shading considerations

- Next… Part-shade of 1, 2, 4 cells
  - MPPT without bypass diodes – string level (8s1p)
  - MPPT with bypass diodes – String level
  - MPPT at array level (8s2p)
- Excel spreadsheet for ease of evaluating more complex shading patterns

Module Partial Shade performance



No Bypass Diode(s)

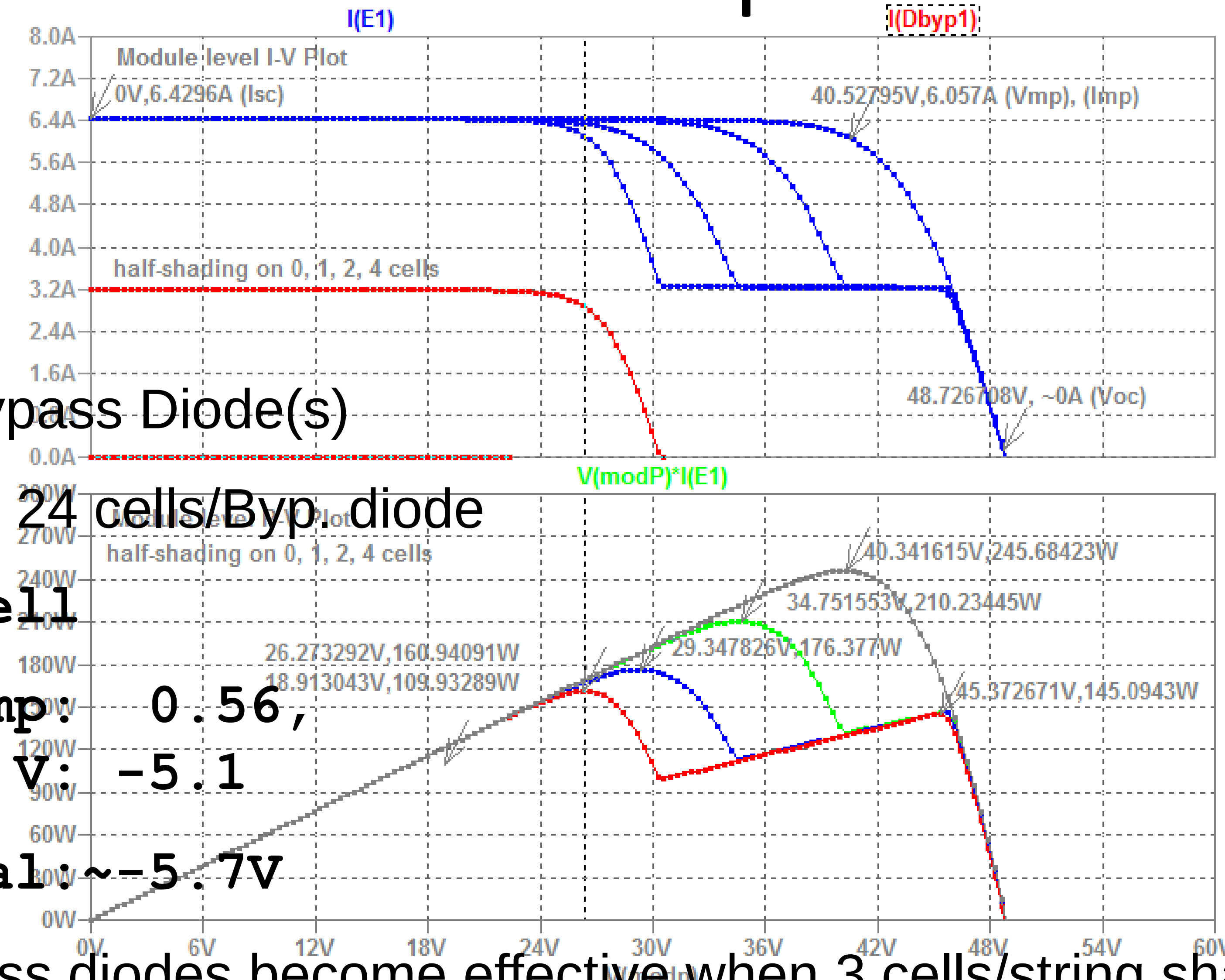
Fwd Vmp: 0.56,

Rev V: -5.1

Total:~-5.7V

Ea. Shaded cell “takes out” itself & 9~10 others!

Module Partial Shade performance



With Bypass Diode(s)

72 / 3 = 24 cells/Byp. diode

Ea. Cell

Fwd Vmp: 0.56,

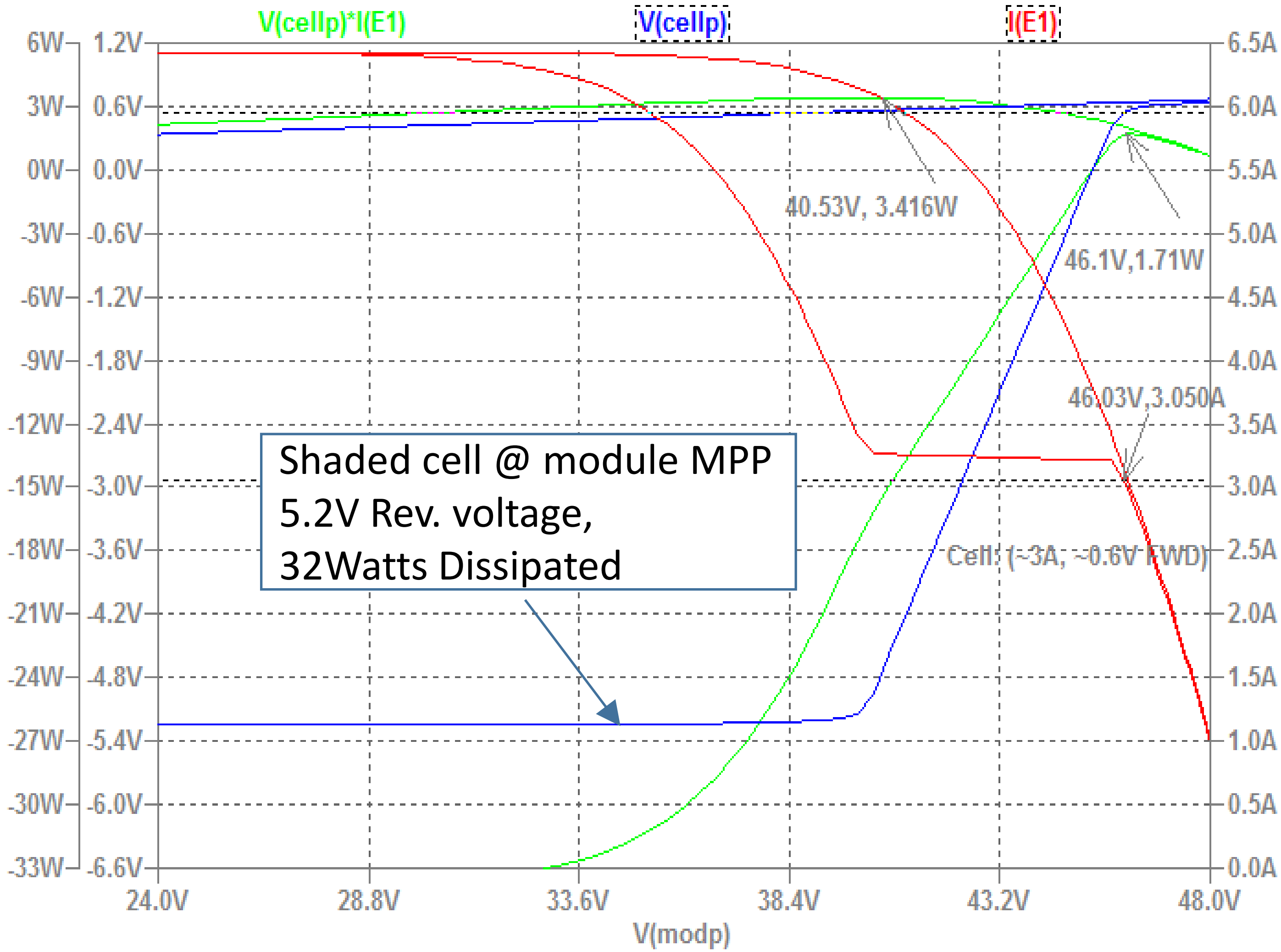
Rev V: -5.1

Total:~-5.7V

→Bypass diodes become effective when 3 cells/string shaded.

Module Partial Shade performance

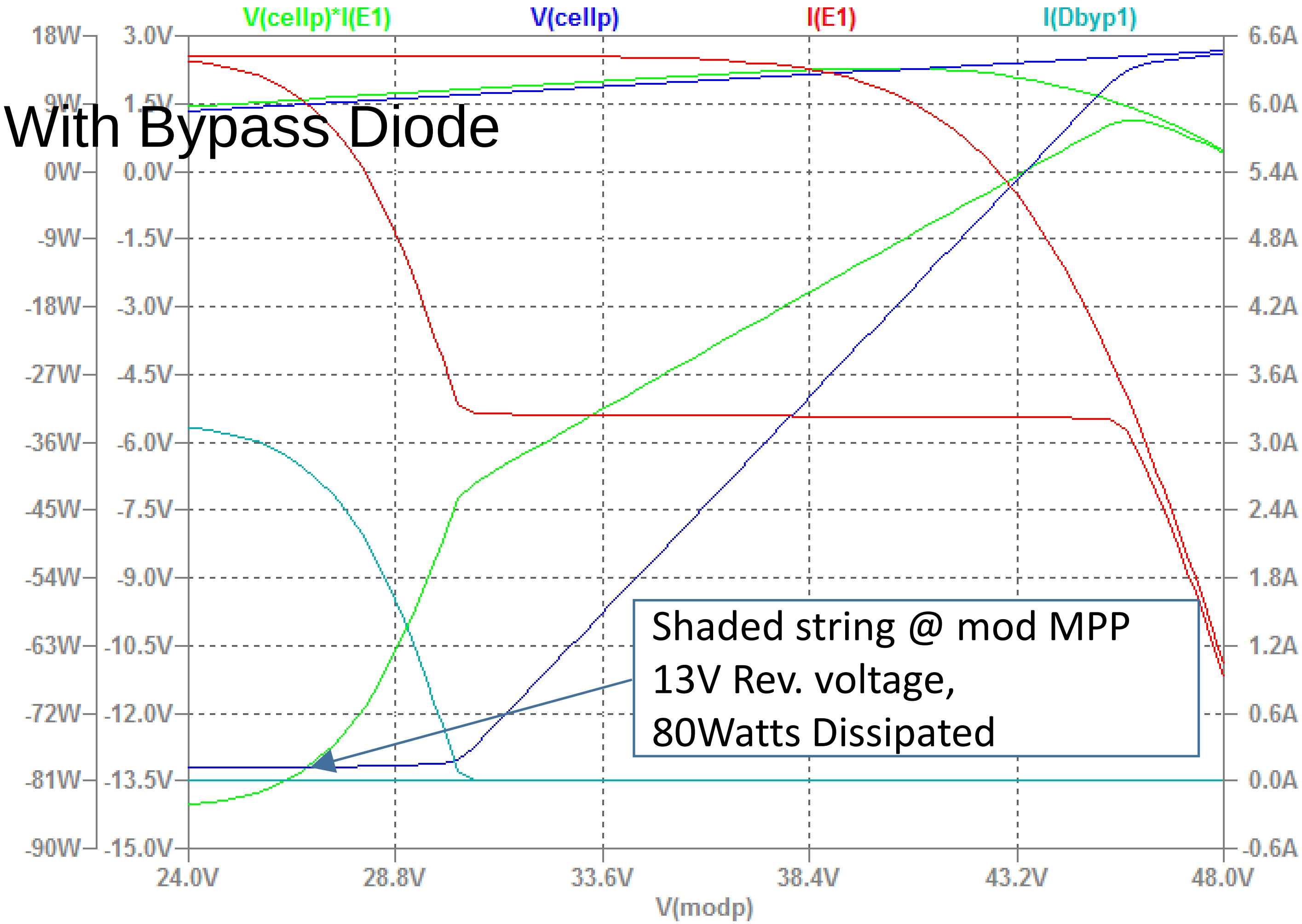
Single partially shaded cell P, V, I vs. String voltage



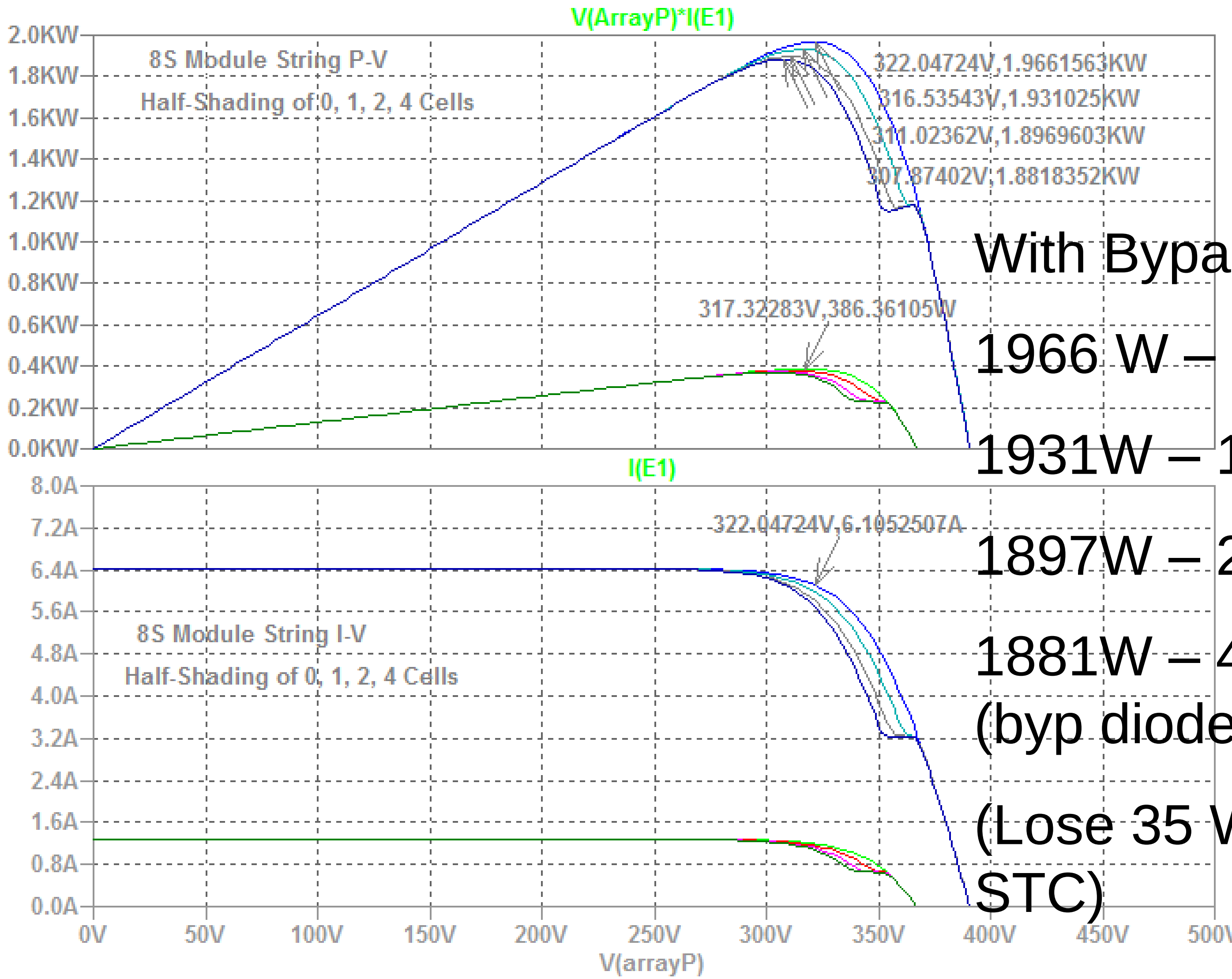
Module Partial Shade performance

Four partially shaded cells in a string P, V, I

With Bypass Diode



Array Partial Shade performance



With Bypass Diode(s)

1966 W – 0 shaded

1931W – 1 shaded

1897W – 2 shaded

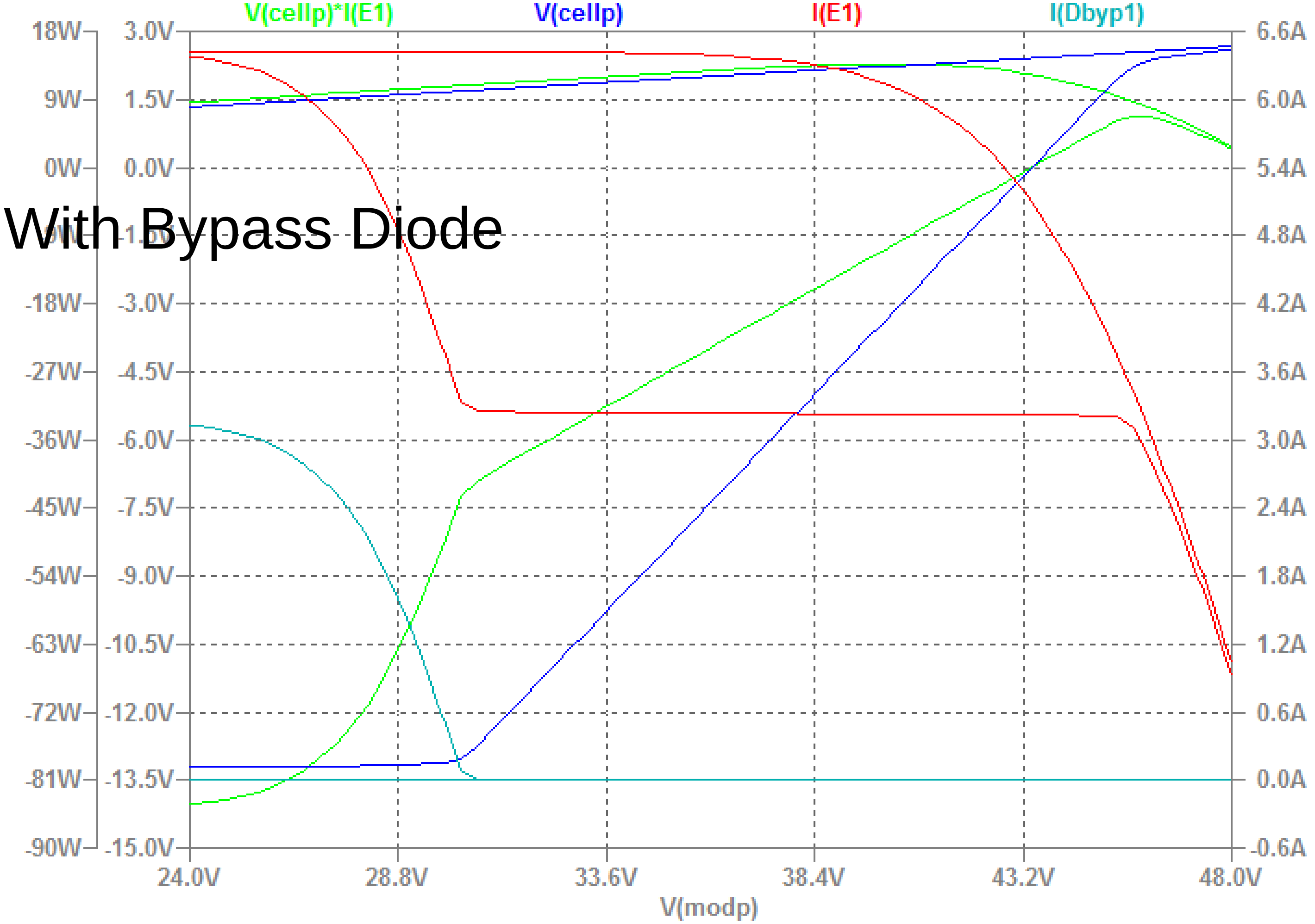
1881W – 4 shaded (byp diode active)

(Lose 35 W/cell! @ STC)

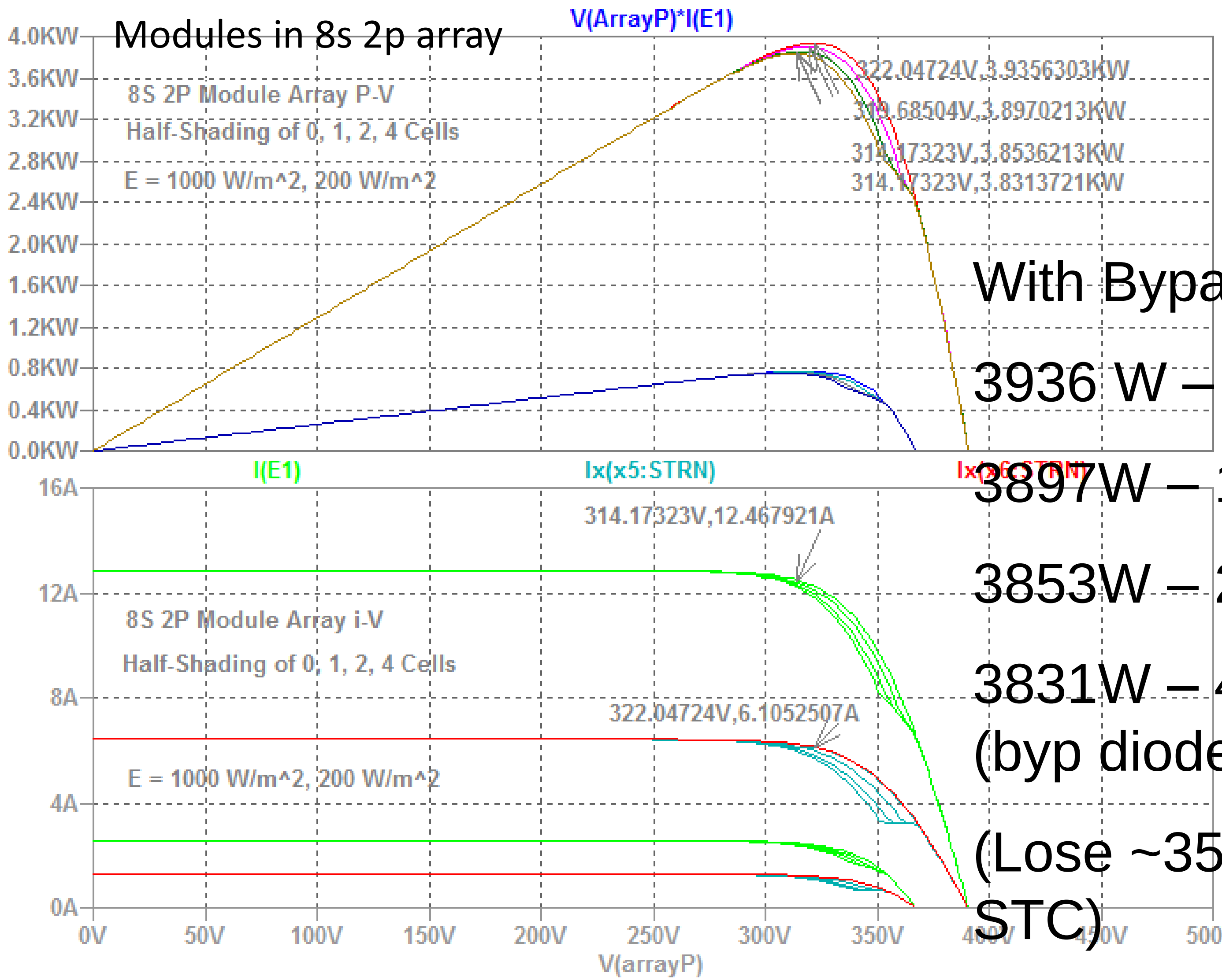
Array Partial Shade performance

Module level I vs. Module voltage

With Bypass Diode



Full Array Partial Shade performance



With Bypass Diode(s)

3936 W – 0 shaded

3897W – 1 shaded

3853W – 2 shaded

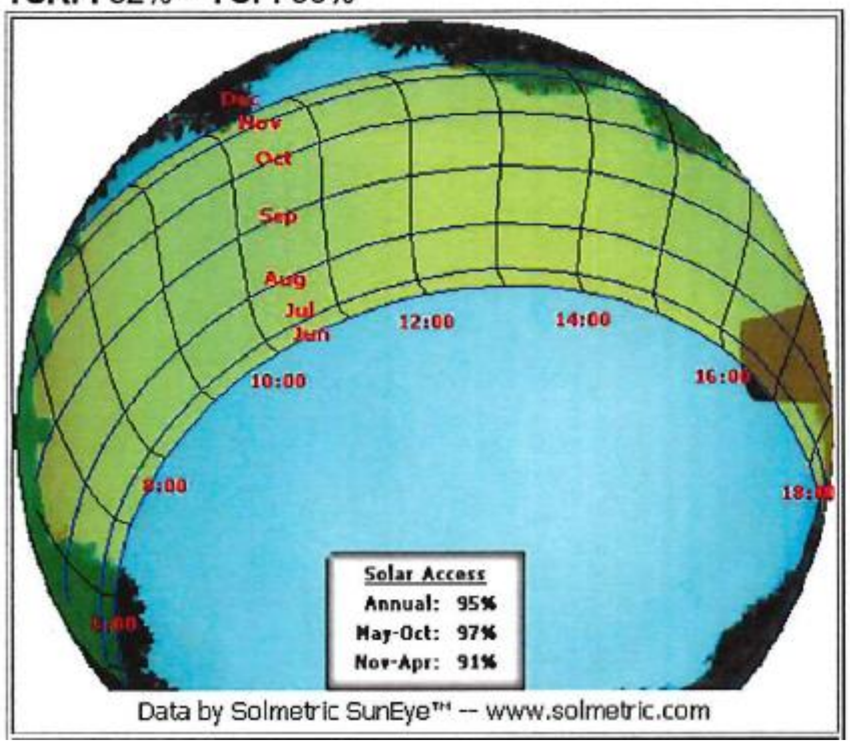
3831W – 4 shaded (byp diode active)

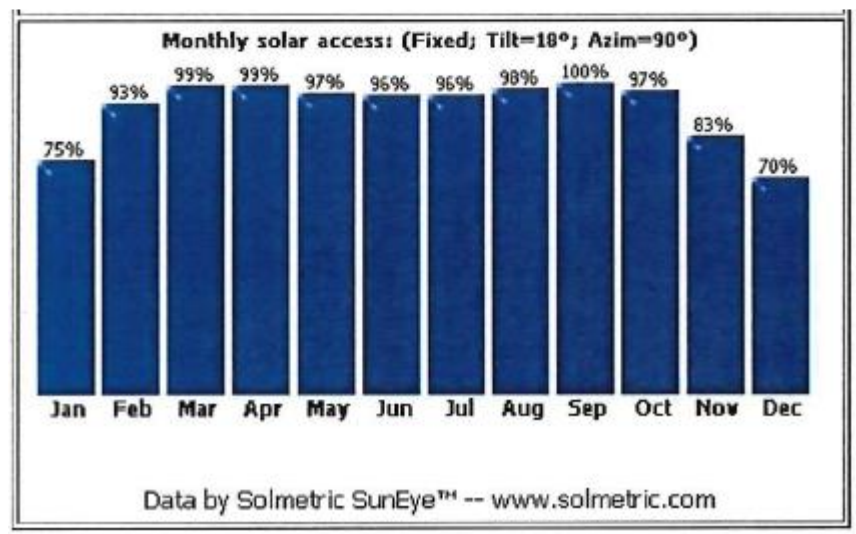
(Lose ~35 W/cell! @ STC)

How Important is Shading Study?

From Site Survey – East Array shown

Panel Orientation: Tilt=18° -- Azimuth=90° – **Skyline Heading=189°**
Solar Access: Annual: 95% -- Summer (May-Oct): 97% -- Winter (Nov-Apr): 91%
TSRF: 82% -- **TOF:** 86%





Site Survey

Panel Orientation: Tilt=18° -- Azimuth=90° -- **Skyline Heading=189°**
Solar Access: Annual: 95% -- Summer (May-Oct): 97% -- Winter (Nov-Apr): 91%
TSRF: 82% -- **TOF:** 86%

Tilt and Orientation Factor (TOF). TOF is the solar insolation at the actual tilt and orientation divided by the insolation at the optimum tilt and orientation, expressed in percent.

Total Solar Resource Fraction (TSRF). TSRF is the ratio of insolation available accounting for both shading and TOF, compared to the total insolation available at a given location at the optimum tilt and orientation and with no shading. TRSF is also expressed in percent, according to the following equation:

TSRF = Solar Access * TOF [2]

Quiz #2 Questions

1. Partial-shading of cells in a PV Module results in a P-V MPP curve with:
   A. Multiple, lower peaks than the unshaded MPP peak
   B. A single, lower MPP peak than the unshaded MPP peak

2. Which factor does NOT affect a PV array power converter's MPP Tracking algorithm?
   A. Irradiance variations (clouds, AOI..)
   B. Fixed Array Orientation; Azimuth & Tilt
   C. Snowcover, severe Soiling (esp. partial)
   D. Shading (Trees, chimneys, dormers, vent stacks, leaves)
   E. Module Temperature

Quiz #2 Answers

1. Partial-shading of cells in a PV Module results in a P-V MPP curve with:
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   C. Snowcover, severe Soiling (esp. partial)
   D. Shading (Trees, chimneys, dormers, vent stacks, leaves)
   E. Module Temperature

System Performance

Some actual performance data points

- Partial snowcover provides test conditions

Data collection procedure:

1. On cloudless day, record Inverter data
   - for East & West arrays; DC Vin, Iin, AC Pout, time
2. Get up on roof,
   A. photograph arrays
   B. Broom sweep, clearing snow from areas that can be safely reached.
   C. Photograph cleared arrays
   D. Estimate Module Cell temperatures
3. Back in basement, record inverter data, time.

System Performance 04 Mar '18


Before:

P_{AC}= 71W

Date	Time	East V	East I	West V	West I	Pac	East Pdc	West Pdc	tot Pdc	est °C
4-Mar-18	12:56	128	nr	276	0.1	71	n/a	27.6	27.6	3


After:

P_{AC}= 708W

(Only E side partly cleared)

Date	Time	East V	East I	West V	West I	Pac	East Pdc	West Pdc	tot Pdc	est °C
4-Mar-18	13:22	278	2.5	277	0.1	708	695	27.7	722.7	5

System Performance 17 Mar '18


Before:

P_{AC}= 276W

Date	Time	East V	East I	West V	West I	Pac	East Pdc	West Pdc	tot Pdc	est °C
17-Mar-18	11:54	350	0.2	146	1.5	276	70	219	289	0


After:

P_{AC}= 3150W

(Only E side Cleared)

Date	Time	East V	East I	West V	West I	Pac	East Pdc	West Pdc	tot Pdc	est °C
17-Mar-18	12:20	334	8.0	171	3.1	3150	2672	530.1	3202.1	5

System Performance

What the arrays were producing

Date	Time	East V	East I	West V	West I	Pac	East Pdc	West Pdc	tot Pdc	Notes
4-Mar-18	12:56	128	nr	276	0.1	71	n/a	28	28	e_1310_04Mar18, W_1311_04Mar18
4-Mar-18	13:22	278	2.5	277	0.1	708	695	28	723	E_1318_04Mar18, W_1311a_04Mar18
17-Mar-18	11:54	350	0.2	146	1.5	276	70	219	289	E_1203_17Mar18, W_1203_17Mar18
17-Mar-18	12:20	334	8.0	171	3.1	3150	2672	530	3202	E_1214_17Mar18, W_1214_17Mar18
18-Mar-18	11:47	332	9.5	334	3.3	3966	3154	1102	4256	E array clr W array Top clr, Bot cov'rd
21-Mar-18	8:27	338	4.7	325	0.4	1694	1589	130	1719	Clear Arrays
21-Mar-18	13:35	323	8.9	328	9.9	5785	2875	3247	6122	Clear Arrays
21-Mar-18	14:41	346	7.7	334	11.1	6099	2664	3707	6372	Clear Arrays

System Performance

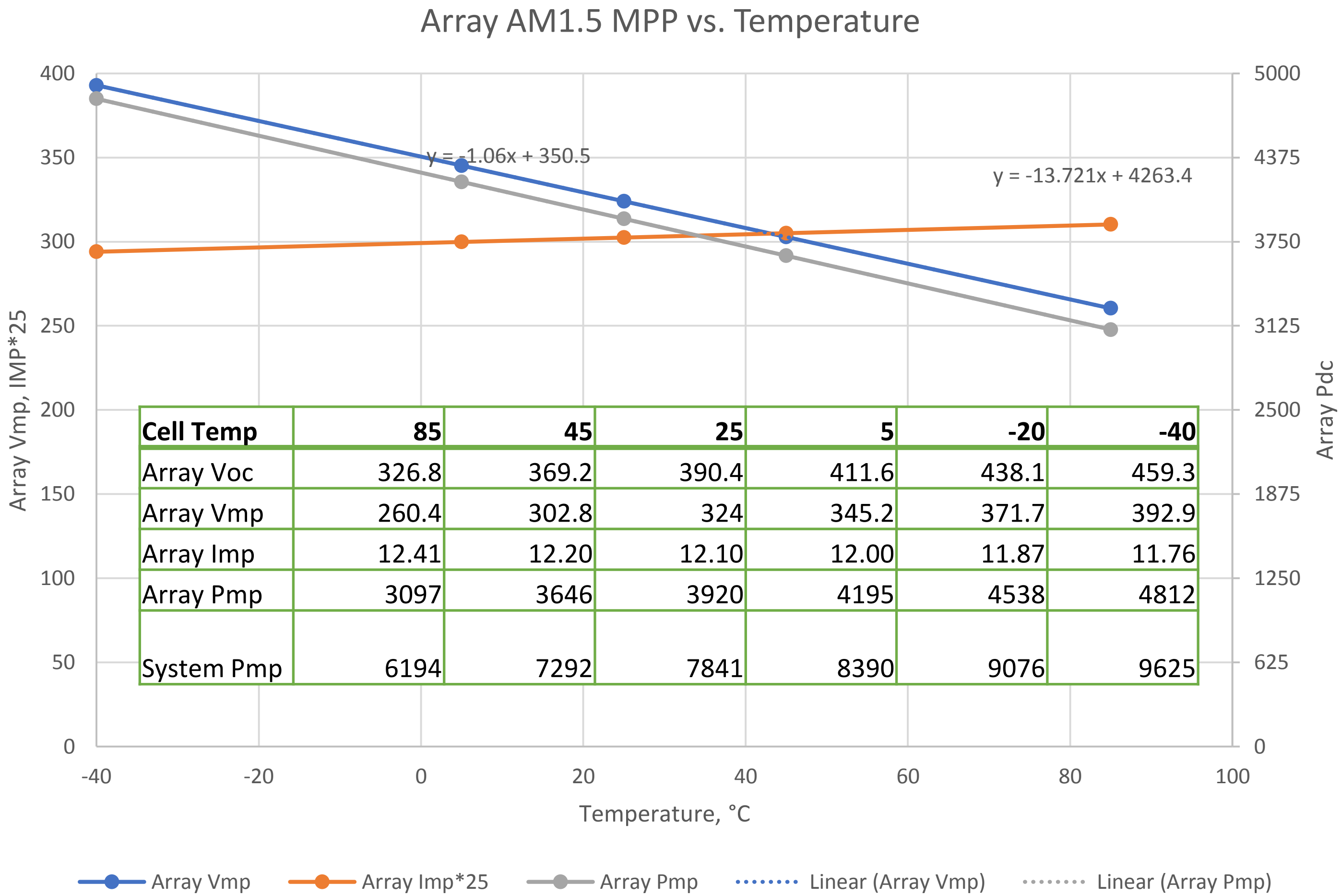
What should the arrays be producing?

- Apply an estimated irradiance correction,
  - (Clear Array Iin)/(Array AM1.5 Impp)

Date	Time	est °C	Ee Adj.	Vmax	Imax	VE/Vmax	IE/Imax	VW/Vmax	IW/Imax	Notes
4-Mar-18	12:56	3	0.6	347.32	7.19	0.3685	n/a	0.7947	0.0139	e_1310_04Mar18, W_1311_04Mar18
4-Mar-18	13:22	5	0.6	345.2	7.20	0.8053	0.3473	0.8024	0.0139	E_1318_04Mar18, W_1311a_04Mar18
17-Mar-18	11:54	0	0.795	350.5	9.52	0.9986	0.0210	0.4165	0.1576	E_1203_17Mar18, W_1203_17Mar18
17-Mar-18	12:20	5	0.795	345.2	9.54	0.9676	0.8389	0.4954	0.3251	E_1214_17Mar18, W_1214_17Mar18
18-Mar-18	11:47	5	0.795	345.2	9.54	0.9618	0.9961	0.9676	0.3460	E array clr W array Top clr, Bot cov'rd
21-Mar-18	8:27	0	0.795	350.5	9.52	0.9643	0.4939	0.9272	0.0420	Clear Arrays
21-Mar-18	13:35	5	0.83	345.2	9.96	0.9357	0.8939	0.9502	0.9943	Clear Arrays
21-Mar-18	14:41	4	0.93	346.26	11.15	0.9992	0.6905	0.9646	0.9954	Clear Arrays

System Performance

What should the arrays be producing?

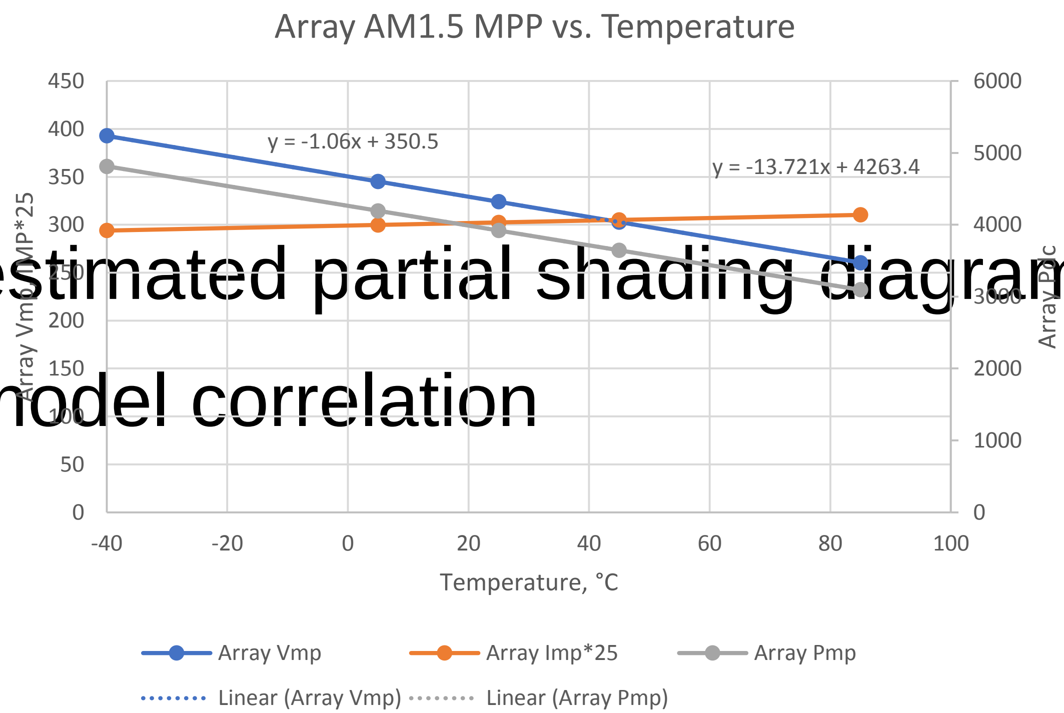


Cell Temp	**85**	**45**	**25**	**5**	**-20**	**-40**
Array Voc	326.8	369.2	390.4	411.6	438.1	459.3
Array Vmp	260.4	302.8	324	345.2	371.7	392.9
Array Imp	12.41	12.20	12.10	12.00	11.87	11.76
Array Pmp	3097	3646	3920	4195	4538	4812
System Pmp	6194	7292	7841	8390	9076	9625

System Performance

Insert summary from Measurements tab of

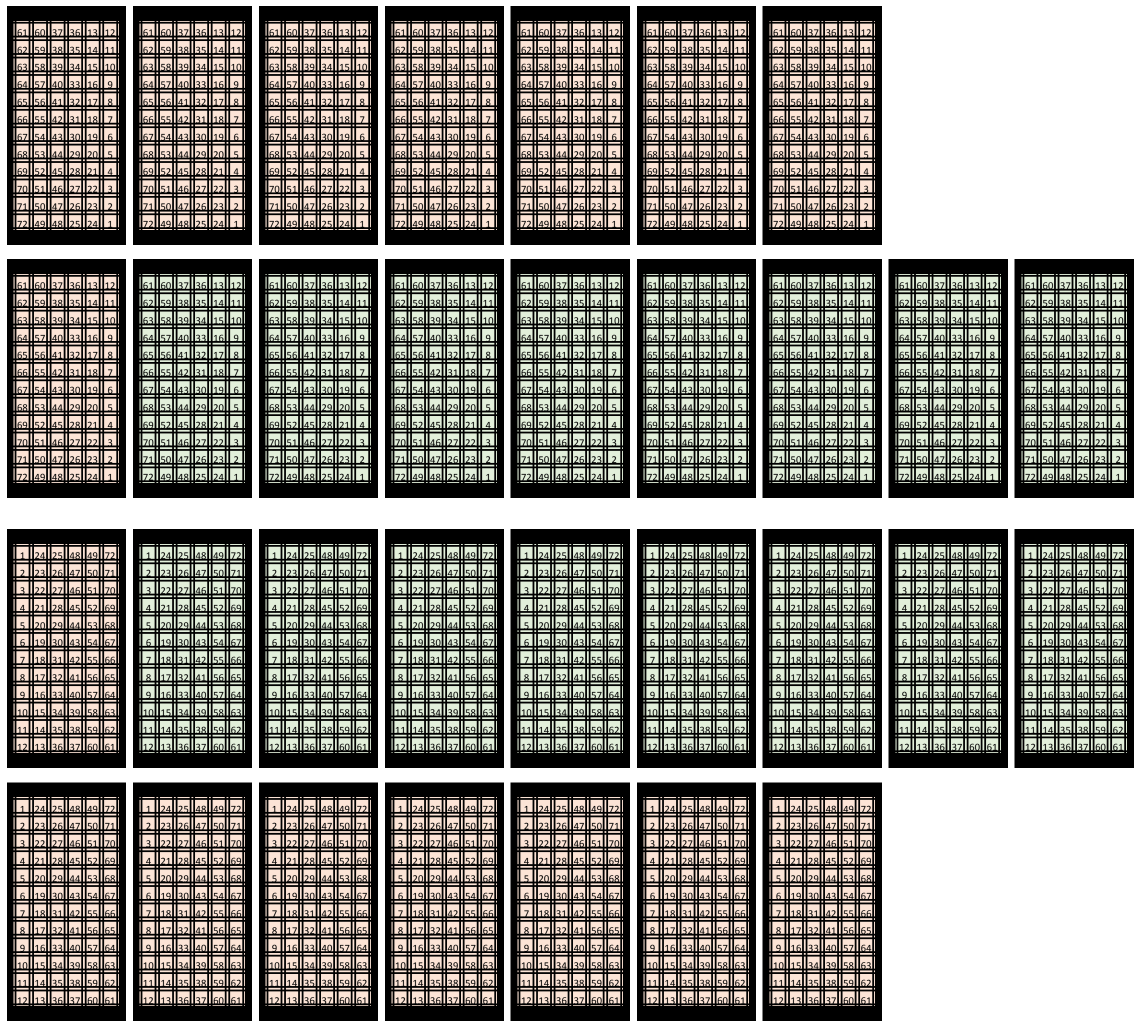
C:\Working\LTSpice\PV_3JCell\PV_Array_Model.xlsx



Show estimated partial shading diagram

Show model correlation

System Performance



System Performance

What else can be done?

Module Optimizers [4] [6]

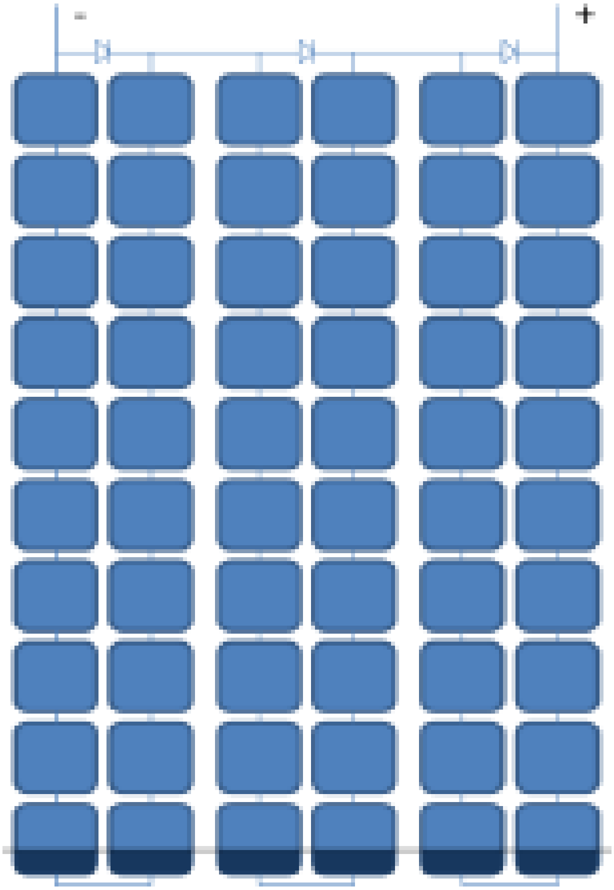
- Runs each Module at Module’s MPP
- Versus (String MPP) or (Array MPP)
- Consider cost – payback economic model

System Performance

Another common case is shade which affects the bottom part of a PV module. We will consider the same PV system as described above. We will assume that the shaded region of the bottom cells is 30% of the cell area. In this case the MPPT in the centralized inverter has the following options:

1. To drive full current through the modules, losing all power from the shaded module: 9*10% + 1*0% = 90% of full power.
2. To drive 70% of the current so all modules produce power. In this case 10*7% = 70%.

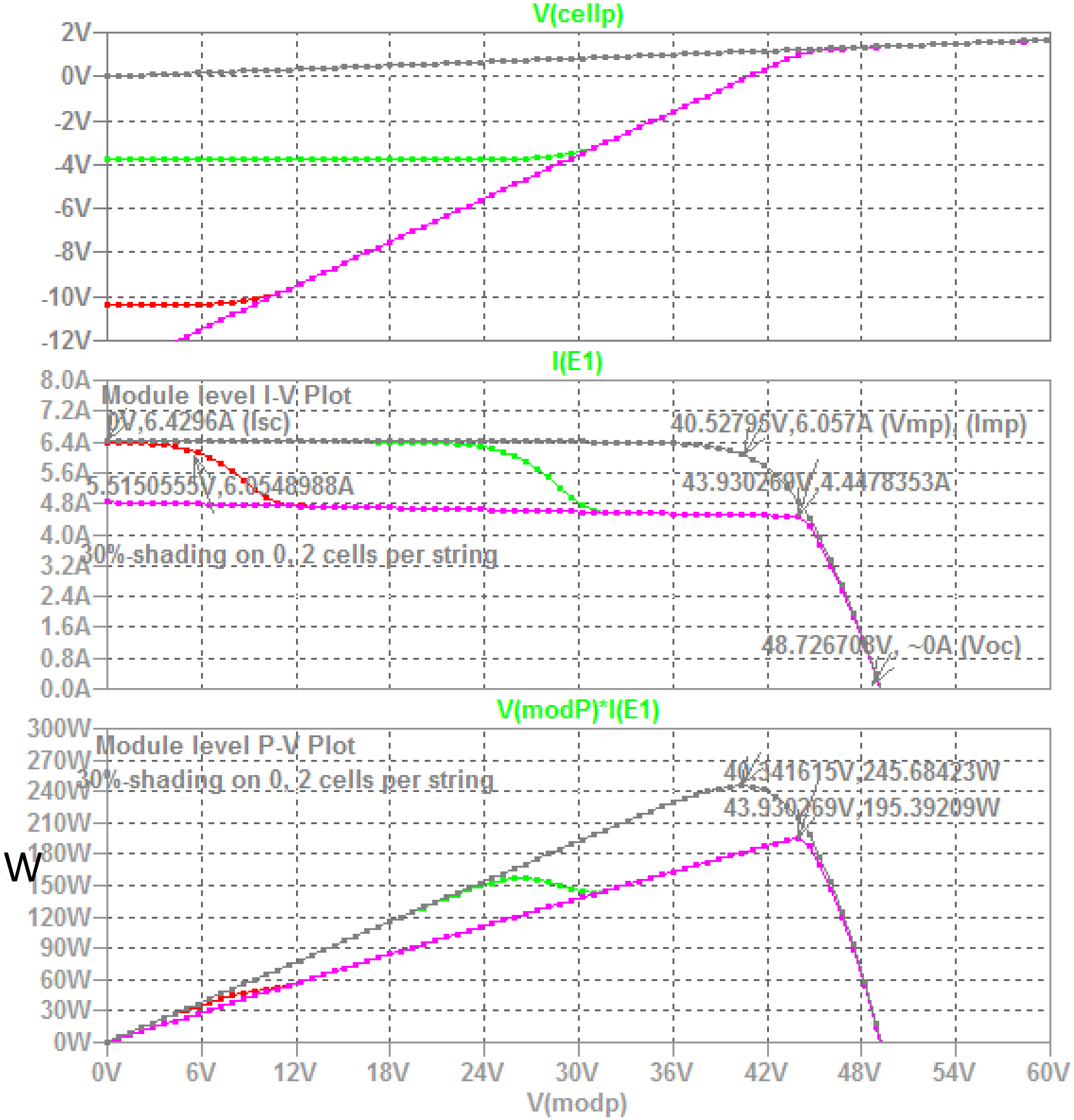
It is clear again that the better option is the first one which produces 90% of the maximum possible power.
A SolarEdge system, with module-level MPP trackers, would in this case enable the production of 9*10% + 1*7% = 97% of full power. This is a 7% increase in power production compared to the optimal case in a traditional system.



System Performance

With “5V RBV” cells,
2 in series avalanche before
String V is driven to zero,
$I_{BPD} = 0$ (BPDs never conduct)
“2V RBV” Cells also shown.

Optimized: 195/245 W
= 80%
Non-opt (>7VrbV): 0/245 W
= 0%
Non-opt (5VrbV): ~30/245 W
= 12%
Non-opt (2Vrbv): 160/245 W
= 65%
(best) Optimizer benefit: +195W



System Performance ROI

Optimizer benefit: +(0.80 – 0.12) * 245 = 166W
*1.2 (annual kWh/kWDC yield factor – PVWatts)
= 200 kWh / yr.
@$0.10/kWh = $20.00 annual benefit

Optimizer module street price: $70

Simple payback: ~70/20 = 3.5 years!
Wait… which one of the 32 modules gets the optimizer?
All 32?! $70 * 32 = $2240
Optimizer gain isn't 32X.
And, if all modules shaded the same, the optimizer's benefit is substantially less.
What about the case where half the modules' output is reduced?

System Performance ROI

In multiple string installations the shading effects can be much larger. The electrical constraint of having all strings which are connected in parallel operating at the same voltage does not enable a shaded string to activate its bypass diodes. In many cases shade on PV modules in one of the strings can actually reduce the power produced by the entire string.

We will take one un-shaded string and one string that is shaded in the manner described in the previous example. The MPPT will enable the production of full power from the first string, and the production of 70% of full power from the second string. In this way both strings reach the same voltage. The power produced in this case would be 85% of maximum possible power.

The SolarEdge system could produce 100% of power from the first string and 97% of power from the second string. This would achieve 98.5% of possible power. This is a 13.5% increase in power production compared the traditional case.

10s 2p array, of 360-W modules. Full output: 7200W
Optimizer cost: 20 * $70 = $1400
Optimizer benefit: 13.5% of 7200W = 972W
* Annual yield factor of 1.2 kWh/kWdc =1166.4 kWh
@ $0.10 /kWh; =$116.64 annual payback

Break-even in 1400/116 = 12 years

Quiz #3 Questions

1. Pick the best answer:
   "Module-level MPP Tracking optimizers are worth the investment …"
   A. True, they pay back in <8years
   B. Yes, the up to 25% gain in module output ROI is 12 years
   C. Yes, they pay back quicker than investing in a Prius Hybrid car.

Quiz #3 Answers

1. Module-level MPP Tracking optimizers are worth the investment
   A. True, they pay back in <8years
   B. Yes, the up to 25% gain in module output ROI is 12 years
   C. Yes, they pay back quicker than investing in a Prius Hybrid car.
      (payback on the Prius for my driving habits was **8 years**, when I calculated it in 2008)

      (…though the next car may be a plug-in Hybrid)

NYSERDA Rebate

(This isn't germaine to the topic, but will matter if you're thinking of going solar in NYS)

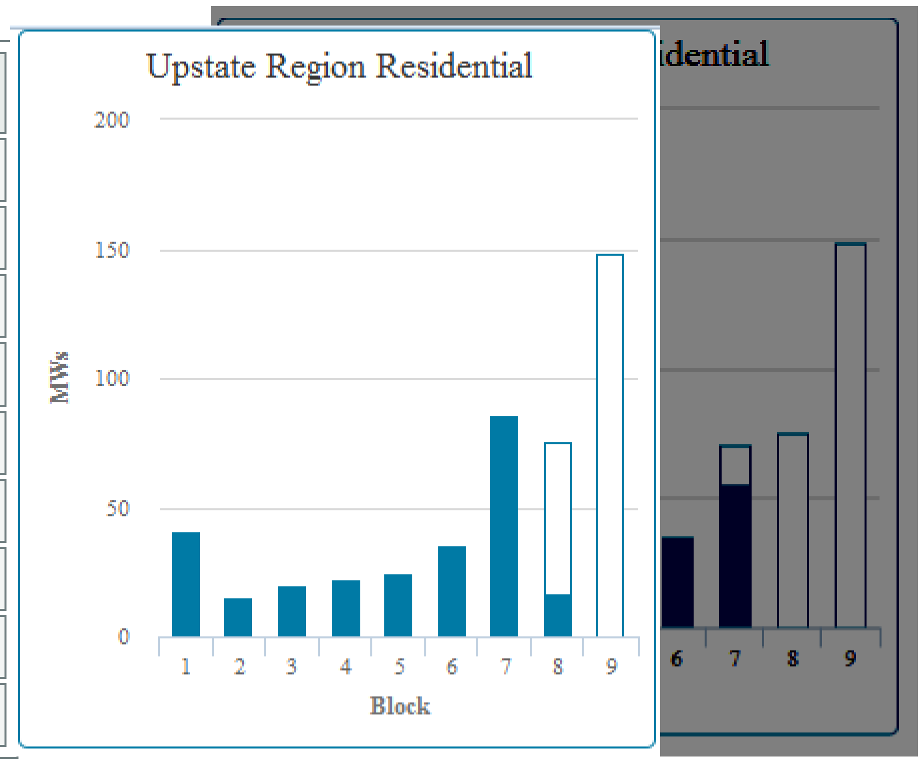
NYSERDA Rebate Block Grant status here:

https://www.nyserda.ny.gov/All-Programs/Programs/NY-Sun/Megawatt-Block-Dashboards/Residential-Small-Commercial-MW-Block

Upstate Residential Block Structure

BLOCK	MEGAWATTS	INCENTIVE/WATT
1	40	$1.00
2	15	$0.90
3	19	$0.80
4	22	$0.70
5	24	$0.60
6	35*	$0.50
7	70	$0.40
8	75	$0.30
9	148	$0.20

*Revised 12/30/2015



Thanks for your attention!

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[4] https://www.solaredge.com/sites/default/files/se_technical_bypass_diode_effect_in_shading.pdf

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[6] https://www.solaredge.com/products/power-optimizer#/