10-PhotovoltiacsPart 3

ECEGR 4530

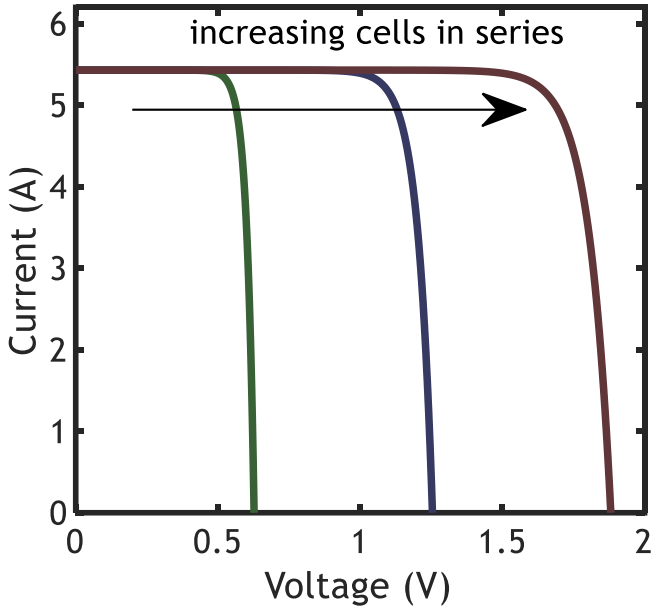
Renewable Energy Systems

Overview

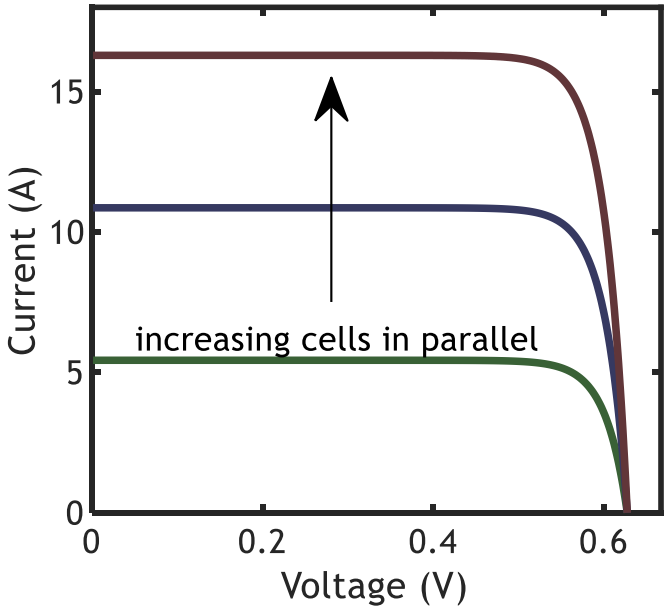
- PV Modules
- PV Specification Sheets
- Standard Test Conditions
- Correcting for Irradiance and Temperature
- Standard Operating Conditions
- Fill Factor
- PV Energy Production
- Shading

PV Modules

- PV modules are made by connecting several PV cells
- Increasing number of series or parallel-connected cells affects the I-V curve of the module



Voltage increases



Current increases

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PV Modules

- Most modules are made from connected PV cells in <u>series</u>
- Module voltage is simply the cell voltage multiplied by the number of series-connected cells:

$$V_{\text{module}} = N_{\text{ser}} \times V_{\text{cell}}$$

$$I_{\text{cell}} = I_G - I_0 \left(e^{V_{\text{cell}}/V_T} - 1 \right)$$

$$I_{\text{module}} = I_G - I_0 \left(e^{V_{\text{module}}/(V_T N_{\text{ser}})} - 1 \right)$$

V_{module} : PV module voltage (V)
I_{module} : PV module current (A)
N_{ser}: number of series-connected cells

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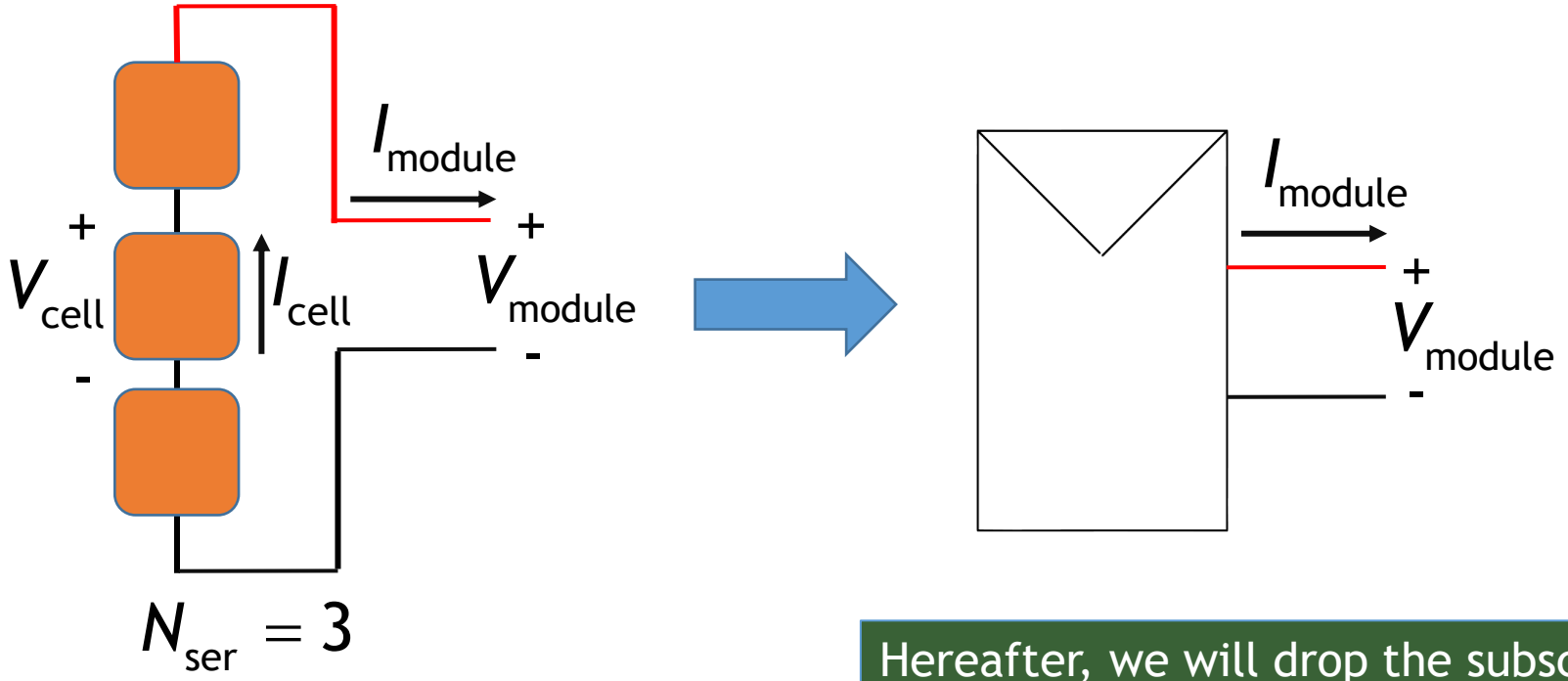
PV Modules



Hereafter, we will drop the subscript "module" since we are usually not interested in the characteristics of an individual cell

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PV Spec Sheets

See handout (also on Canvas)

Itek SE 72-Cell Module

Design & Engineering Data

GENERAL DATA

Cell Type	• 72 high-efficiency monocrystalline p-type cells • 6 x 12 cell matrix
Solar Glass	• Ultra-clear anti-reflective treatment • Tempered, with low iron content • Anti-glare prismatic subsurface texture
Backsheet	• Multi-layered • Engineered adhesion for maximum weather protection
Frame	• High-strength corrosion-resistant anodized aluminum • Compatible with standard racking, accommodating both top-down clamps and bottom-flange mounting
Cable	• 90ºC 12AWG PV wire
Junction Box	• 3 bypass diodes • 1000 VDC MC4 connectors • Tigo TS4
Grounding	• Certified for Wiley Electronics WEEB™ grounding clips • Eight standard grounding locations per module for reduced ground wire length

QUALIFICATIONS

Fire Rating	Type 1
PID Free	500+ hours

ARRA, BAA, and TAA Compliant

ELECTRICAL DATA*

	350 SE	355 SE	360 SE	365 SE	370 SE
Maximum Power - P_{max} (Wp)	350	355	360	365	370
Maximum Power Voltage - V_{mpp}(V)	38.55	38.74	38.94	39.12	39.32
Maximum Power Current - I_{mpp}(A)	9.08	9.16	9.25	9.33	9.41
Maximum Current - I_{MPP}(A) (O,L)	12	12	12	12	12
Maximum Voltage (TS4-L only) - V_{MPP}(V)	43.57	43.77	43.99	44.19	44.40
Open Circuit Voltage - V_{OC}(V) (D,M,S,O)	47.43	47.64	47.87	48.08	48.31
Short Circuit Current - I_{SC}(A) (D,M,S)	9.49	9.55	9.62	9.69	9.76
Module Efficiency	17.54%	17.79%	18.05%	18.30%	18.55%

MECHANICAL DATA

Dimensions	1001mm x 1993mm x 40mm
Weight	49 lbs/22.2kg

MAXIMUM RATINGS

Operational Temperature	-40...+90ºC
Maximum System Voltage	1000 VDC
Maximum Design Load (UL 1703)	113 psf/(5400pa)
Max Series Fuse Rating	15A
Max Reverse Current	15A

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	45.01ºC
Temperature Coefficient of P_{MPP}	-0.39%/ºC
Temperature Coefficient of V_{OC} (D,M,S,O)	-0.29%/ºC
Temperature Coefficient of V_{OC} (TS4 - L only)	0.0%/ºC
Temperature Coefficient of I_{SC}	+0.04%/ºC
Temperature Coefficient of V_{MPP}	-0.38%/ºC

*Electrical characteristics may vary within ±2% of the indicated values at Standard Test Conditions (STC): Irradiance of 1,000W/m², AM 1.5 spectrum, cell temperature at 25°C.

Note: specifications subject to change without notice.

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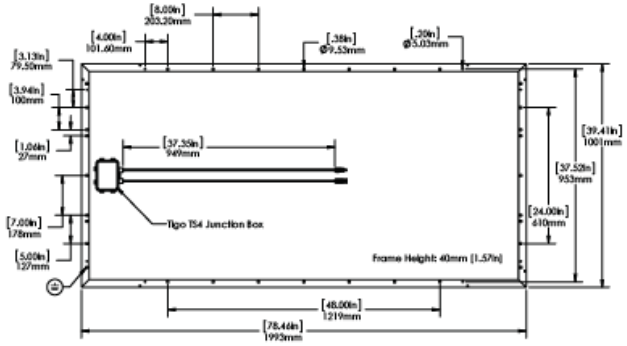
:hoose from Safety | Safety + Optimization | Safety + Optimization + Long Strings

All of these options include Monitoring

54 Platform



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What PV Capacity (Power rating) Means

Itek SE 350 module has a maximum power rating of 350 W

- How should that be interpreted?
- Will it produce 350 W on a winter day in Seattle?
- Will it produce 350 W on a summer day in Las Vegas?
- Will it ever produce more than 350 W?
- Do the characteristics of the load or battery that it is connected to matter?

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Main Factors Affecting PV Power Production

Irradiance

Temperature

Load

Spectral distribution of irradiance also affects production

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PV Module Spec Sheets

- Modules rated at Standard Test Conditions (STC)
  - Irradiance: 1000 W/m^2
  - Cell temperature: 25°C
  - Spectral distribution: AM 1.5
- PV modules rarely operate under STC

Itek SE 72-Cell Module

Design & Engineering Data

GENERAL DATA

Cell Type	• 72 high-efficiency monocrystalline p-type cells • 6 x 12 cell matrix
Solar Glass	• Ultra-clear anti-reflective treatment • Tempered, with low iron content • Anti-glare prismatic subsurface texture
Backsheet	• Multi-layered • Engineered adhesion for maximum weather protection
Frame	• High-strength corrosion-resistant anodized aluminum • Compatible with standard racking, accommodating both top-down clamps and bottom-flange mounting
Cable	• 90°C 12AWG PV wire
Junction Box	• 3 bypass diodes • 1000 VDC MC4 connectors • Tigo TS4
Grounding	• Certified for Wiley Electronics WEEB™ grounding clips • Eight standard grounding locations per module for reduced ground wire length

QUALIFICATIONS

Fire Rating	Type 1
PID Free	500+ hours

ARRA, BAA, and TAA Compliant

ELECTRICAL DATA*

	350 SE	355 SE	360 SE	365 SE	370 SE
Maximum Power - P_{max} (Wp)	350	355	360	365	370
Maximum Power Voltage - V_{mp}(V)	38.55	38.74	38.94	39.12	39.32
Maximum Power Current - I_{mp}(A)	9.08	9.16	9.25	9.33	9.41
Maximum Current - I_{MAX}(A) (O,L)	12	12	12	12	12
Maximum Voltage (TS4-L only) - V_{MAX}(V)	43.57	43.77	43.99	44.19	44.40
Open Circuit Voltage - V_{OC}(V) (D,M,S,O)	47.43	47.64	47.87	48.08	48.31
Short Circuit Current - I_{SC}(A) (D,M,S)	9.49	9.55	9.62	9.69	9.76
Module Efficiency	17.54%	17.79%	18.05%	18.30%	18.55%

MECHANICAL DATA

Dimensions	1001mm x 1993mm x 40mm
Weight	49 lbs/22.2kg

MAXIMUM RATINGS

Operational Temperature	-40...+90°C
Maximum System Voltage	1000 VDC
Maximum Design Load (UL 1703)	113 psf/(5400pa)
Max Series Fuse Rating	15A
Max Reverse Current	15A

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	45.01°C
Temperature Coefficient of P_{MAX}	-0.39%/°C
Temperature Coefficient of V_{OC} (D,M,S,O)	-0.29%/°C
Temperature Coefficient of V_{OC} (TS4 - L only)	0.0%/°C
Temperature Coefficient of I_{SC}	+0.04%/°C
Temperature Coefficient of V_{MP}	-0.38%/°C

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All of these options include Monitoring

S4 Platform

TS4-L LONG STRINGS

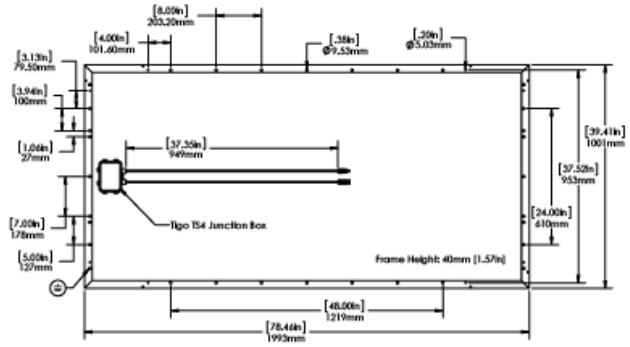
TS4-O OPTIMIZATION

TS4-S SAFETY

TS4-M MONITORING

TS4-D DIODES

Tigo



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Standard Test Conditions

- We use subscript "STC" to denote a variable referenced to Standard Test Conditions
- Examples:

G_{STC}: irradiance at STC $(G_{STC} \triangleq 1000\ \mathrm{W/m^2})$

P^*_{STC} : maximum power output under STC

V^*_{STC} : voltage at the maximum power point under STC

$I_{SC,STC}$: short-circuit current under STC

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Spec Sheet Interpretation

For the 350 SE module, determine:

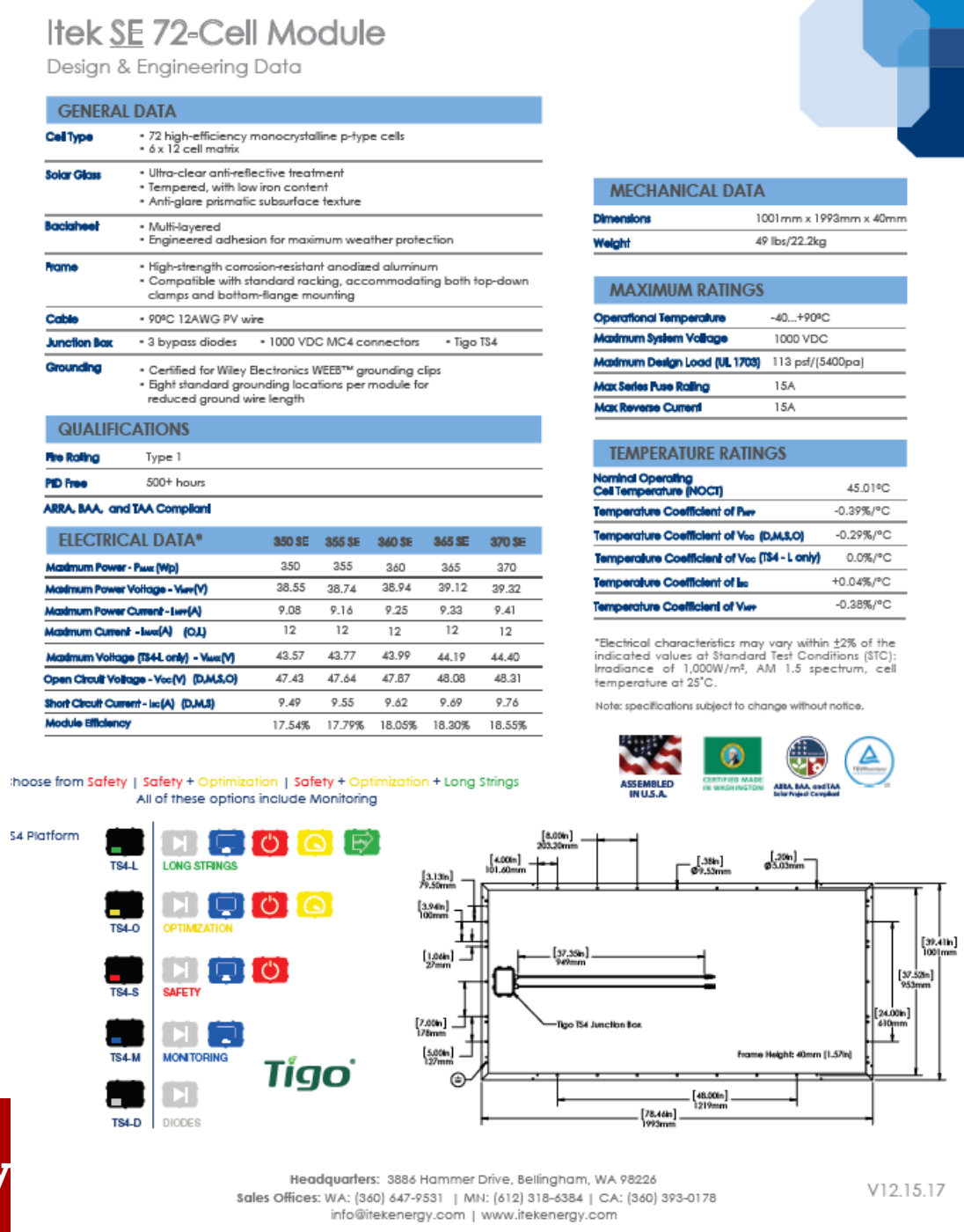
P^*_{STC} _____

V^*_{STC} _____

$V_{OC,STC}$ _____

I^*_{STC} _____

$I_{SC,STC}$ _____



Itek SE 72-Cell Module

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Cable	• 90ºC 12AWG PV wire
Junction Box	• 3 bypass diodes • 1000 VDC MC4 connectors • Tigo TS4
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ARRA, BAA, and TAA Compliant	

ELECTRICAL DATA*

	350 SE	355 SE	360 SE	365 SE	370 SE
Maximum Power - Pmax (Wp)	350	355	360	365	370
Maximum Power Voltage - Vmp(V)	38.55	38.74	38.94	39.12	39.32
Maximum Power Current - Imp(A)	9.08	9.16	9.25	9.33	9.41
Maximum Current - Imp(A) (D,L)	12	12	12	12	12
Maximum Voltage (TS4-L only) - Vmp(V)	43.57	43.77	43.99	44.19	44.40
Open Circuit Voltage - Voc(V) (D,M,S,O)	47.43	47.64	47.87	48.08	48.31
Short Circuit Current - Isc(A) (D,M,S)	9.49	9.55	9.62	9.69	9.76
Module Efficiency	17.54%	17.79%	18.05%	18.30%	18.55%

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Dimensions	1001mm x 1993mm x 40mm
Weight	49 lbs/22.2kg

MAXIMUM RATINGS

Operational Temperature	-40...+90ºC
Maximum System Voltage	1000 VDC
Maximum Design Load (UL 1703)	113 psf/(5400pa)
Max Series Fuse Rating	15A
Max Reverse Current	15A

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	45.01ºC
Temperature Coefficient of Pmax	-0.39%/ºC
Temperature Coefficient of Voc (D,M,S,O)	-0.29%/ºC
Temperature Coefficient of Voc (TS4 - L only)	0.0%/ºC
Temperature Coefficient of Isc	+0.04%/ºC
Temperature Coefficient of Vmp	-0.38%/ºC

*Electrical characteristics may vary within ±2% of the indicated values at Standard Test Conditions (STC): Irradiance of 1,000W/m², AM 1.5 spectrum, cell temperature at 25°C.

Note: specifications subject to change without notice.

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TS4-L LONG STRINGS

TS4-O OPTIMIZATION

TS4-S SAFETY

TS4-M MONITORING

TS4-D DIODES

Tigo

Tigo TS4 Junction Box

Frame Height: 40mm (1.57in)

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Rated Power Interpretation

The 350 SE module will produce 350 W when the irradiance incident to it is 1000 W/m^2, the cell temperature is 25° C, the spectral distribution of the irradiance is AM 1.5, and it is connected to a load that maximizes the power production under these conditions

We will generally assume that that the load maximizes power production (i.e. the module operates at the MMP for a given set of conditions)

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Correcting for Irradiance

- Irradiance varies throughout the day
- Whenever the irradiance differs from G_{STC} (1000 W/m^2), the maximum power output is affected
  - Maximum power is a function of irradiance $P^*(G)$
- Maximum power is approximately proportional to the irradiance
  - Doubling irradiance doubles maximum power

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Correcting for Irradiance

Maximum power accounting for actual irradiance

$$P^*(G) = P^*_{STC} \times \frac{G}{G_{STC}}$$

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Exercise

Estimate the power produced by the Itek SE 370 if the irradiance is 750 W/m^2

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Exercise

Estimate the power produced by the Itek SE 370 if the irradiance is 750 W/m^2

$$P^*(G) = P^*_{STC} \times \frac{G}{G_{STC}}$$

$$P^*(G) = 370 \times \frac{750}{1000} = 277.5 \text{ W}$$

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Correcting for Irradiance

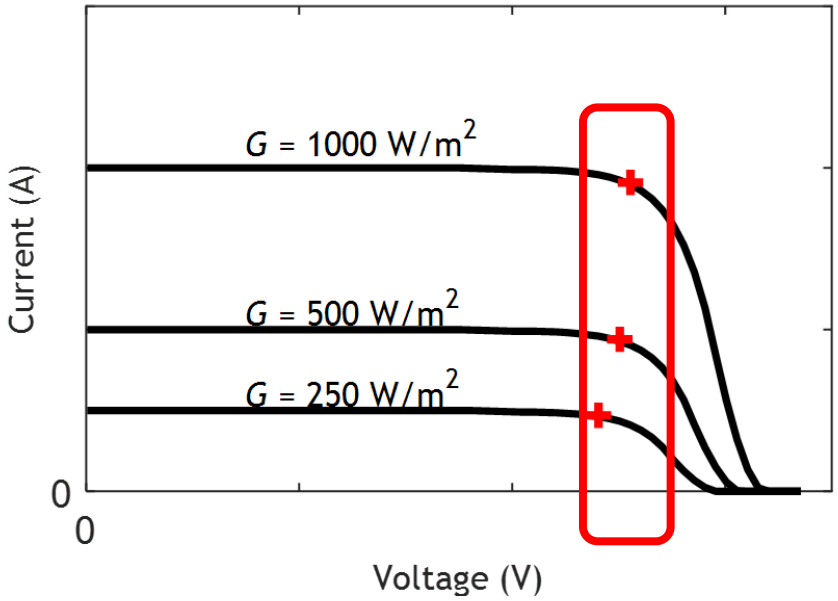
The model assumes (approximates)

$$V^*(G) = V^*_{STC}$$

Voltage at MPP is not affected by irradiance

$$I^*(G) = I^*_{STC} \times \frac{G}{G_{STC}}$$

Current at MPP changes in proportion to irradiance



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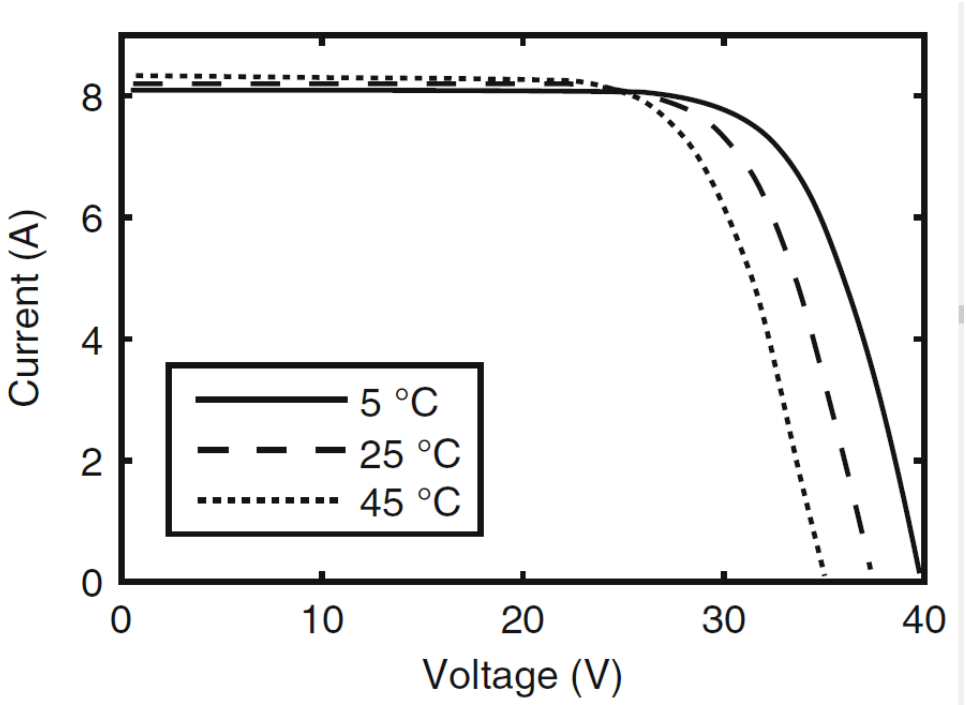
Correcting for Temperature

- I-V characteristic of PV module is influenced by the temperature
- Increasing temperature:
  - Decreases voltage
  - Increases current
- Change in voltage dominates the change in current, so power (voltage x current) decreases



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How does temperature affect the design and operation of PV systems?

- Charge controllers/inverters have a maximum input voltage rating; cold temperatures can increase the PV module voltage, possibly exceeding (and damaging) the charge controller/inverter

- Overall energy reduction will be reduced (perhaps significantly) due to temperature-related losses

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Correcting for Temperature

- Sensitivity of voltage, current, and power to temperature is empirically determined and reported by the manufacturer as "temperature coefficients"
- Coefficients are used to determine how open-circuit voltage, short-circuit current, and maximum change as the cell temperature deviates from 25° C
- Power can be reduced by 10 to 15% because cell temperature is often >20° C higher than that of STC

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Temperature Coefficients

α_v: open-circuit voltage temperature coefficient (%/K or %/C)

α_i: short-circuit current temperature coefficient (%/K or %/C)

α_p: maximum power temperature coefficient (%/K or %/C)

Temperature coefficients are provided in module spec sheet

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Correcting for Temperature

$$I_{SC}(T_C) = I_{SC}(25^\circ \text{C})\left(1 + \frac{\alpha_i}{100} \times (T_c - 25)\right)$$

$$V_{OC}(T_C) = V_{OC}(25^\circ \text{C})\left(1 + \frac{\alpha_v}{100} \times (T_c - 25)\right)$$

$$P^*(T_C) = P^*(25^\circ \text{C})\left(1 + \frac{\alpha_p}{100} \times (T_c - 25)\right)$$

V_{oc}: open-circuit voltage at 25° C (V)
I_{oc}: short-circuit current at 25° C (A)
T_c: temperature of the PV cell, (C)

Note that if the cell temperature is 25° C, then no correction is applied. This makes sense since because 25° C corresponds to STC

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Example

The cell temperature of the Itek 370 SE module is 47° C. What is the short-circuit current at this temperature? Assume that other than temperature, the module is operating under STC.

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Example

Referring to the spec sheet, we see that α_i = +0.04%/C and $I_{SC,STC}$ is 9.76A.

$$I_{SC}(T_C) = I_{SC}(25^\circ C)\left(1 + \frac{\alpha_i}{100} \times (T_C - 25)\right)$$

$$I_{SC}(47^\circ C) = 9.76\left(1 + \frac{0.04}{100} \times (47 - 25)\right)$$

$$I_{SC}(47^\circ C) = 9.846A$$

We shouldn't be concerned about the units being in Celsius, since the temperature is also expressed in these units (moreover, the difference in one degree Celsius is the same as the difference in one degree Kelvin)

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How do we determine the temperature of the cell?

- Manufacturers report the cell temperature when the PV module is exposed to "Standard Operating Conditions" (SOC)
- The reported temperature is known as "Nominal Operating Cell Temperature" (NOCT)
  - typically between 45° C and 50° C
- When module is not exposed to SOC (often the case), then the cell temperature will likely not be NOCT and the cell temperature must be estimated

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Standard Operating Conditions

Standard Operating Conditions

- Irradiance: 800 W/m^2 (0.8 G_{STC})
- Ambient temperature: 20°C
- Wind speed: 1 m/s
- Spectral distribution: AM 1.5
- Power output: 0 W (no load)
- see IEC 61215 for test procedure

Do not confuse SOC with STC!

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Nominal Operating Cell Temperature

What happens when the module does not operate under SOC?

Approximate the cell temperature from:

$$T_C = T_a + (NOCT - 20)\frac{G}{800}$$

T_a: ambient temperature (C)

Other formulations exist for correcting for non-SOC wind speed, but it is not commonly employed

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Example

What is the cell temperature of the Itek 370 SE when the irradiance is 400 W/m^2, and the ambient temperature is 15° C? (Assume SOC otherwise)

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Example

From the spec sheet the NOCT is 45.01° C

$$T_C = T_a + (NOCT - 20)\frac{G}{800}$$

This is a cold day (about 59° F)

$$T_C = 15 + (45.01 - 20)\frac{400}{800}$$

$$T_C = 27.5^{\circ}C$$

We see that the PV module is hotter than the ambient temperature

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Exercise

What is the maximum power produced by the Itek SE 370 when the ambient temperature is 30° C and the irradiance on the module is 1000 W/m^2?

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Exercise

What is the maximum power produced by the Itek SE 370 when the ambient temperature is 30° C and the irradiance on the module is 1000 W/m^2?

The temperature coefficient for power is -0.39%/°C

The NOCT is 45.01° C

The irradiance corresponds to G_{STC}, so use P^*_{STC} from the spec sheet (370 W)

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Exercise

First compute cell temperature

$$T_C = T_a + (NOCT - 20)\frac{G}{800}$$

$$T_C = 30 + (45.01 - 20)\frac{1000}{800}$$

$$T_C = 61.27^\circ C$$

Now compute maximum power

$$P^*(T_C) = P^*(25^\circ C)\left(1 + \frac{\alpha_p}{100} \times (T_C - 25)\right)$$

$$P^*(30^\circ C) = 370\left(1 + \frac{-0.39}{100} \times (T_C - 25)\right)$$

$$P^*(30^\circ C) = 317.7 \text{ W}$$

Power has been reduced by 14% due to temperature

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Correcting for Temperature & Irradiance

- Last example conveniently had an irradiance of 1000 W/m^2 (STC)
- What about when the cell temperature AND irradiance deviate from STC?
  - Mostly concerned about maximum power, not open-circuit voltage or short-circuit current

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PV Power Production

- Several different methods possible
- Osterwald's method:

$$P = P^*_{STC} \times \frac{G}{1000} \times \left(1 + \frac{\alpha_P}{100} \times (T_C - 25)\right)$$

P: power produced by PV module (W)
P^*_{STC} : rated power under Standard Test Conditions (W)
G: irradiance (W/m^2)
α_P : power coefficient (% /K)
T_C : PV cell temperature (C)

Osterwald's Method

$$P = P^{*}_{STC} \times \frac{G}{1000} \times \left(1 + \frac{\alpha_P}{100} \times (T_C - 25)\right)$$

Corrects for temperature

Corrects for irradiance

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Exercise

What is the maximum power produced by the Itek SE 370 when the ambient temperature is 30° C and the irradiance on the module is 900 W/m^2?

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Exercise

What is the maximum power produced by the Itek SE 370 when the ambient temperature is 30° C and the irradiance on the module is 900 W/m^2?

The temperature coefficient is -0.39%/°C

The NOCT is 45.01° C

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Exercise

First compute cell temperature

$$T_C = T_a + (NOCT - 20)\frac{G}{800}$$

$$T_C = 30 + (45.01 - 20)\frac{900}{800}$$

$$T_C = 58.14^{\circ}C$$

Now compute maximum power

$$P = P^*_{STC} \times \frac{G}{1000} \times \left(1 + \frac{\alpha_P}{100} \times (T_C - 25)\right)$$

$$P = 370 \times \frac{900}{1000} \times \left(1 + \frac{-0.39}{100} \times (58.14 - 25)\right)$$

$$P = 289.96\ W$$

Compare this to the result of the previous exercise

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Short-Circuit Current

- We generally only correct the short-circuit current based on irradiance (not temperature) using:

$$I_{STC}(G) = I_{SC,STC} \times \frac{G}{G_{STC}}$$

- Important when determining fuse ratings and charge controller compatibility

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Open-Circuit Voltage

- We generally only correct the open-circuit current based on temperature (not irradiance) using:

$$V_{OC}(T_C) = V_{OC}(25^\circ C)\left(1 + \frac{\alpha_v}{100} \times (T_C - 25)\right)$$

- Important when determining insulation ratings and charge controller compatibility

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Fill Factor

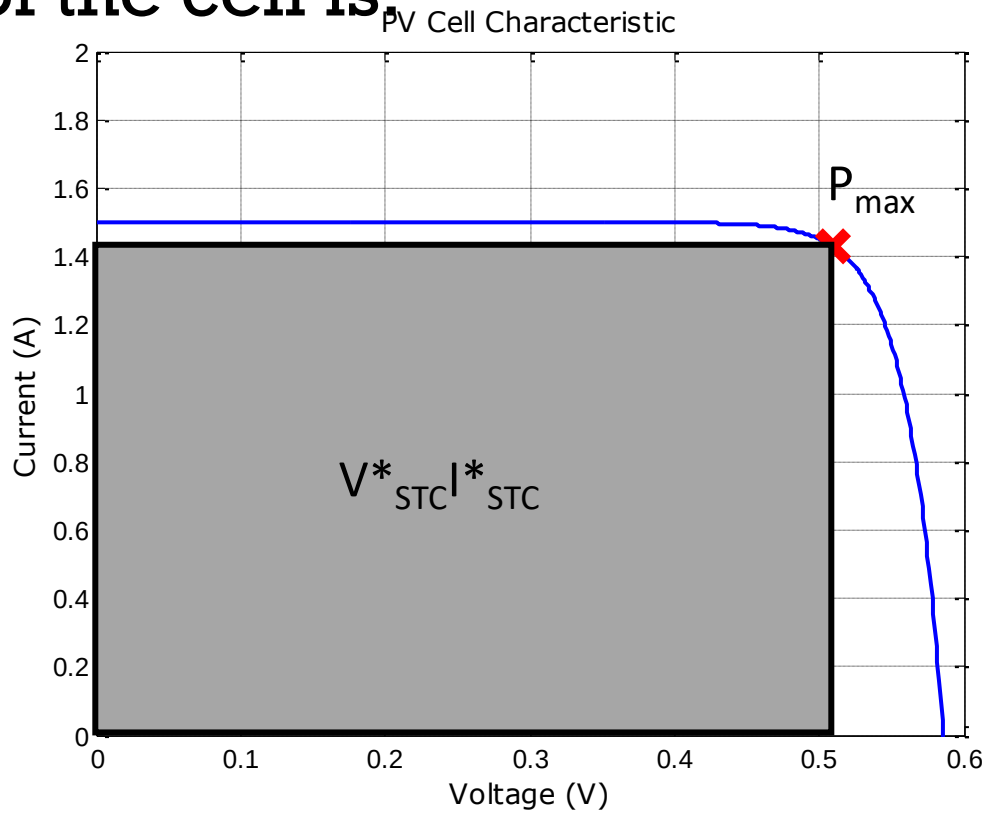
- Theoretical maximum power output of a PV cell is found by multiplying open circuit voltage with the short circuit current
- The ratio of actual maximum power to theoretical is known as the Fill Factor, and provides a metric to compare PV cell quality

Fill Factor

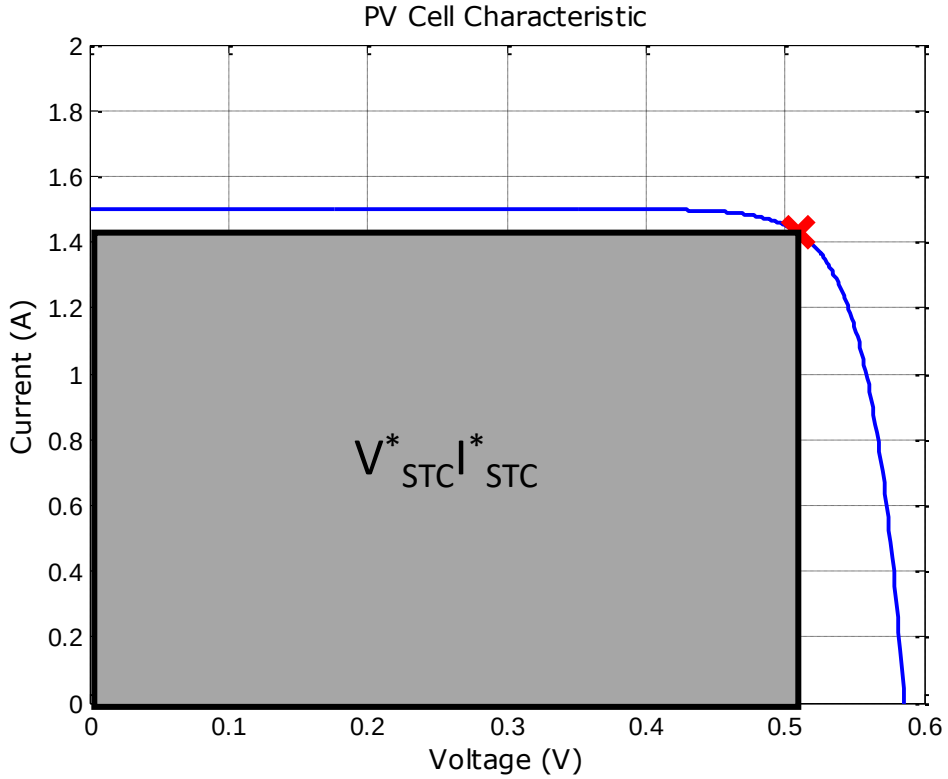
- The maximum power output of the cell is:

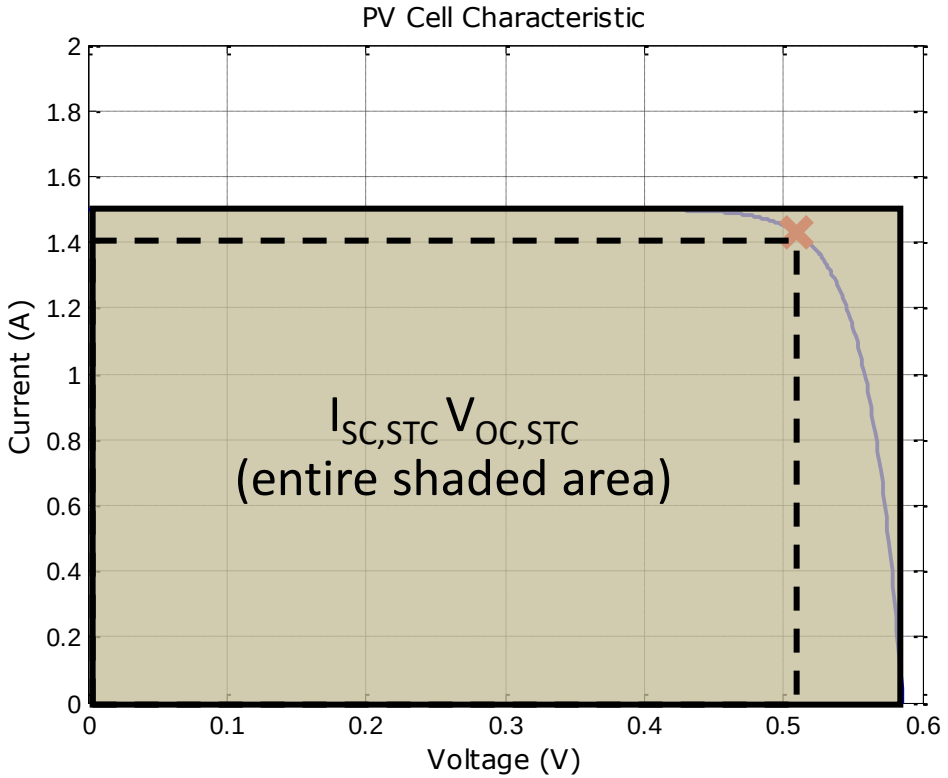
$$P^*_{STC} = I^*_{STC} V^*_{STC} = F I_{SC,STC} V_{OC,STC}$$

- Where
  - F: fill factor
- Typical value of F
  - 0.5 to 0.83



Fill Factor


PV Cell Characteristic
Current (A)
Voltage (V)
$V^*_{STC} I^*_{STC}$


PV Cell Characteristic
Current (A)
Voltage (V)
$I_{SC,STC}\, V_{OC,STC}$
(entire shaded area)

Fill Factor

- Assuming F is independent of:
  - Temperature
  - Irradiance
- MPP under various conditions can be estimated
  - Compute or measure $V_{oc}(G)$
  - Compute or measure $I_{sc}(G)$

$$P^*(G) = FI_{SC}(G)V_{OC}(G)$$ (assumes constant Fill Factor)

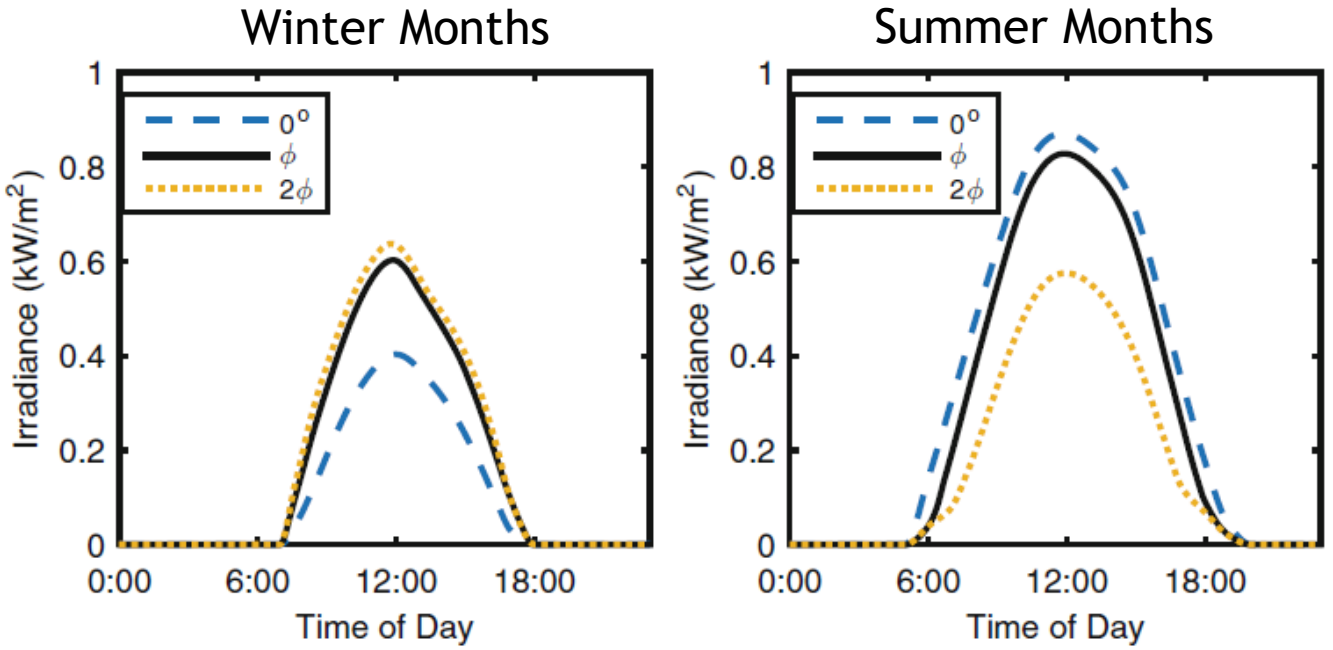
PV Energy Production

Average daily PV array energy production can be estimated from array's average daily *insolation* (kWh/m^2/day)

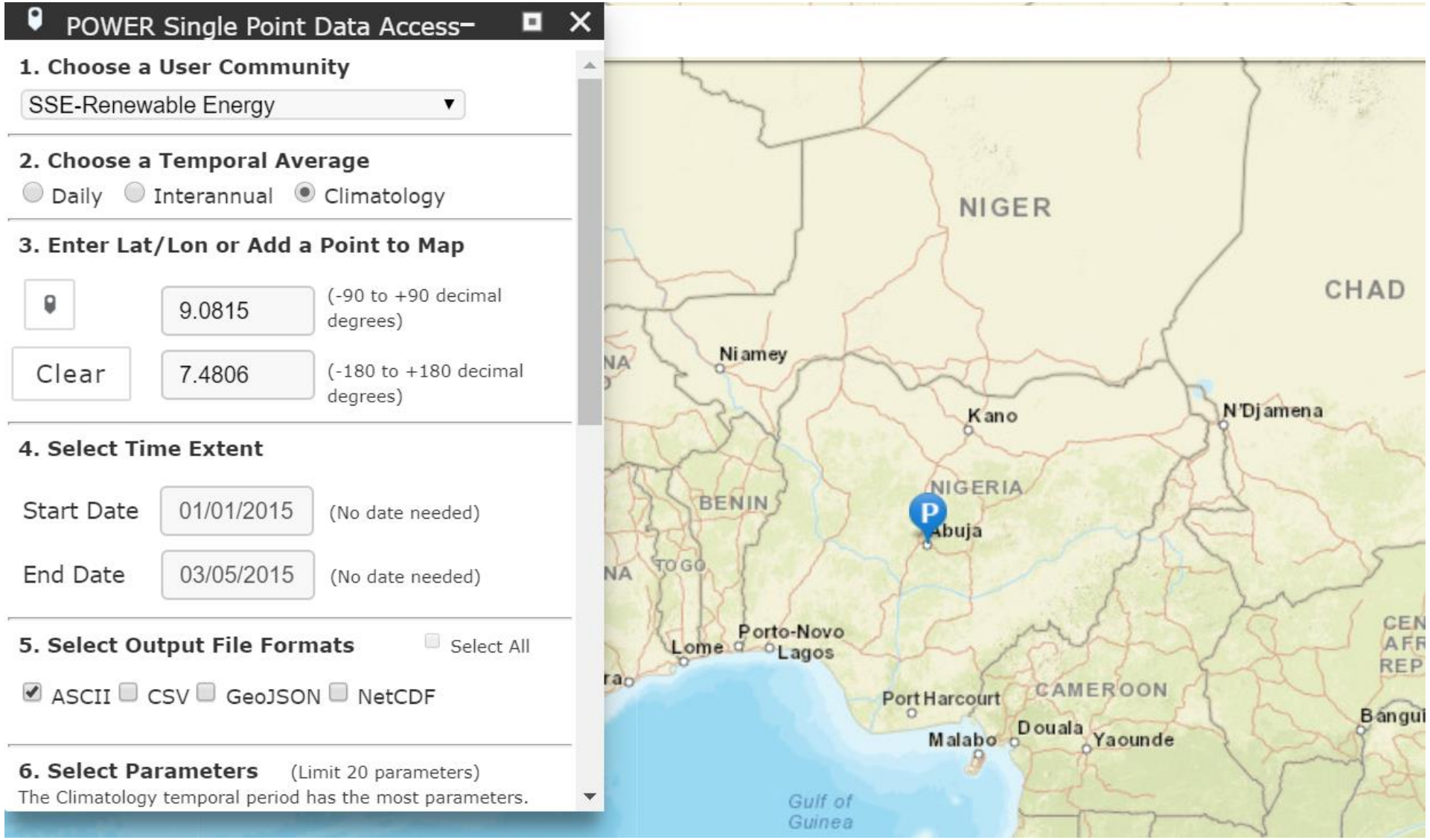
- Insolation: integral of irradiance
- Typical insolation for SSA 4 to 7 kWh/m^2/day

$$\bar{E}_{PV} = P^*_{STC} \times \bar{I}$$

$\bar{E}_{PV}$: average PV array energy production, kWh/day
$\bar{I}$: average insolation, kWh/m^2/day



Insolation depends on: array location, tilt, azimuth, season



https://power.larc.nasa.gov/data-access-viewer/

Parameter Charts

All Sky Insolation Incident on a Horizontal Surface ▼

Latitude: 9.0815 **Longitude:** 7.4806

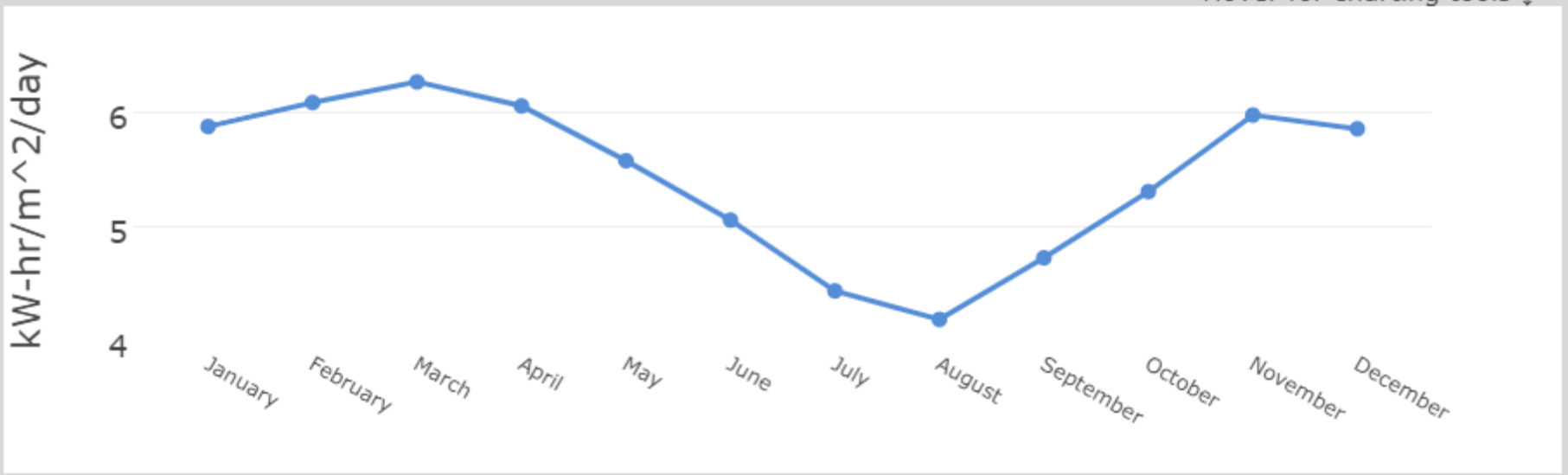
Time Extent:

22 Year Solar Climatological Averages (Jul 1983 - Jun 2005)

30 Year Meteorology Climatological Averages (Jan 1984 - Dec 2013)

Elevation: 404.65 meters

Hover for charting tools ↓



Knowledge Check

The average insolation on the a 350 W module for the month of September is 4.7 kWh/m^2/day. What is the average daily energy produced by the module?

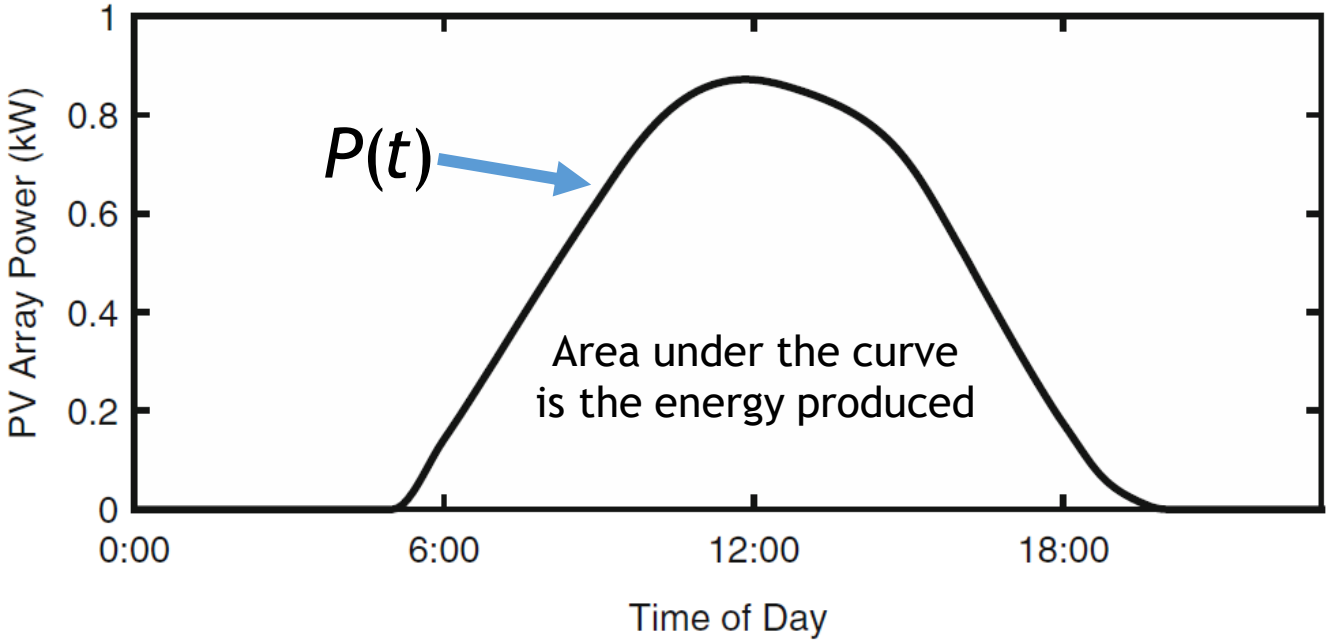
Knowledge Check

The average insolation on the a 350 W module for the month of September is 4.7 kWh/m^2/day. What is the average daily energy produced by the module?

$$\bar{E}_{PV} = 350 \times 4.7 = 1645 \text{ Wh}$$

Energy Production from PV Arrays

The energy produced by a PV array over the course of a day is found by integrating its power production



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Energy Production from PV Arrays

Integrate power between sunrise and sunset times (be careful of the units)

$$P(t) = P^{*}_{STC} \times \frac{G(t)}{1000} \times \left(1 + \alpha_p \times \left(T_c(t) - 25\right)\right)$$

We expect both the irradiance and cell temperature to vary with time (t)

$$E = \int_{t_{rise}}^{t_{set}} P(t)dt$$

t_{set}: time the sun sets
t_{rise}: time the sun rises

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Shading

- Complete or partial shading of PV module or array can severely reduce power production
- Avoid locations where shading occurs

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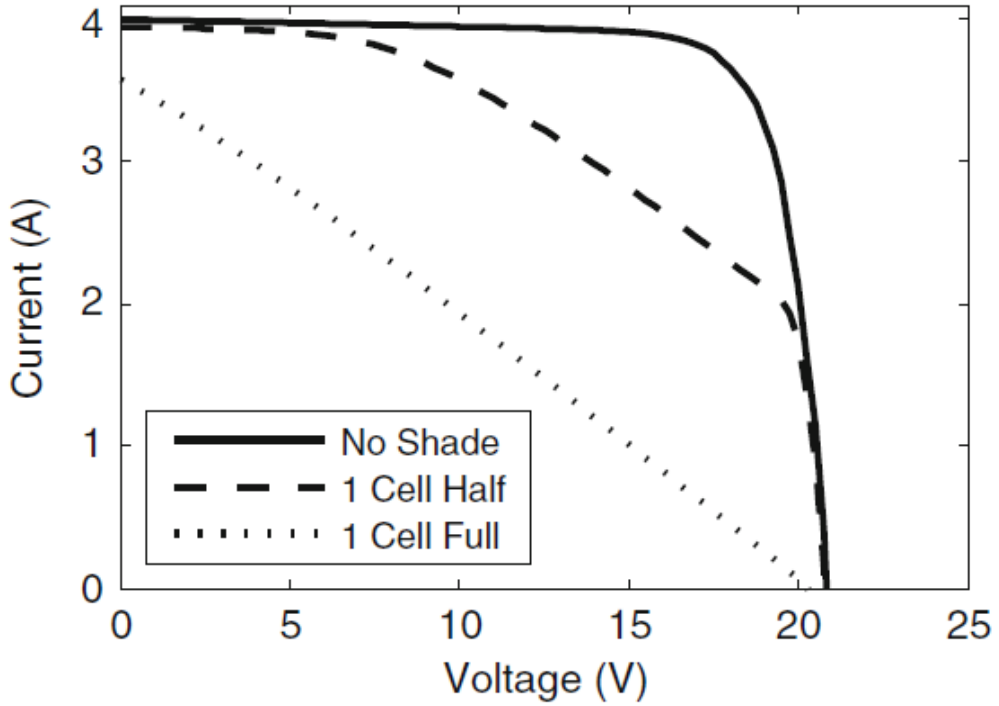
Shading

Read Chapter 7.12 for details, including how to mitigate the effects of shading by using diodes

"The current supplied by a PV module is limited to the current produced by its least productive cell."---not exactly correct, but easy to remember



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