05-Off-Grid Photovoltaic Arrays

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 5

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries*, *2nd Edition*, *2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
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Learning Outcomes

At the end of this lecture, you will be able to:

✓Describe the use of solar power in off-grid electrification, emphasizing the key technical, economic, environmental, and social considerations

✓Derive and utilize circuit models of photovoltaic (PV) cells, modules, and arrays to calculate their voltage, current, and power production under different irradiance, temperature, and load conditions

✓Define and describe the relevance of terminology such as Standard Test Conditions and Standard Operating Conditions

✓Explain how shading and other abnormal operating conditions affect PV module performance and identify strategies to mitigate the effects

Introduction

- Photovoltiac Effect is the mechanism by which solar photovoltaic (PV) works
- DC electricity is directly generated
- Discovered by Edmond Becquerel in 1839
- Established for power generation in 1954 by Chapin, Fuller and Pearson

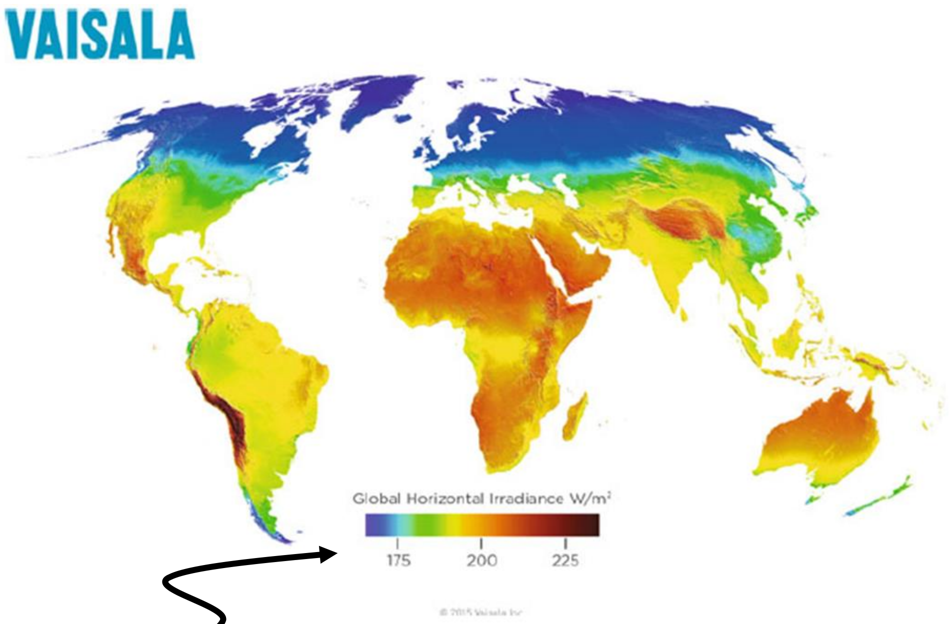
Edmond Becquerel

Irradiance and Insolation

- Irradiance (*G*): density of the power produced by sunlight (W/m^2)

- Insolation (not "insulation") (*I*): energy provided by sunlight per square meter of area over a period of time, usually per day (kWh/m^2/day)

Solar Resource



units are average irradiance

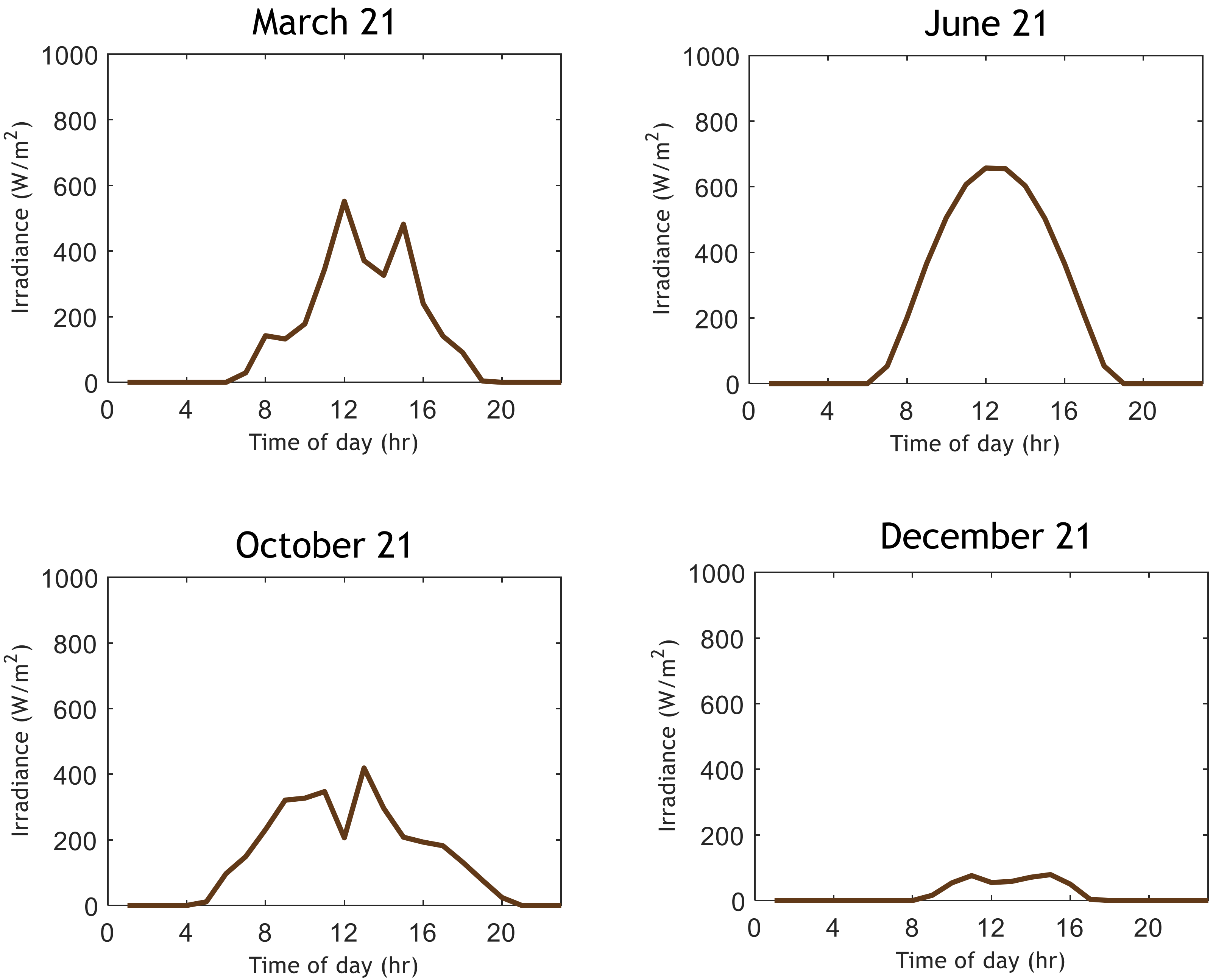
(*courtesy of Viasala, Copyright (c) 2017 Vaisala*)

Typical Values

- Irradiance of 1000 W/m^2 is approximately the sunlight a horizontal surface receives at 12:00 on a clear sunny day in the mid-continental U.S.
- Typical insolation: 3.5 to 6 $kWh/m^2/day$

Irradiance varies across the day and season

Global Horizontal Irradiance (GHI) in Seattle



Physical Description

Silicon cells are most commonly used in off-grid systems

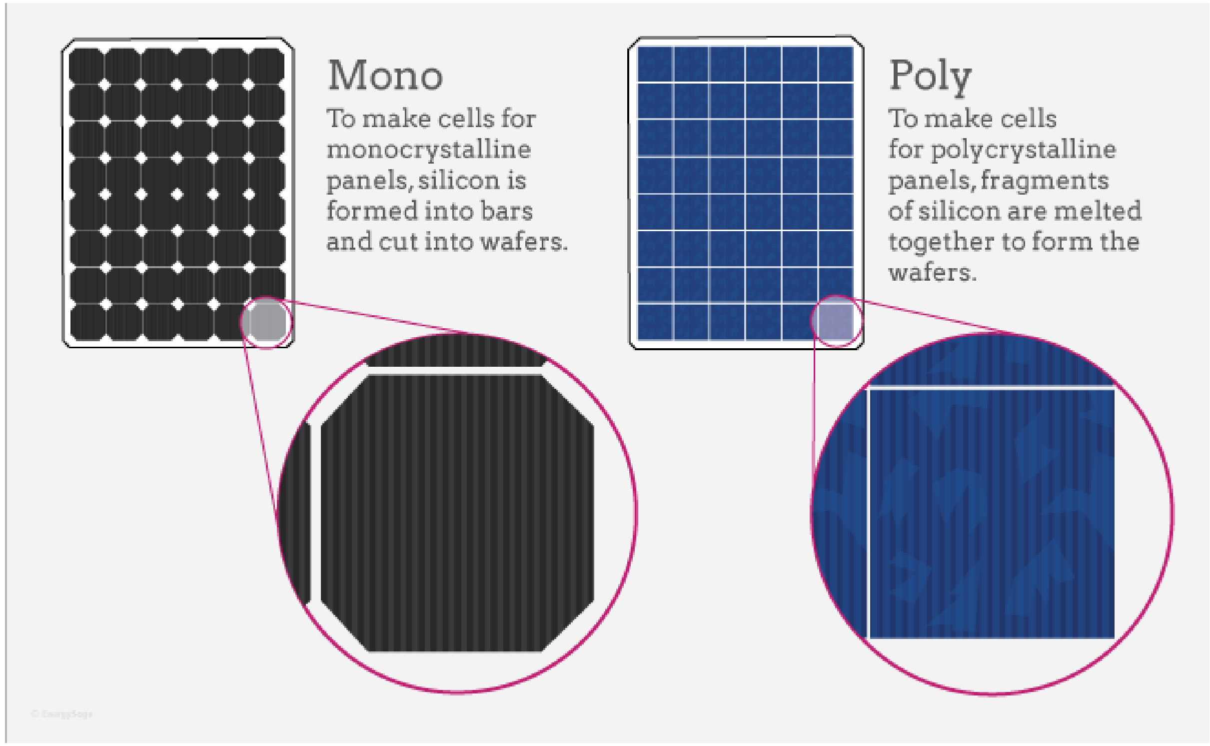
PV cells are connected in series to form PV modules

PV cell

monocrystalline

polycrystalline

Physical Description

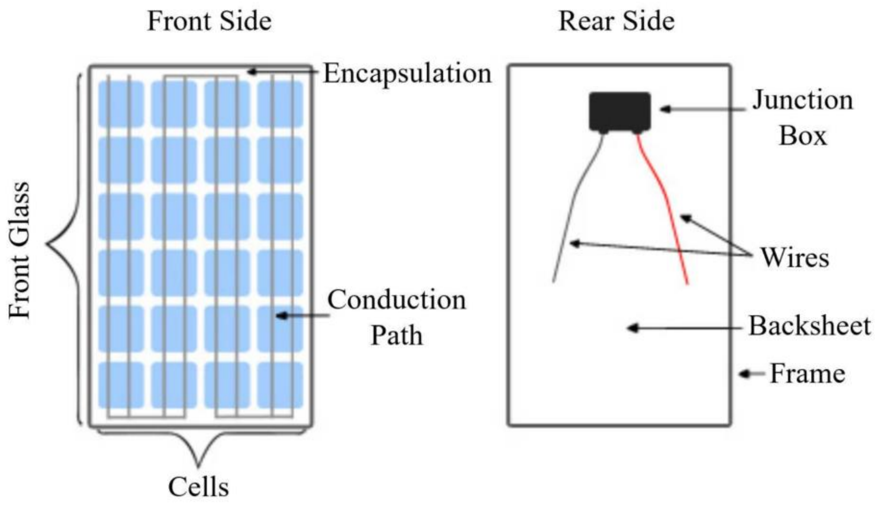


There are two common types of PV cells: mono-crystalline and poly-crystalline

A typical 0.156 m x 0.156 m (6.1 in x 6.1 in) cell produces 2 to 4 W

source https://www.civicsolar.com/support/installer/articles/monocrystalline-cells-vs-polycrystalline-cells-whats-difference

Traditional PV Module



PV Modules

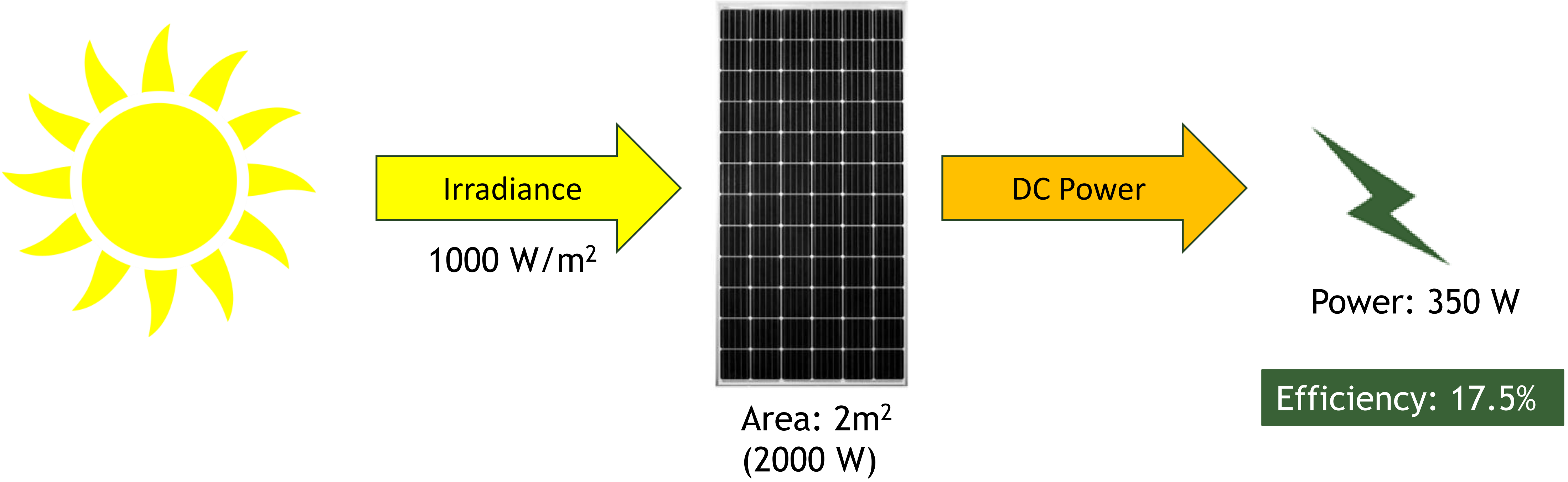
- PV modules are made from several cells that are connected together (in series)
- Physical size of a 550 W module (shown in picture)
    - 2.4 m x 1.1m x 0.04 m
    - 35 kg

(*courtesy P. Dauenhauer*)

Basic Principles

- Electricity is produced via the *photovoltaic* effect
- Power produced by PV module is approximately proportional to incident irradiance
- Power is inherently DC
- Efficiency typically 14-23%

Example Efficiency



Basic Principles

- PV cell is a p-n junction (diode)
- Recall p-n junctions are made from doped silicon crystals, which have internal built-in electric fields
- Photons from sunlight excite electrons into the conduction band, built-in field separates charge and voltage appears

Illuminated p-n Junction

- No net current in un-illuminated p-n junction
  - exception: external battery connected
- What happens when a photon hits the p-n junction?
- Recall:
  - photons can excite electrons into the conduction band

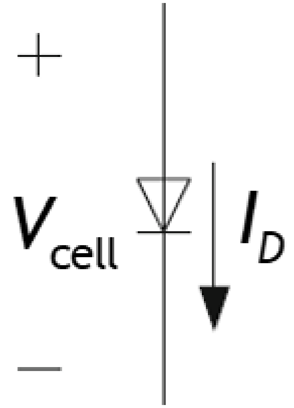
Unilluminated PV Cell

A PV cell in the dark (unilluminated) operates as a diode

$$I_D = I_0\left(e^{V_D/nV_T} - 1\right)$$

$$V_T = \frac{kT}{q}$$

V_T: 25.8 mV at room temperature
I_0: usually small (e.g. 10^{-8} A/m^2 of cell area)



k: Boltzmann's constant (1.38×10^{-23} J/K)
n: ideality factor (unitless), is equal to 1 for an ideal diode, but is often >1
T: temperature (K)
q: charge 1.602×10^{-19} (C)
I_0: reverse bias saturation current (A)

Illuminated PV Cell

Effect of photons exciting electrons is modeled as "illumination current"

- always positive
- approx. proportional to incident irradiance, cell area, and cell efficiency
- typical range: 0.5 to 9 A

$$I_{\text{cell}} = I_{\text{G}} - I_0\left(e^{V_{\text{cell}}/nV_{\text{T}}} - 1\right)$$

characteristic equation of PV cell

$$I_{\text{cell}} = I_{\text{G}} - I_{\text{D}}$$

I_G: illumination current (A)
I_{cell}: current out of PV cell (A)
V_{cell}: PV cell voltage (V)

PV Cell Open-Circuit Voltage

Open-circuit voltage of a PV cell is computed from

$$I_{\text{cell}} = I_{\text{G}} - I_0\left(e^{V_{\text{cell}}/nV_{\text{T}}} - 1\right)$$

$$\frac{I_{\text{G}} - I_{\text{cell}}}{I_0} + 1 = e^{V_{\text{cell}}/nV_{\text{T}}}$$

$$nV_{\text{T}}\ln\left(\frac{I_{\text{G}} - I_{\text{cell}}}{I_0} + 1\right) = V_{\text{cell}}$$

$$V_{\text{cell,OC}} = nV_{\text{T}}\ln\left(\frac{I_{\text{G}}}{I_0} + 1\right)$$

Typical open-circuit voltage is between 0.6 and 0.74 V

Short-Circuit Current

Under short-circuit conditions $V_{\text{cell}} = 0$ V

$$I_{\text{cell}} = I_{\text{G}} - I_0\left(e^{V_{\text{cell}}/nV_{\text{T}}} - 1\right)$$

$$I_{\text{SC}} = I_{\text{G}} - I_0\left(e^{0/nV_T} - 1\right)$$

$$I_{\text{SC}} = I_{\text{G}} - I_0\left(1 - 1\right)$$

$$I_{\text{SC}} = I_{\text{G}}$$

The short-circuit current is equal to the illumination current. The illumination current can be determined by shorting the PV cell and measuring the current (assuming the PV cell is ideal)

Example 5.1

Compute the open-circuit voltage and short-circuit current of a PV cell whose reverse bias saturation current is 9^{-9} A, illumination current is 8.46 A, ideality factor is 1.0, and thermal voltage is 28 mV.

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Compute the open-circuit voltage and short-circuit current of a PV cell whose reverse bias saturation current is 9^{-9} A, illumination current is 8.46 A, ideality factor is 1.0, and thermal voltage is 28 mV.

The short-circuit current of a PV cell is equal to the illumination current so that the short-circuit current = 8.46 A.

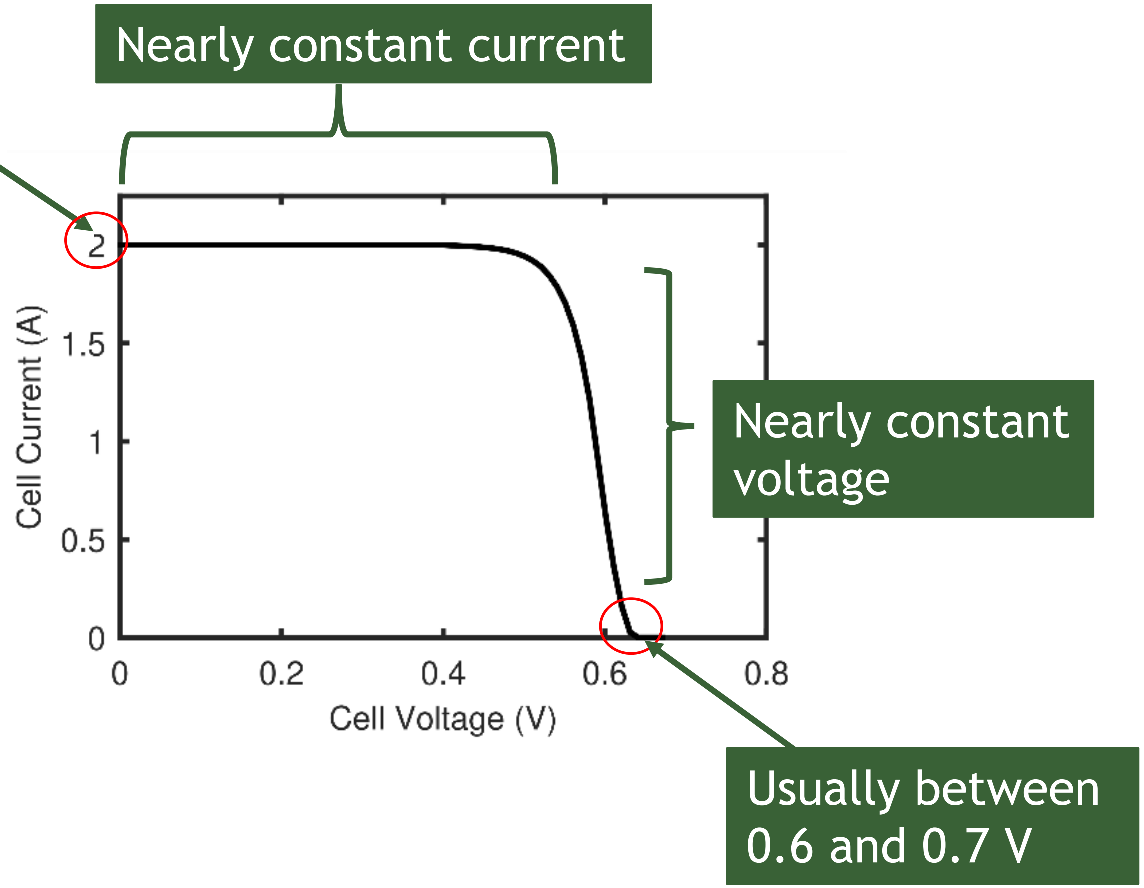
$$V_{\text{cell,OC}} = nV_T \ln\left(\frac{I_G}{I_0} + 1\right) = 1 \times 0.028 \times \ln\left(\frac{8.46}{9^{-9}} + 1\right) = 0.613\,\text{V}$$

I-V Curve

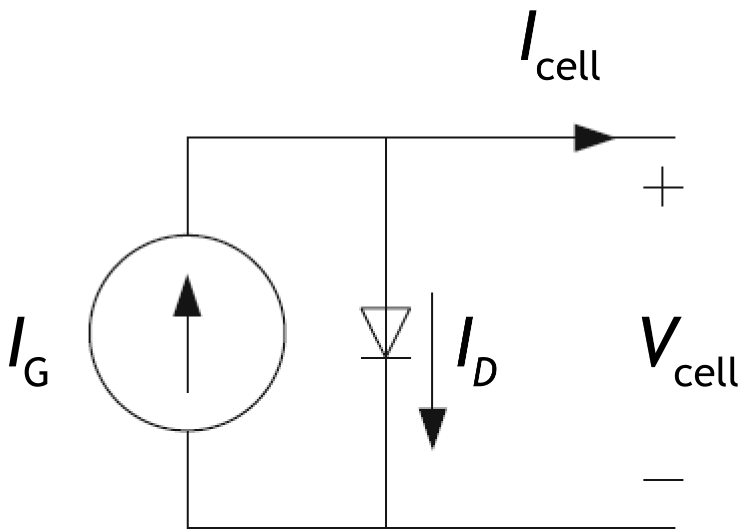
The current—voltage curve of a PV cell can be plotted by solving

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

for different values of V_{cell}



Ideal Circuit Model



Assume PV cell is
ideal unless stated otherwise

Exercise

Which variable should be set to zero when the PV cell is operated under open-circuit conditions?

A. I_{G}
B. I_0
C. I_{cell}
D. V_{T}

$$I_{\mathrm{cell}} = I_{\mathrm{G}} - I_0\left(e^{V_{\mathrm{cell}}/nV_{\mathrm{T}}} - 1\right)$$

Exercise

Which variable should be set to zero when the PV cell is operated under open-circuit conditions?

A. I_G
B. I_0
C. I_{cell}
D. V_T

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

Exercise

Which of these affects the open-circuit voltage of a PV cell?

A. Temperature
B. Ideality factor
C. Irradiance
D. Reverse saturation current?

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Which of these affects the open-circuit voltage of a PV cell?

A. Temperature
B. Ideality factor
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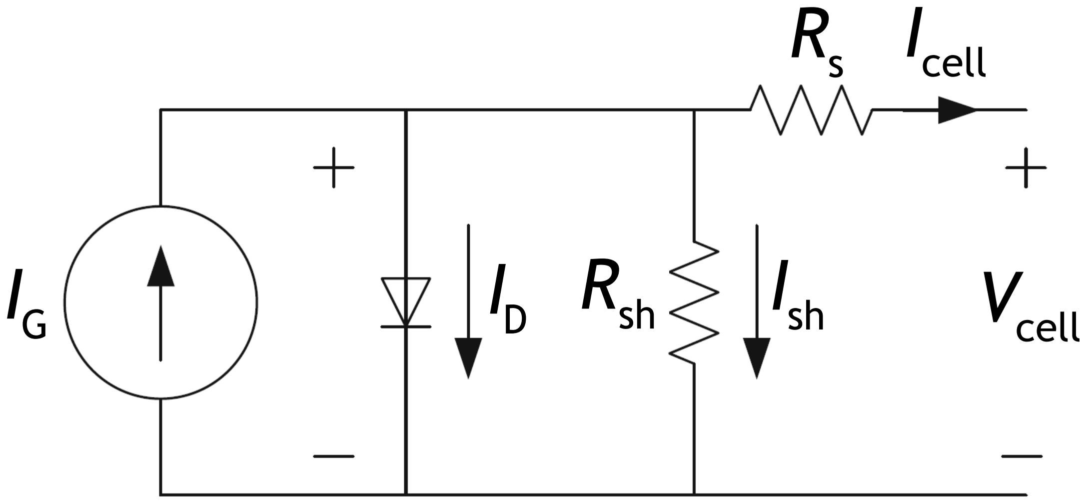
$$V_{\text{cell,OC}} = nV_{\text{T}}\ln\left(\frac{I_{\text{G}}}{I_0}+1\right)$$

Circuit Model with Losses (non-ideal)

$$I_{\text{cell}} = I_{\text{G}} - I_{\text{D}} - I_{\text{sh}}$$

$$I_{\text{cell}} = I_{\text{G}} - I_0\left(e^{(V_{\text{cell}} + I_{\text{cell}}R_{\text{s}})/V_{\text{T}}} - 1\right) - \frac{V_{\text{cell}} + I_{\text{cell}}R_{\text{s}}}{R_{\text{sh}}}$$

Implicit equation, must be solved numerically



Maximum Power Point

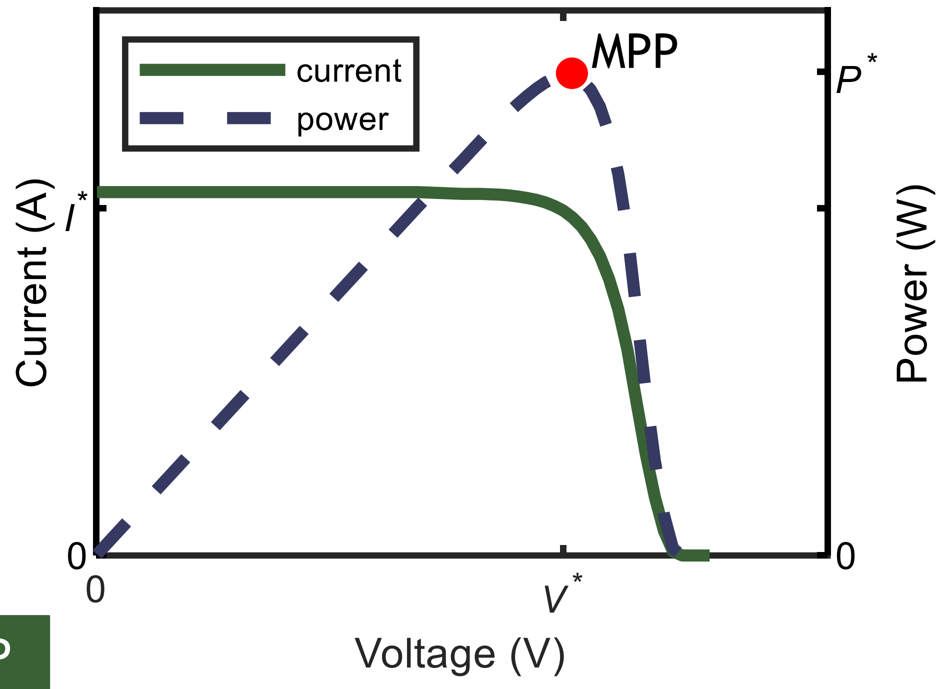
- Power output is found from

$$P_{\text{cell}} = I_{\text{cell}} V_{\text{cell}}$$

- PV arrays have a unique maximum power operating point (maximum power point, MPP)

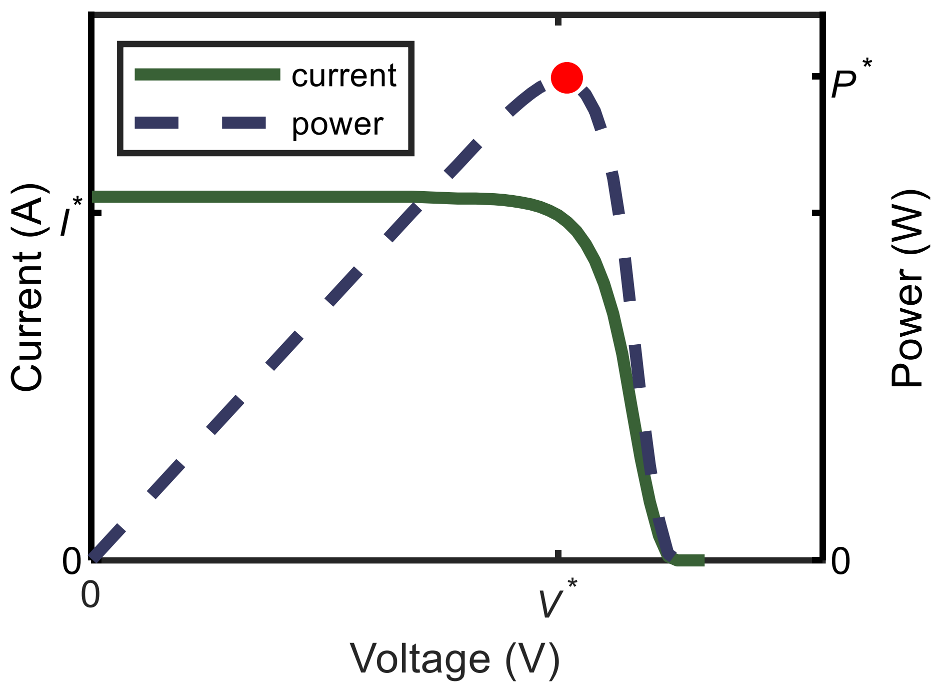
$$P^*_{\text{cell}} = V^*_{\text{cell}} I^*_{\text{cell}}$$

here the * indicates that the values correspond to the MPP (not complex conjugate)



Maximum Power Point

- MPP voltage might not correspond to load input impedance or battery voltage
- Use a "maximum power point tracker" to ensure PV cell (module) is operating at the maximum power point (discussed in Chap. 11 and 13)

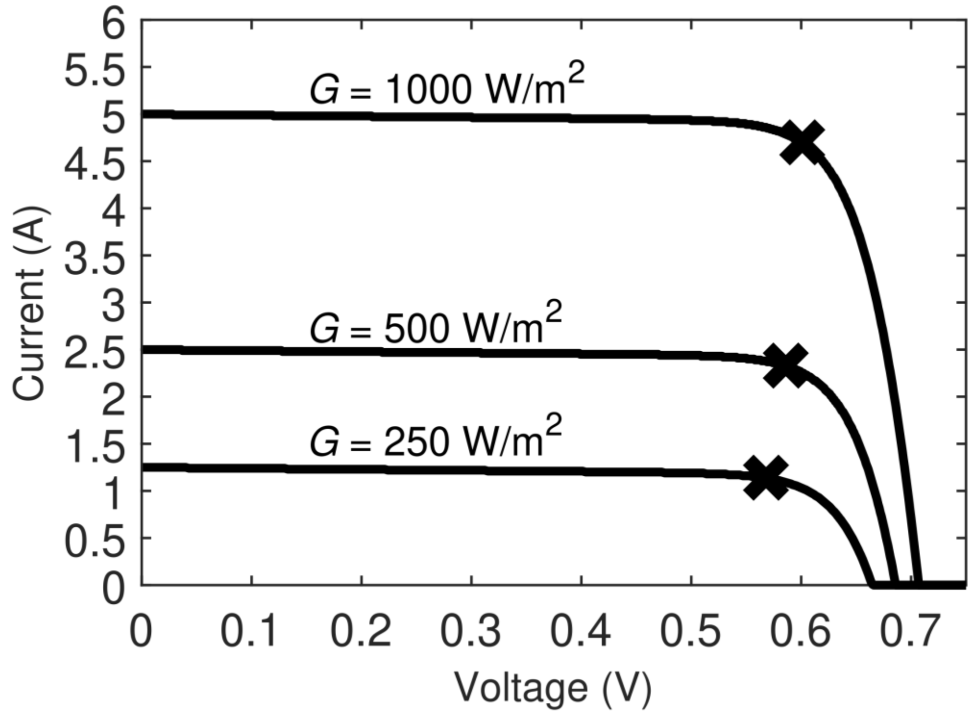


Maximum Power Point at Different Irradiances

Maximum power point voltage and current depends on the irradiance

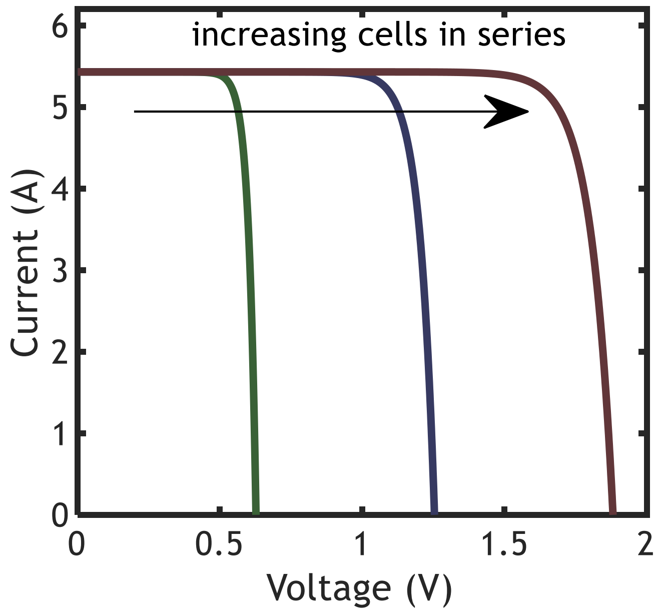
$$P^*_{\text{cell}}(G) = V^*_{\text{cell}}(G) I^*_{\text{cell}}(G)$$

Here we show that the voltage, current, and power at the maximum power point are functions of the irradiance

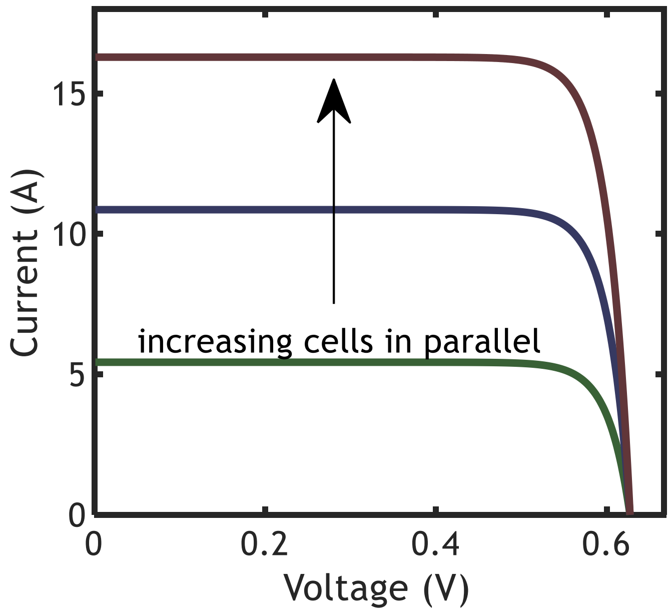


PV Modules

- 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

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:

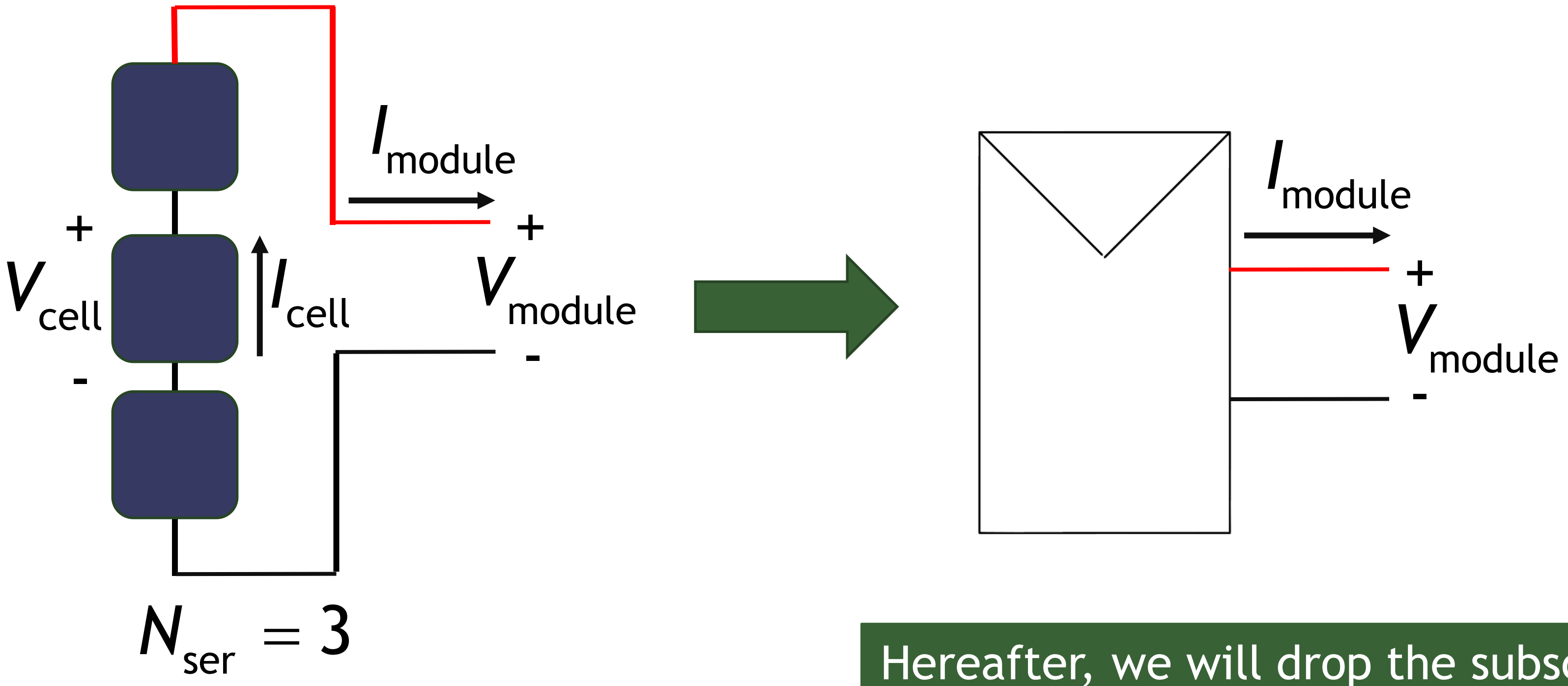
$$V_{\text{module}} = N_{\text{ser}} \times V_{\text{cell}}$$

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

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

V_{module} : PV module voltage (V)
I_{module} : PV module current (A)
N_{ser}: number of series-connected cells
N_{par} : number of parallel-connected cells (usually 1)

PV Modules



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

PV Module Specifications

- Manufacturer-provided information
- Used to understand and estimate how the module will perform under different conditions

Characteristic at STC	Value
Maximum Power	185.3 W
Optimum Operating Voltage (V^*)	36.4 V
Optimum Operating Current (I^*)	5.08 A
Open-Circuit Voltage (V_{OC})	45.0 V
Short-Circuit Current (I_{SC})	5.43 A
Short-Circuit Current Temp. Coeff. (α_i)	0.055 %/K
Open-Circuit Temp. Coeff. (α_v)	-0.37 %/K
Max. Power Temp. Coeff. (α_P)	-0.48 %/K
NOCT	45 °C
Number of Cells	72 (series)

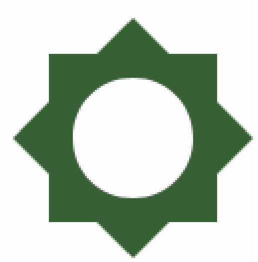
What PV Capacity (Power rating) Means

A certain PV 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 Lusaka?
- Will it ever produce more than 350 W?
- Do the characteristics of the load or battery that it is connected to matter?

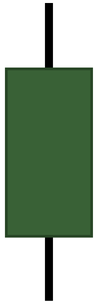
Main Factors Affecting PV Power Production

Irradiance



Temperature

Load



Spectral distribution of irradiance also affects production

Standard Test Conditions

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

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

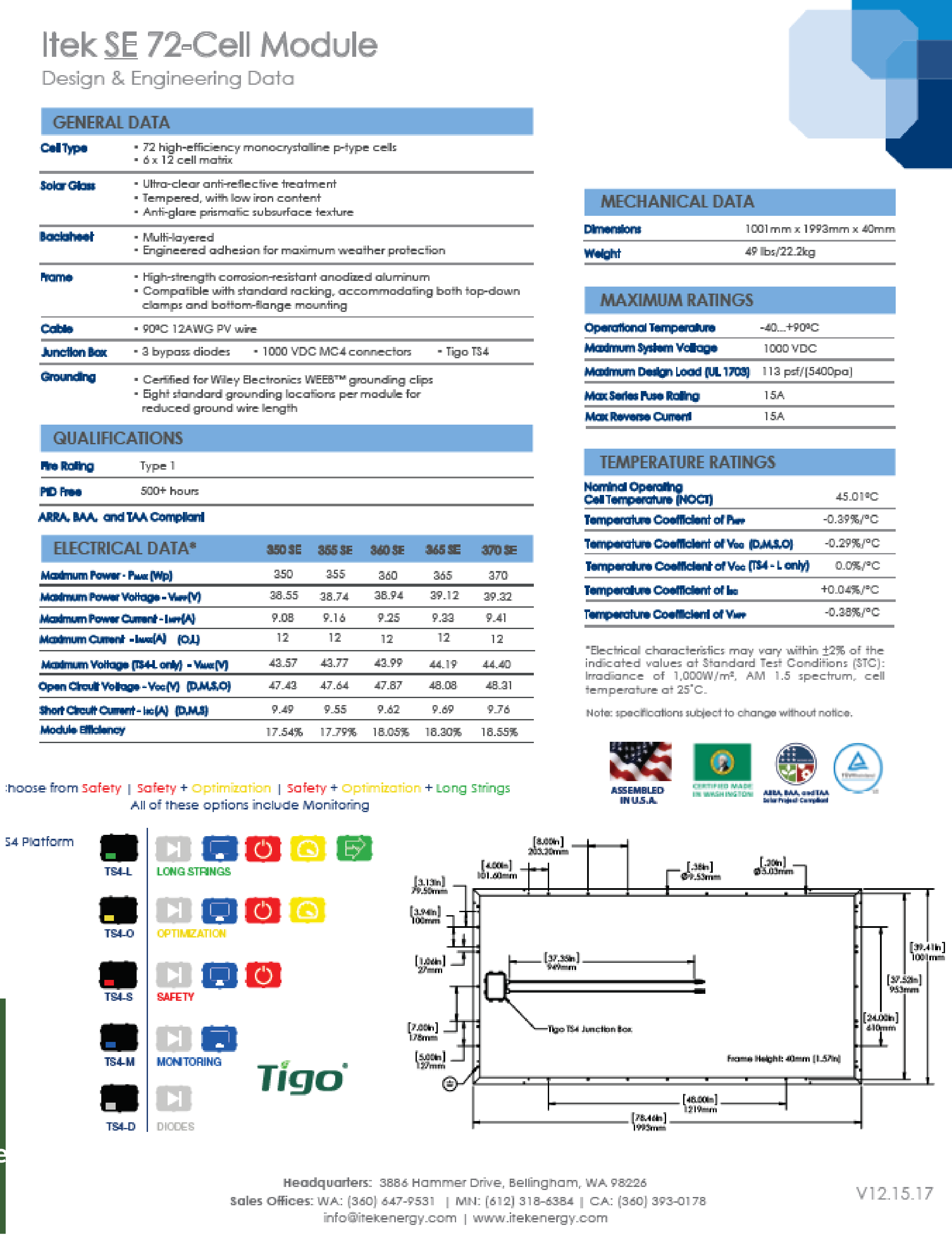
P^*_{STC} : maximum power output under STC

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

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

PV Module Spec Sheets

- Modules rated at Standard Test Conditions (STC)
  - Irradiance: 1000 W/m^2
  - Cell temperature: 25 ^{o}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	• 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_{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 - 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%

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_{MP}	-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

*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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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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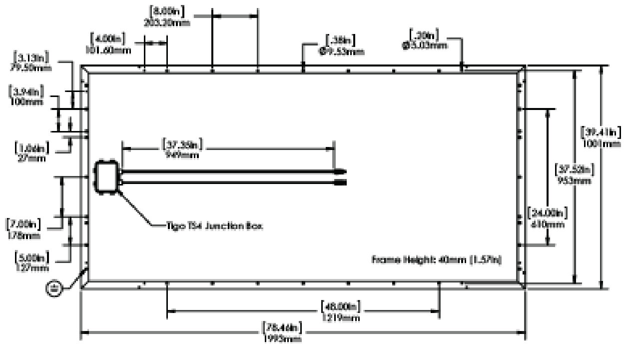

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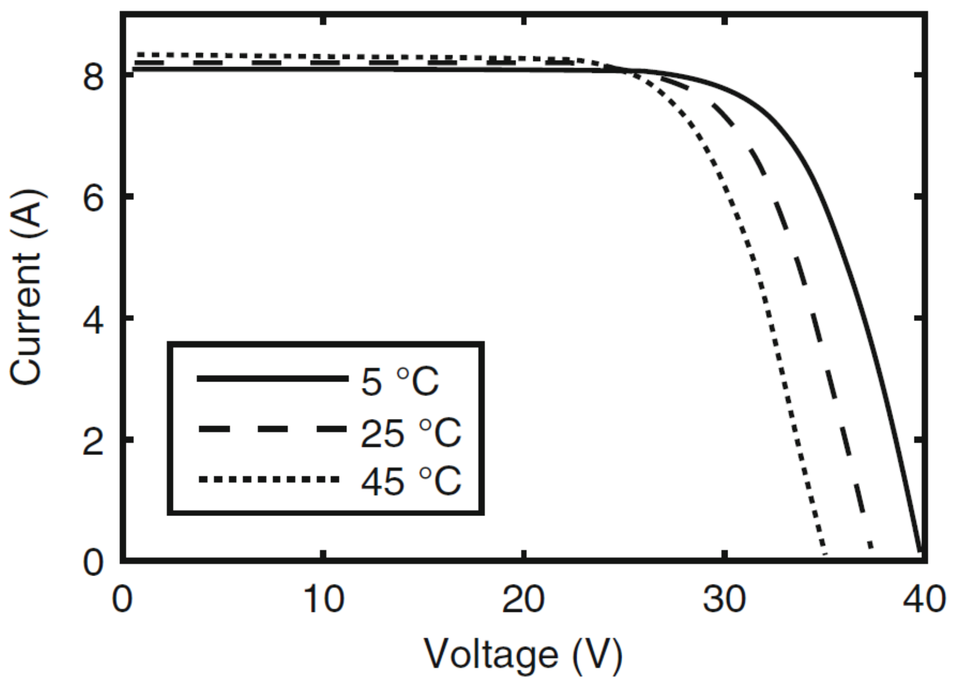
Rated Power Interpretation

The 350 SE module will produce 350 W when the irradiance incident to it is 1000 W/m^2, the cell temperature is 25^o 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)

Correcting for Temperature

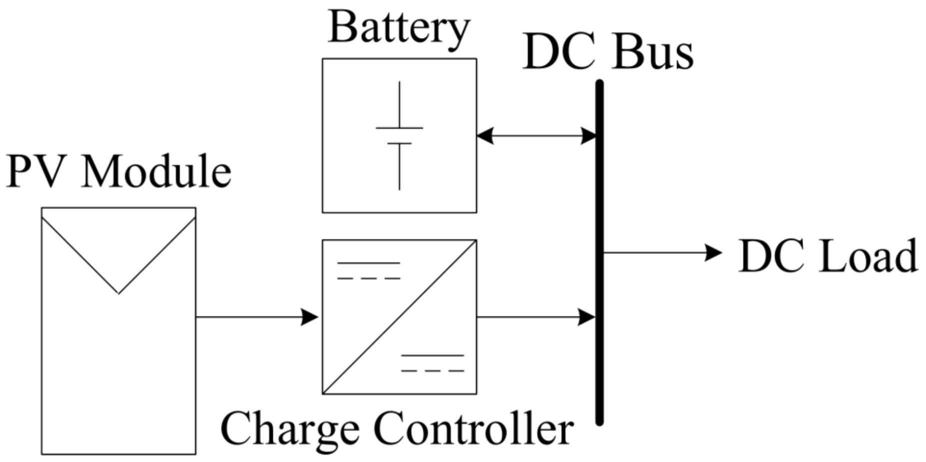
- I-V characteristic of PV module is influenced by the temperature
- Increasing temperature:
  - decreases voltage
  - increases current
- Change in voltage dominates the change in current, so power (voltage x current) decreases



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

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

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



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 <u>cell temperature</u> deviates from 25 ^{o}C
- Power can be reduced by 10 to 15% because cell temperature is often >20 ^{o}C higher than that of STC

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

Correcting for Temperature

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

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

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

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

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

Example 5.3

The temperature of a PV module with characteristics in the Table is 47 °C. Compute the short-circuit current, open-circuit voltage, and maximum power

Characteristic at STC	Value
Maximum Power	185.3 W
Optimum Operating Voltage (V^*)	36.4 V
Optimum Operating Current (I^*)	5.08 A
Open-Circuit Voltage (V_{OC})	45.0 V
Short-Circuit Current (I_{SC})	5.43 A
Short-Circuit Current Temp. Coeff. (α_i)	0.055 %/K
Open-Circuit Temp. Coeff. (α_v)	-0.37 %/K
Max. Power Temp. Coeff. (α_P)	-0.48 %/K
NOCT	45 °C
Number of Cells	72 (series)

Example 5.3

We assume that the module is operating at STC with the exception of temperature.

$$I_{SC}(T_C) = 5.43\left(1 + 0.00055 \times \left(47 - 25\right)\right) = 5.496 \text{ A}$$

$$V_{OC}(T_C) = 45.0\left(1 - 0.00370 \times \left(47 - 25\right)\right) = 41.337 \text{ V}$$

$$P^{*}(T_C) = 185.3\left(1 - 0.0048 \times \left(47 - 25\right)\right) = 165.732 \text{ W}$$

Notice that the magnitude of the percentage change in voltage is greater than that of the current, and the percentage change in power is greater still.

We shouldn’t be concerned about the units being in degree 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)

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 "Nominal Operating Cell Temperature" (NOCT)
  - typically between 45 ^oC and 50 ^oC
- 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

Standard Operating Conditions

Standard Operating Conditions

- Irradiance: 800 W/m^2 (0.8 G_{STC})
- Ambient temperature: 20 ^oC
- 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!

Nominal Operating Cell Temperature

What happens when the module does not operate under SOC?

Approximate the cell temperature from:

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

T_a: ambient temperature (^{o}C)

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

Example 5.4

Compute the module temperature of a PV module whose reported NOCT is 45°C when exposed to irradiance of 600 W/m^2 and an ambient temperature of 34°C.

Example 5.4

Compute the module temperature of a PV module whose reported NOCT is 45°C when exposed to irradiance of 600 W/m^2 and an ambient temperature of 34°C.

The PV module is not operating under SOC, and so a correction must be applied.

$$T_c = T_a + (NOCT - 20)\frac{G}{800} = 34 + (45 - 20)\frac{600}{800} = 52.75°C$$

Short-Circuit Current

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

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

- Important when determining conductor ratings and charge controller compatibility

Open-Circuit Voltage

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

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

- Important when determining insulation ratings and charge controller compatibility

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

Correcting for Irradiance

Maximum power accounting for actual irradiance

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

Correcting for Irradiance

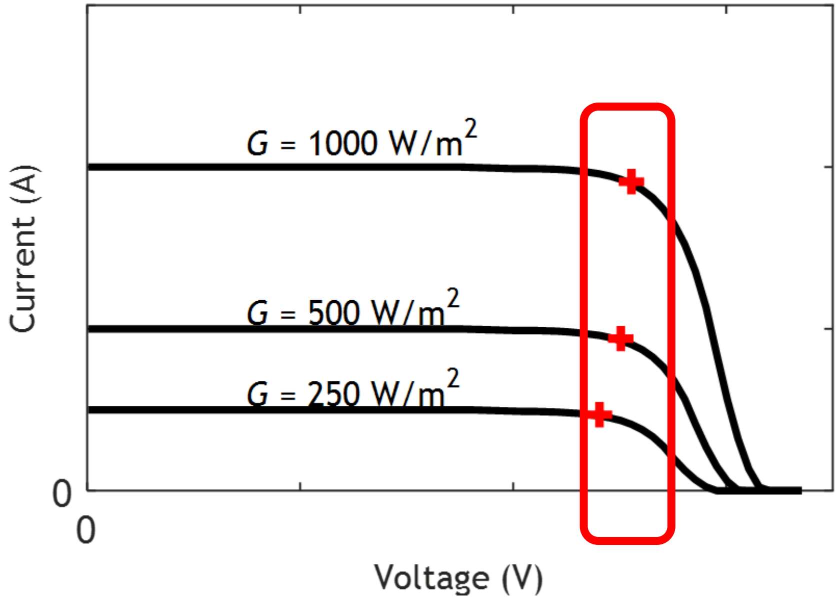
The model assumes (approximates)

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

Voltage at MPP is not affected by irradiance

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

Current at MPP changes in proportion to irradiance



Example 5.5

Compute the maximum power of the PV module whose characteristics are described in the Table assuming the irradiance is 600 W/m^2.

Characteristic at STC	Value
Maximum Power	185.3 W
Optimum Operating Voltage (V^*)	36.4 V
Optimum Operating Current (I^*)	5.08 A
Open-Circuit Voltage (V_{OC})	45.0 V
Short-Circuit Current (I_{SC})	5.43 A
Short-Circuit Current Temp. Coeff. (α_i)	0.055 %/K
Open-Circuit Temp. Coeff. (α_v)	-0.37 %/K
Max. Power Temp. Coeff. (α_P)	-0.48 %/K
NOCT	45 °C
Number of Cells	72 (series)

Example 5.5

Compute the maximum power of the PV module whose characteristics are described in the Table assuming the irradiance is 600 W/m².

Characteristic at STC	Value
Maximum Power	185.3 W
Optimum Operating Voltage (V^*)	36.4 V
Optimum Operating Current (I^*)	5.08 A
Open-Circuit Voltage (V_{OC})	45.0 V
Short-Circuit Current (I_{SC})	5.43 A
Short-Circuit Current Temp. Coeff. (α_i)	0.055 %/K
Open-Circuit Temp. Coeff. (α_v)	-0.37 %/K
Max. Power Temp. Coeff. (α_P)	-0.48 %/K
NOCT	45 °C
Number of Cells	72 (series)

$$P^*(G) = P^*_{\text{STC}} \times \frac{G}{G_{\text{STC}}} = 185.3 \times \frac{600}{1000} = 111.18\,\text{W}$$

Notice that power has been reduced

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

PV Power Production

- Several different methods possible
- Osterwald's method:

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

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

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

Corrects for temperature

Corrects for irradiance

Example 5.6

Compute the maximum power of the PV module whose characteristics are described in the Table assuming the irradiance is 600 W/m^2, and the ambient temperature is 34°C, using Osterwald's method.

Example 5.6

Compute the maximum power of the PV module whose characteristics are described in the Table assuming the irradiance is 600 W/m^2, and the ambient temperature is 34°C, using Osterwald's method.

$$P = P^{*}_{\mathrm{STC}} \times \frac{G}{1000} \times \left(1 + \frac{\alpha_{\mathrm{p}}}{100} \times \left(T_{\mathrm{C}} - 25\right)\right)$$

$$= 185.3 \times \frac{600}{1000} \times \left(1 + \frac{-0.48}{100} \times \left(52.75 - 25\right)\right) = 96.37\,\mathrm{W}$$

PV Power Production

PV power production is increased when:

- irradiance is high
- temperature is low
- load corresponds to the maximum power point (or maximum power point tracker is used)

Soiling and Snow Coverage

- Complete or partial shading of PV module or array can severely reduce power production
- Energy output reduced 10-20% or more
- Partial shading reduces power production and can damage cells due to overheating
- Avoid locations where shading occurs

(*courtesy: D. Nausner*)

source: Global Himalayan Expedition

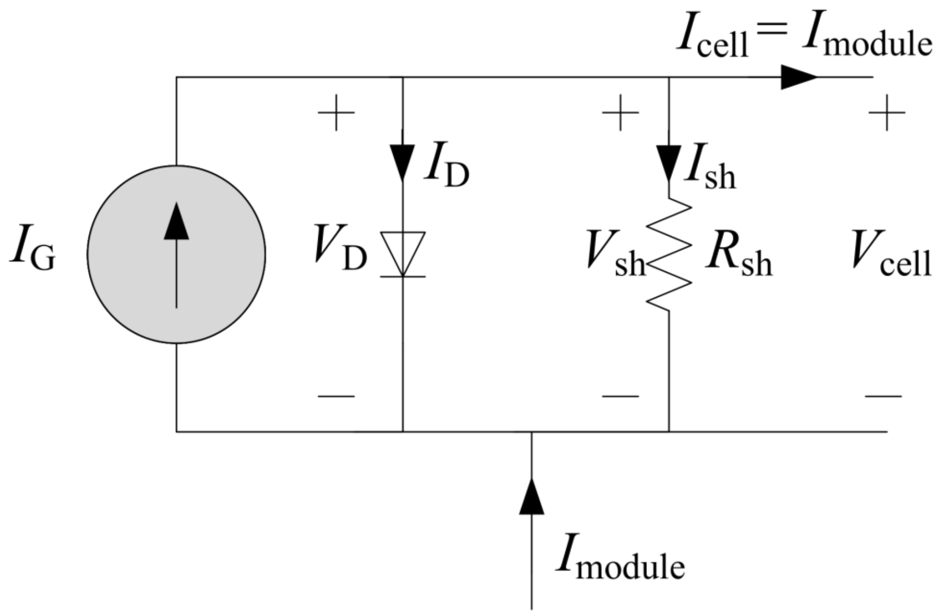
Soiling

- Increased tilt reduces dust accumulation
- Dusty PV modules can be wiped clean

(*courtesy: H. Louie*)

Shaded Cell

- Consider a PV module with one partially shaded cell
- Assume PV module's operating point is such that $I_{module} > I_G$
- All cells are series-connected so that: $I_{cell} = I_{module}$



Shaded Cell

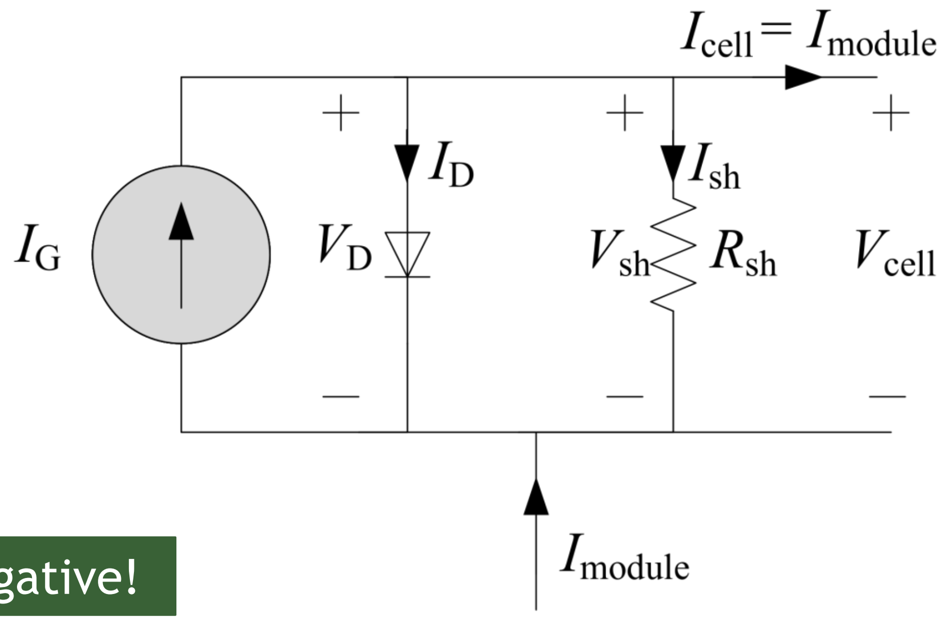
- KCL at the bottom node

$$I_{\text{module}} - I_{\text{G}} = -I_{\text{D}} - I_{\text{sh}}$$

With $I_{\text{module}} > I_{\text{G}}$, the diode and shunt currents and voltages must be negative

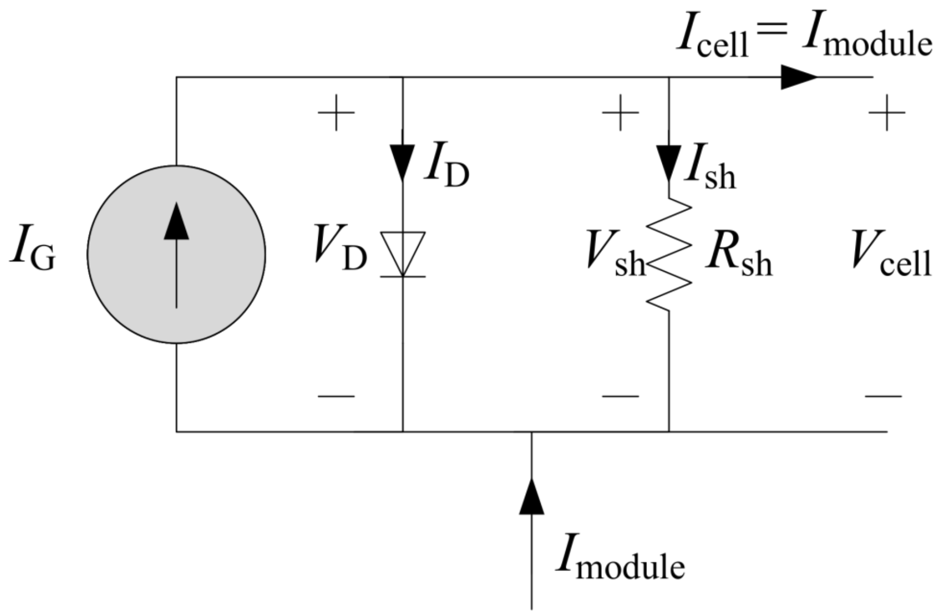
- Diode is reverse biased so $I_{\text{D}} = 0$

and $V_{\text{cell}} = -\left(I_{\text{module}} - I_{\text{G}}\right)R_{\text{sh}}$ the cell voltage is negative!

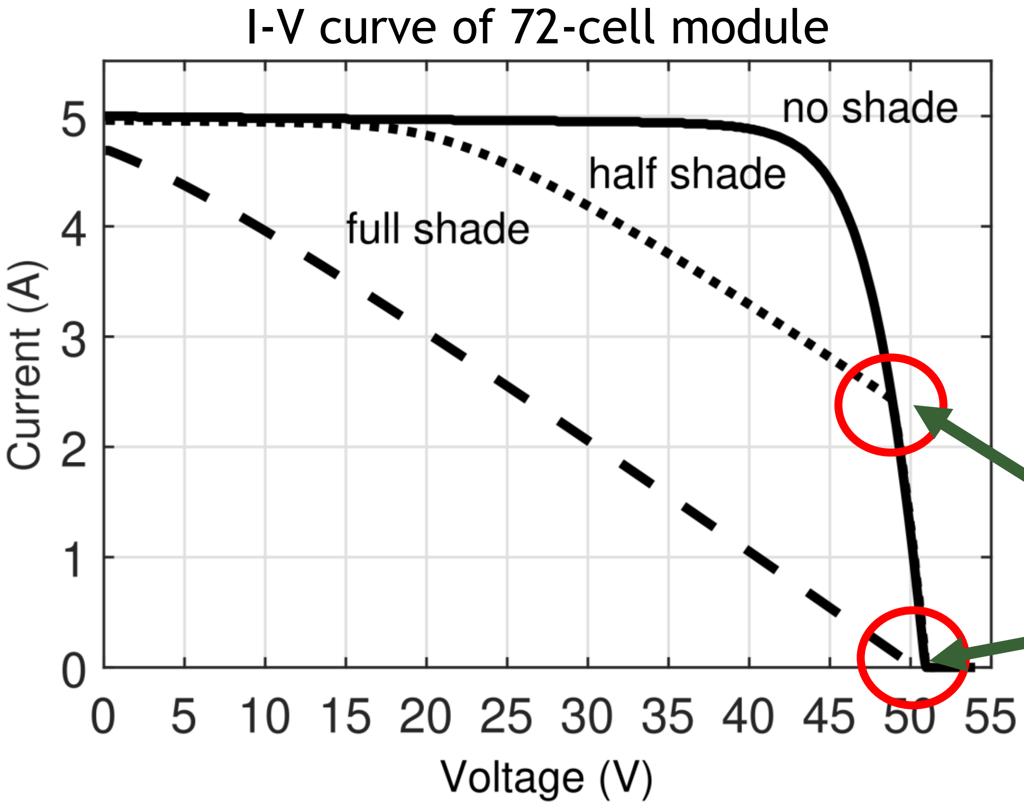


Shaded Cell

- Cell voltage is negative and its magnitude can exceed tens of volts
- Shunt resistance dissipates power
  - may cause damage or fire due to overheating
  - reduces power output by the PV module



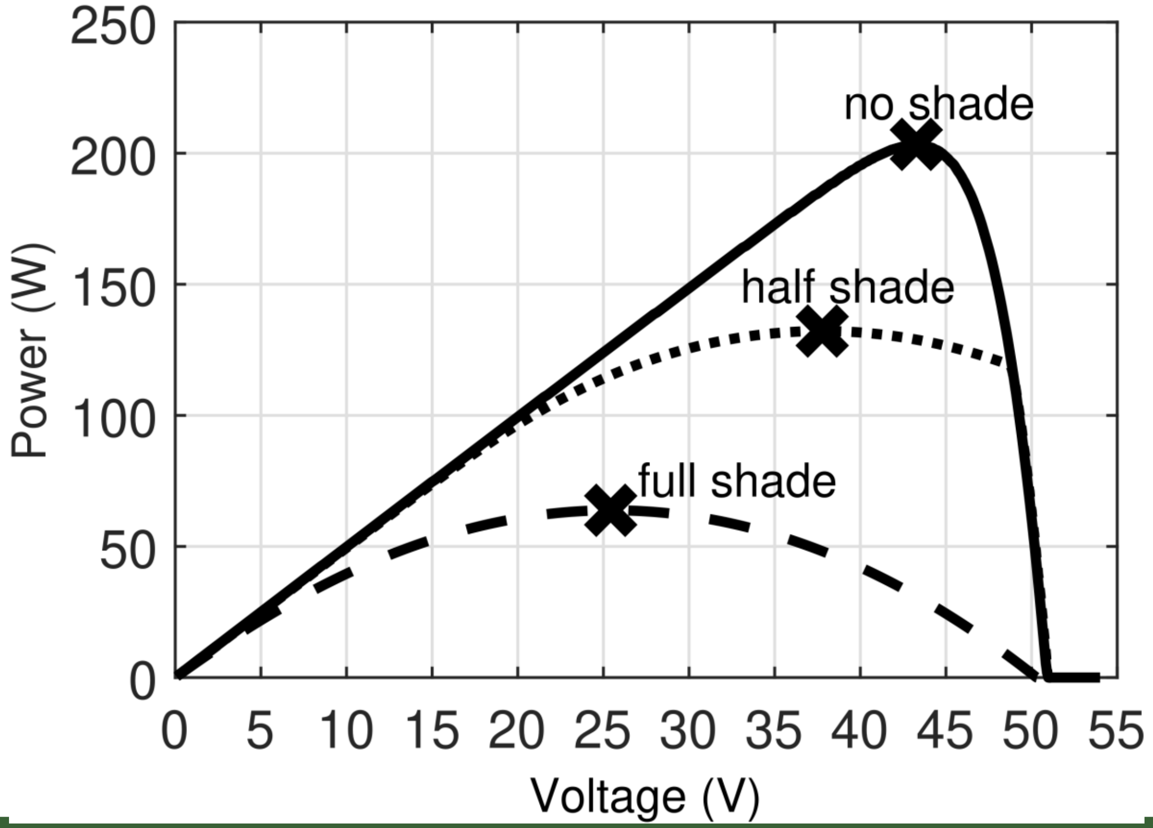
I-V Curve of Shaded Module with One Shaded Cell



Half shade I_G = 2.5 A
Full shade I_G = 0 A

Rejoins unshaded curve when $I_G = I_{module}$

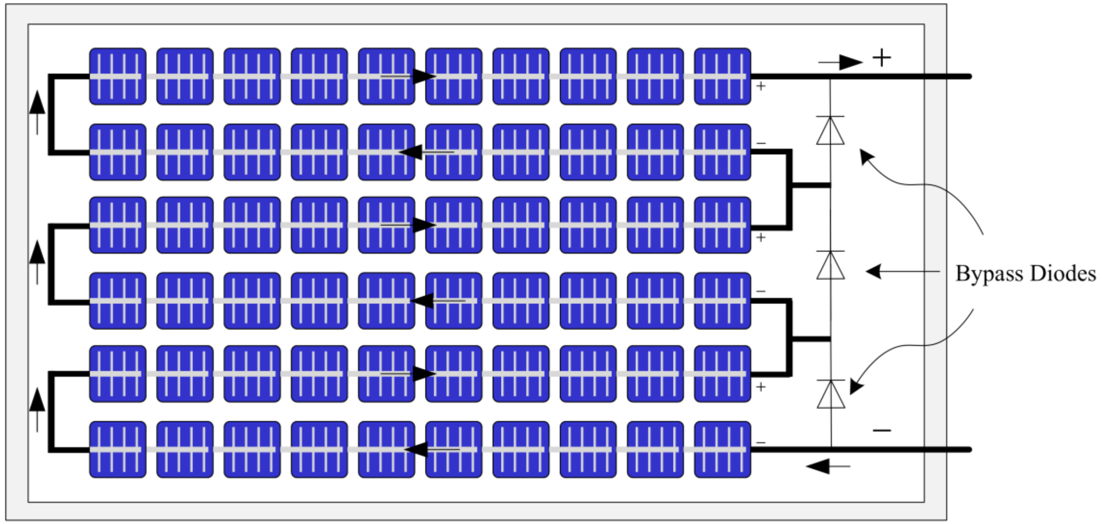
P-V Curve of Shaded Module with One Shaded Cell



maximum power reduced due to shading AND voltage at which the MPP occurs changes

Bypass Diodes

- Solution to partial shading is to use bypass diodes
- Provide a parallel path for a portion of the module current around shaded cell(s)
- Bypass diodes are integrated into most PV modules



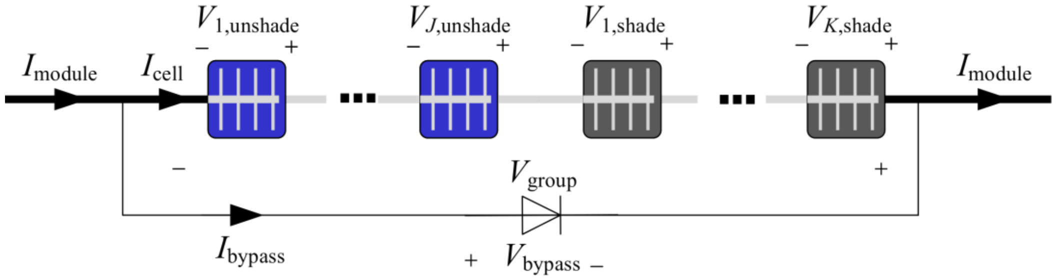
Bypass Diodes

- Cells connected in parallel to a bypass diode are a “group”

$$V_{\text{group}} = \sum_{j=1}^{J} V_{j,\text{unshade}} + \sum_{k=1}^{K} V_{k,\text{shade}}$$

$$V_{\text{bypass}} = -V_{\text{group}}$$

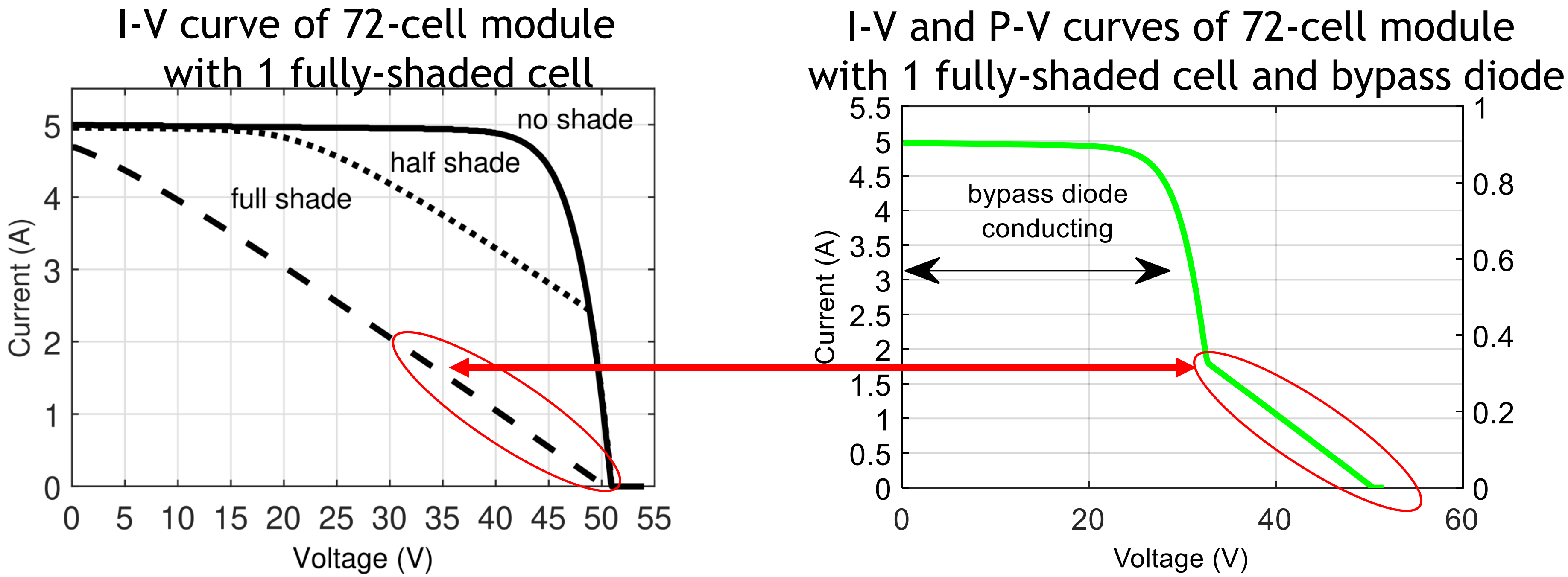
$$I_{\text{module}} = I_{\text{cell}} + I_{\text{bypass}}$$



When shaded cell(s) voltage is negative, the group voltage can be negative and a portion of the diode current conducts through the bypass diode

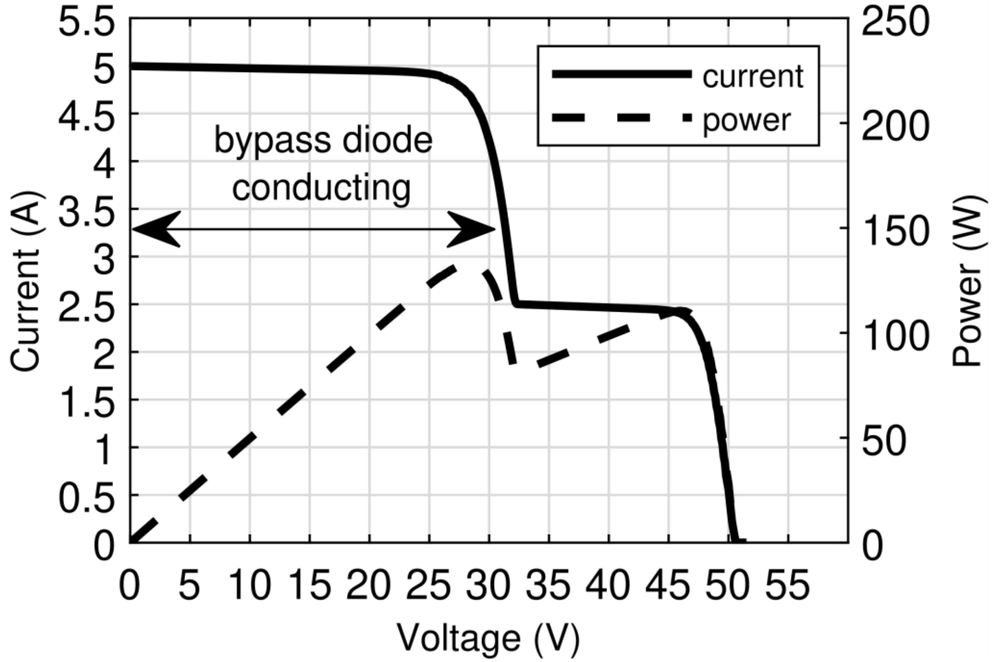
I-V Curve with Bypass Diode

When bypass diode is not forward biased ($V_{bypass} > 0$), the I-V curve resembles that of a PV module without a bypass diode



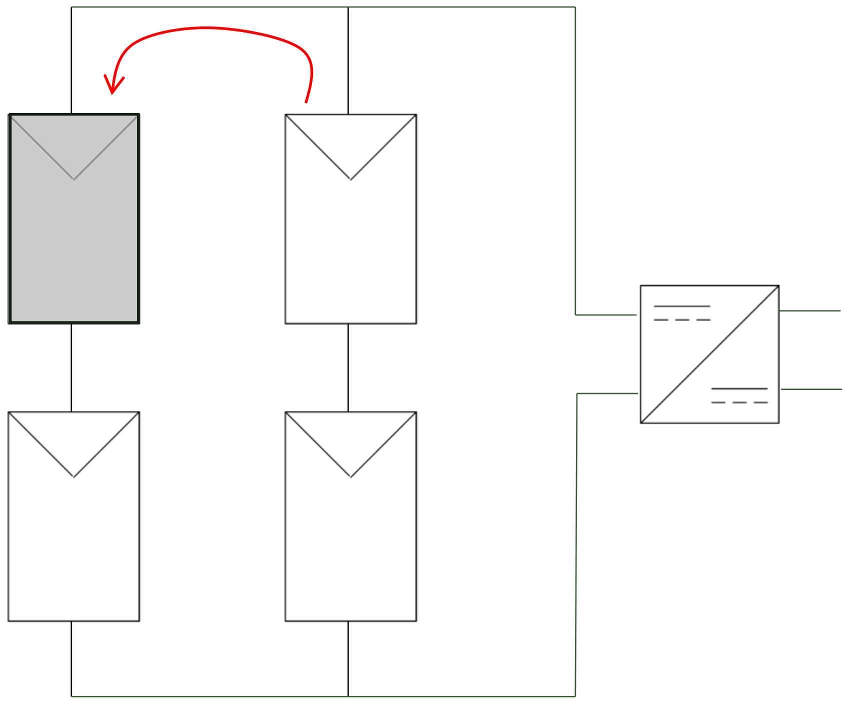
Bypass Diodes

- Partial shaded conditions with bypass diodes can lead to strange P-V curves
- Two unequal “peaks”
- Can confuse MPPT algorithms, resulting in sub-maximal operation at the lower peak



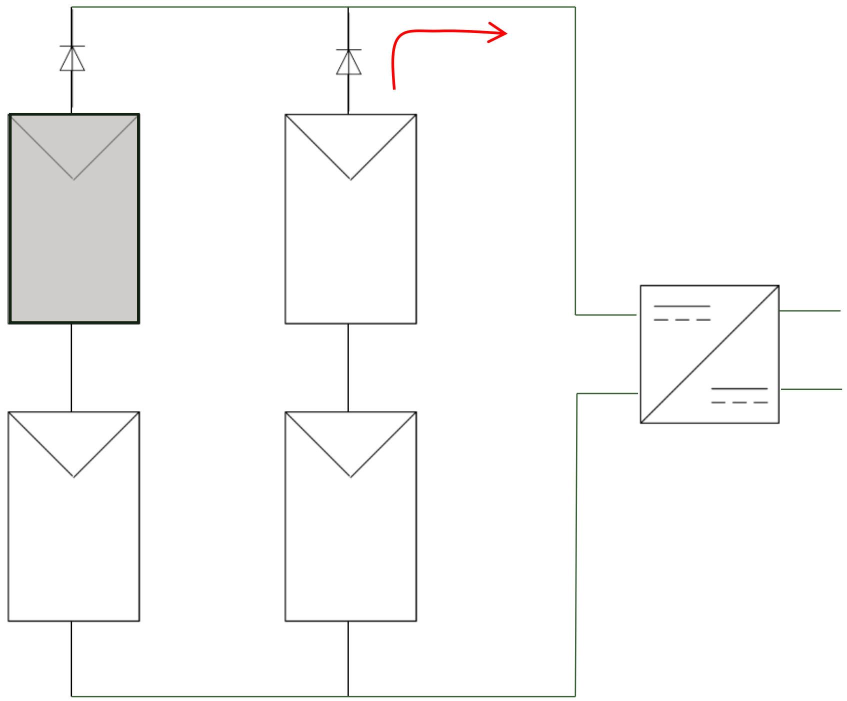
Blocking Diodes

- Shading or other abnormal conditions can result in current of the opposite polarity in a PV module or array
- Any strings in parallel may have current flow through the shaded string



Blocking Diodes

- Blocking diodes installed when strings are in parallel to prevent on string from sending current through the other
- Under unshaded operation, there is loss associated with the blocking diodes



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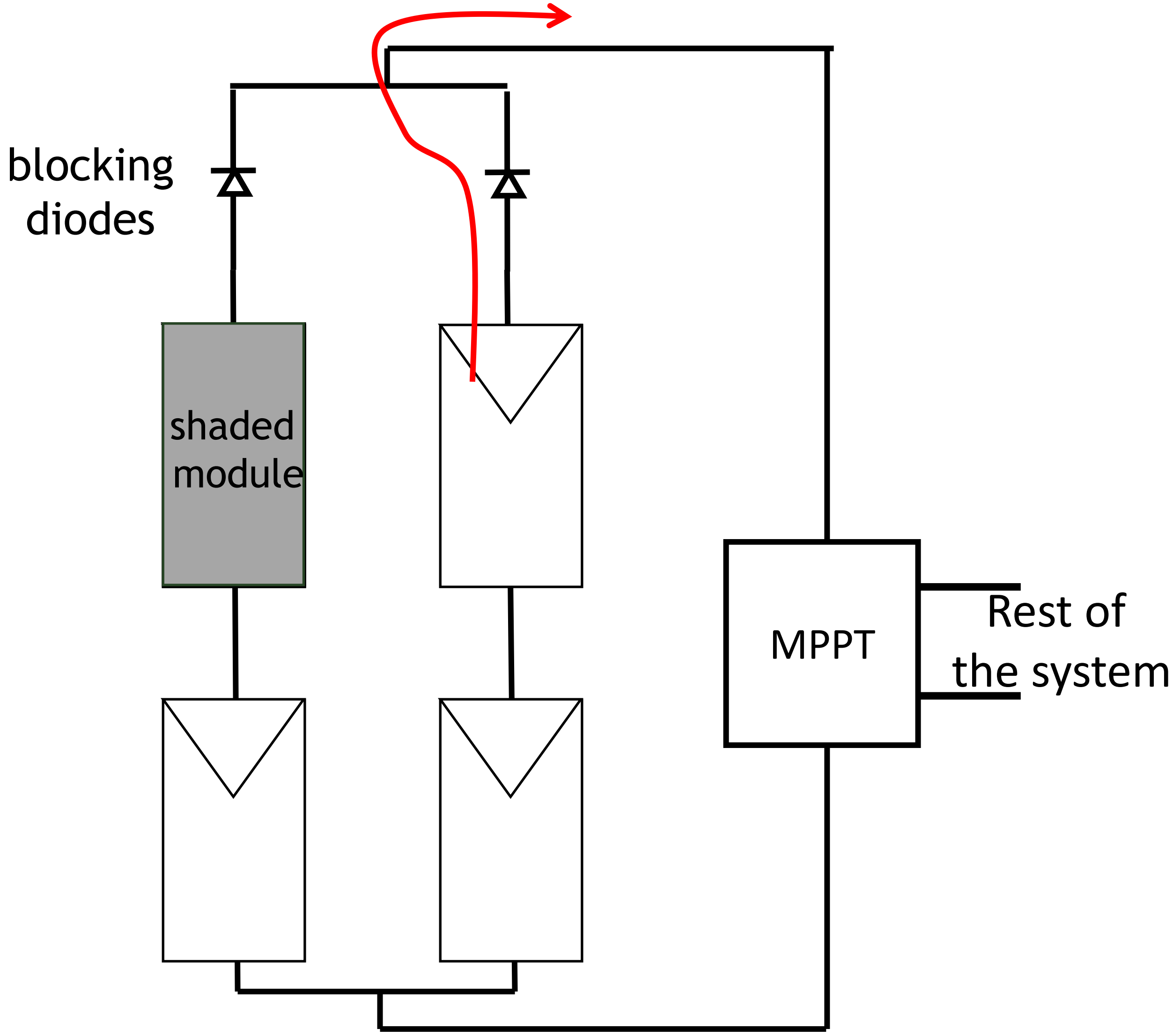

Bifacial Modules

- New variant to traditional PV module
- Can convert reflected irradiance from the rear of the PV module
- Improves power production
- Highly dependent on orientation of module and albedo (reflection) of surface underneath

(*courtesy H. Louie*)

Bifacial Modules

- Power produced by bifacial module is sum of front (f) and rear (r) -side power production, accounting for differing irradiance received

$$P = P_{\mathrm{f}}(G_{\mathrm{f}}) + P_{\mathrm{r}}(G_{\mathrm{r}})$$

- Bifaciality coefficient relates rear-side power under STC to front-side power

$$\psi = \frac{P^{*}_{\mathrm{STC,r}}}{P^{*}_{\mathrm{STC,f}}}$$

usually 0.70 to 0.90

Bifacial Modules

- Power is estimated as

$$P = P_{\mathrm{f}}(G_{\mathrm{f}}) + \left(\psi \times P_{\mathrm{f}}(G_{\mathrm{r}})\right)$$

- Osterwald's method can be adapted as:

$$P = P_{\mathrm{STC}}^{*} \times \frac{G_{\mathrm{f}} + \psi G_{\mathrm{r}}}{1000} \times \left(1 + \frac{\alpha_{\mathrm{p}}}{100} \times \left(T_{\mathrm{C}} - 25\right)\right)$$

Bifacial Name Plate Irradiance (BNPI)

- Similar concept to STC
- Assumes irradiance of 1000 W/m^2 on front and 135 W/m^2 on rear
- In practice, irradiance on rear side varies widely

Notice: 570 + (0.80 x 0.135 x 570) = 632 W

Characteristic at STC	Value
Maximum Power	570 W
Optimum Operating Voltage (V^*)	39.2 V
Optimum Operating Current (I^*)	14.56 A
Open-Circuit Voltage (V_{OC})	46.4 V
Short-Circuit Current (I_{SC})	15.49 A
Short-Circuit Current Temp. Coeff. (α_i)	0.05 %/K
Open-Circuit Temp. Coeff. (α_v)	-0.25 %/K
Max. Power Temp. Coeff. (α_P)	-0.29 %/K
NOCT	41 °C
Number of Cells	132
Bifaciality Coeff.	0.80
Characteristic at BNPI	**Value**
Maximum Power	632 W
Open-Circuit Voltage (V_{OC})	46.7 V
Short-Circuit Current (I_{SC})	17.16 A

Example 5.10

Consider the bifacial PV module described in the Table. The PV module is exposed to a front side irradiance of 900 W/m^2 and rear side irradiance of 100 W/m^2. The cell temperature is 44 °C. Determine the power output of the module.

Characteristic at STC	Value
Maximum Power	570 W
Optimum Operating Voltage (V^*)	39.2 V
Optimum Operating Current (I^*)	14.56 A
Open-Circuit Voltage (V_{OC})	46.4 V
Short-Circuit Current (I_{SC})	15.49 A
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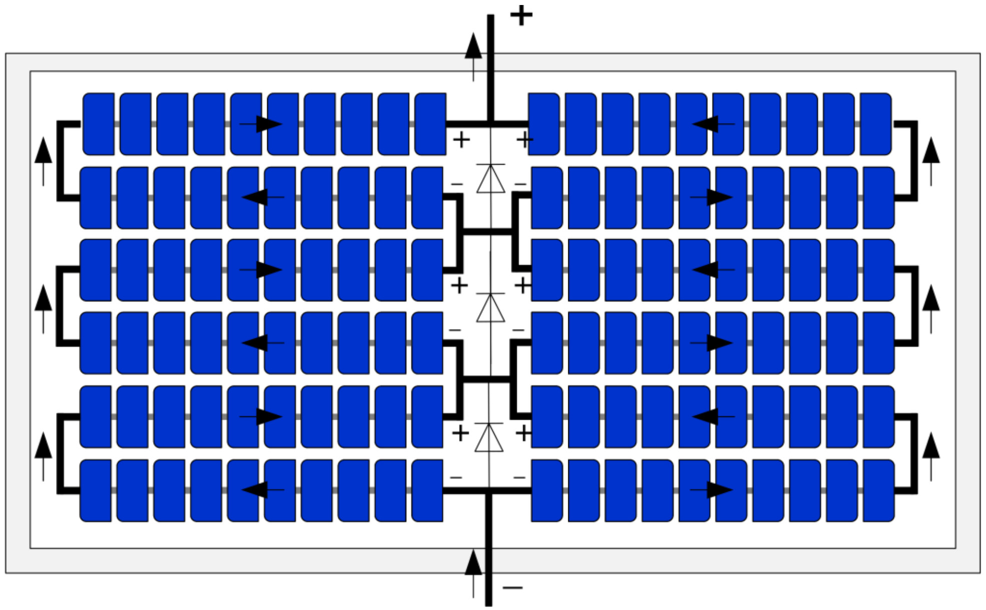
Characteristic at BNPI	**Value**
Maximum Power	632 W
Open-Circuit Voltage (V_{OC})	46.7 V
Short-Circuit Current (I_{SC})	17.16 A

$$P = P_{\text{STC}}^{*} \times \frac{G_{\text{f}} + \psi G_{\text{r}}}{1000} \times \left(1 + \frac{\alpha_{\text{p}}}{100} \times \left(T_{\text{C}} - 25\right)\right)$$

$$= 570 \times \frac{900 + (0.80 \times 100)}{1000} \times \left(1 + \frac{-0.29}{100} \times \left(44 - 25\right)\right) = 527.8 \text{ W}$$

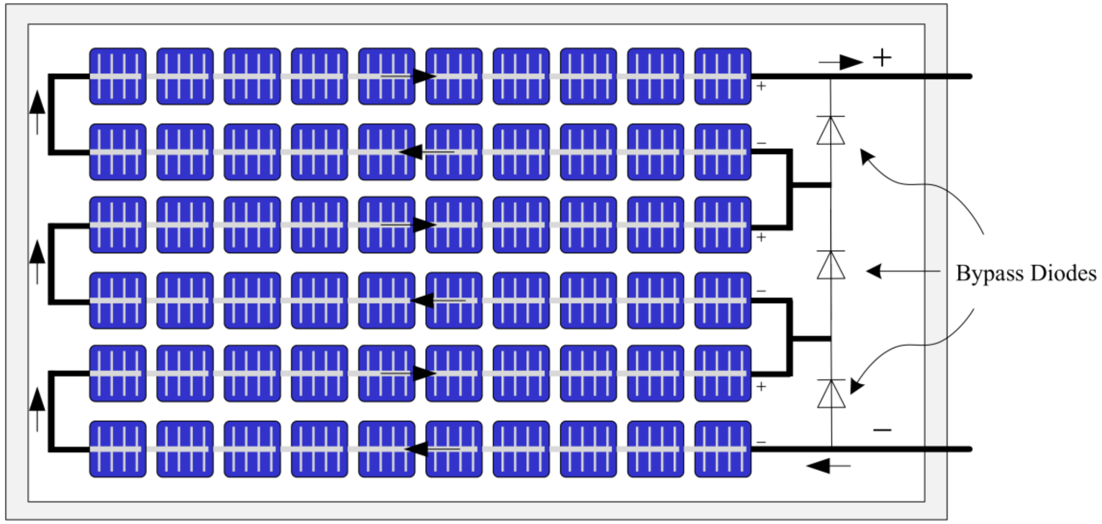
Half-Cut Cell Modules

- Larger panels often use half-cut cells
- Regular cell is cut in half
- Arrangement in PV module is changed to make two sub-modules in parallel
- Reduces I^2R losses and effects of shading

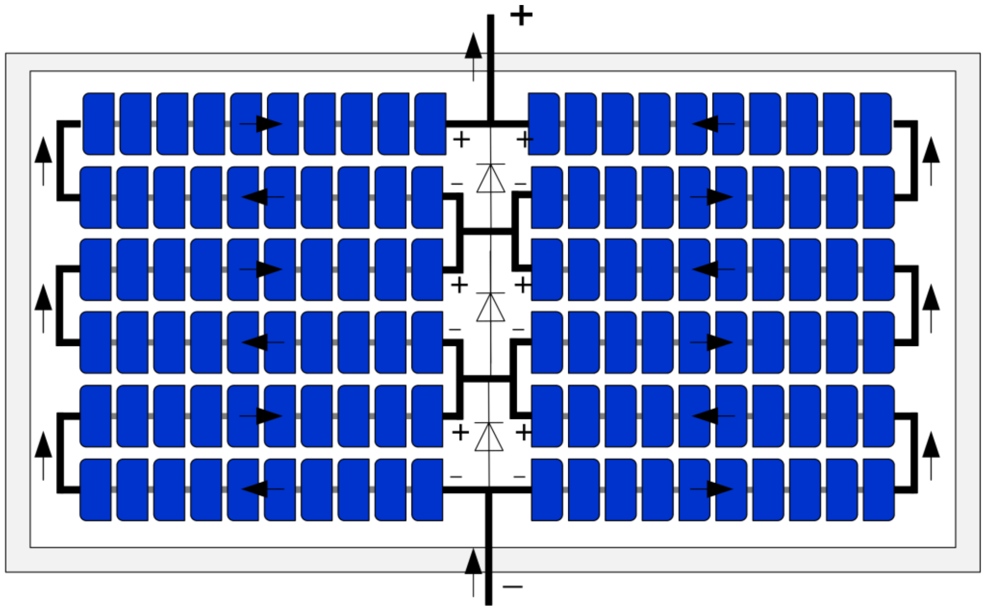


Half-Cut Cell Modules

Traditional module with 60 cells



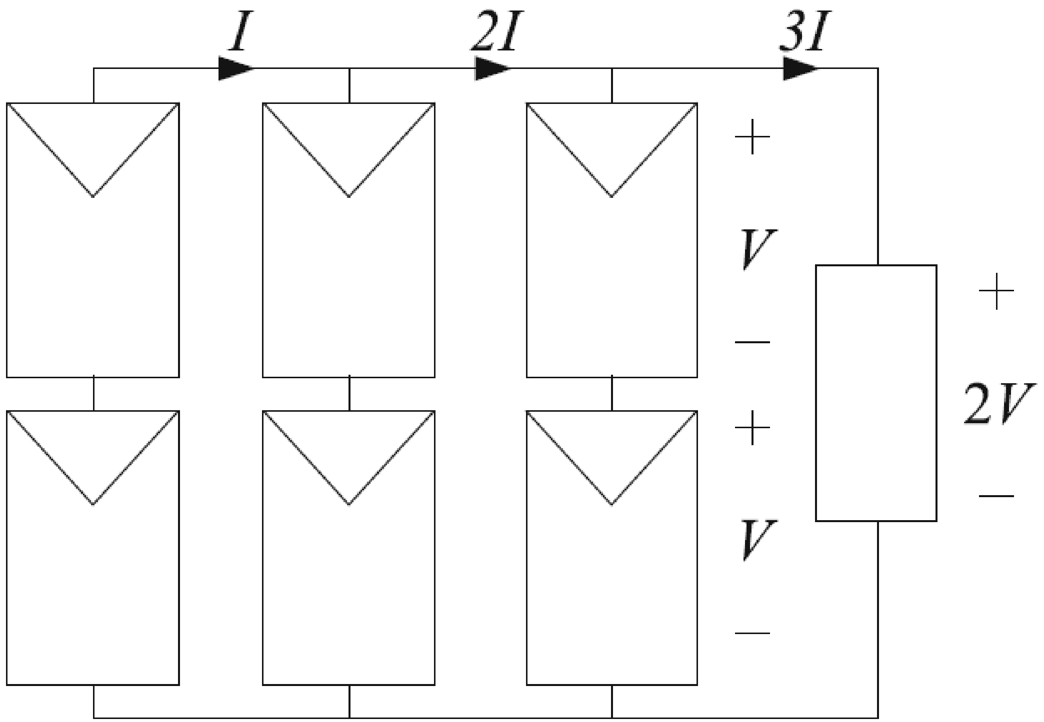
Module with 60 half-cut cells (120 halves)



PV Arrays

- PV modules connected together are known as a *PV Array*
- Series-connected modules are known as "strings"
- Strings with the <u>same</u> number of series-connected modules can be connected in parallel
- Assume that all modules in the array are operating under the same conditions

PV Arrays



This array has three strings of two modules

$$V_{array} = N_{ser,str} \times V$$

$$I_{array} = N_{par} \times I$$

$N_{ser,str}$: number of modules connected in series per string
$N_{par,}$: number of strings connected in parallel

PV Array Power

- Power produced by the array:

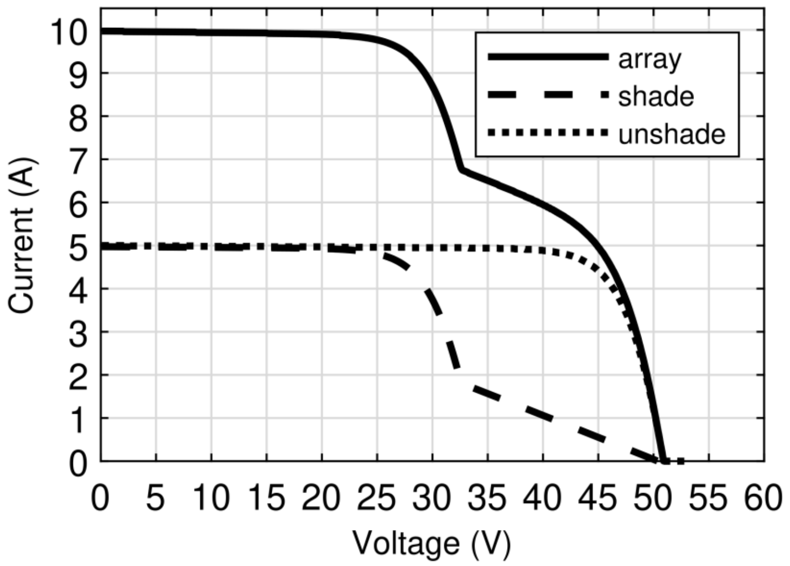
$$P_{\text{array}} = V_{\text{array}} \times I_{\text{array}} = N_{\text{ser,str}} \times V \times N_{\text{par}} \times I$$
$$= N_{\text{ser,str}} \times N_{\text{par}} \times P$$
$$= \text{Number of modules} \times P$$

- In other words, the power produced is independent of how the modules are connected (as long as each string has the same number of modules connected in series)

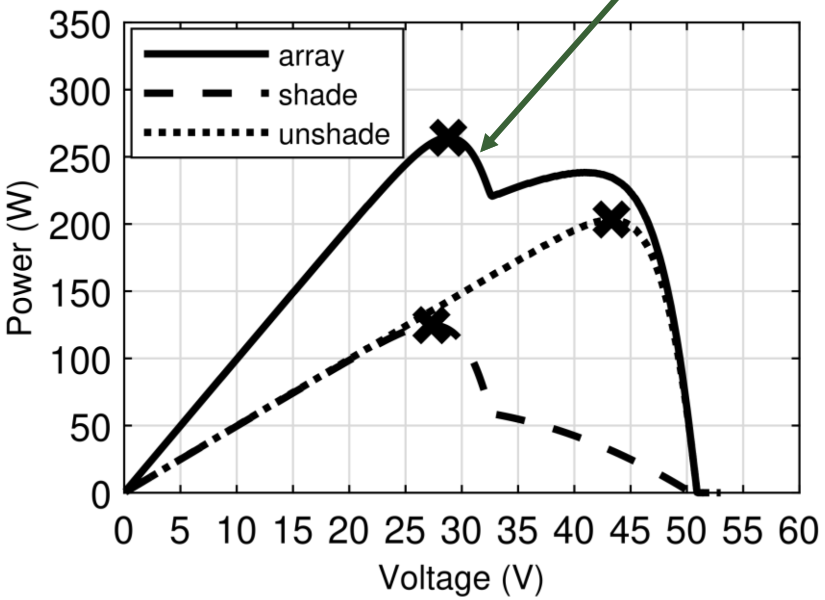
Module Mismatch

- PV modules in an array have some variation in their irradiance and temperature
    - I-V and P-V curves do not exactly match
- Each module has a different maximum power point
- Modules in parallel operate at same voltage, modules in series operate at same current
- Modules with different P-V curves connected together cannot each operate at their own maximum power point
- Lost power production is known as “mismatch loss”

Module Mismatch of Parallel Modules

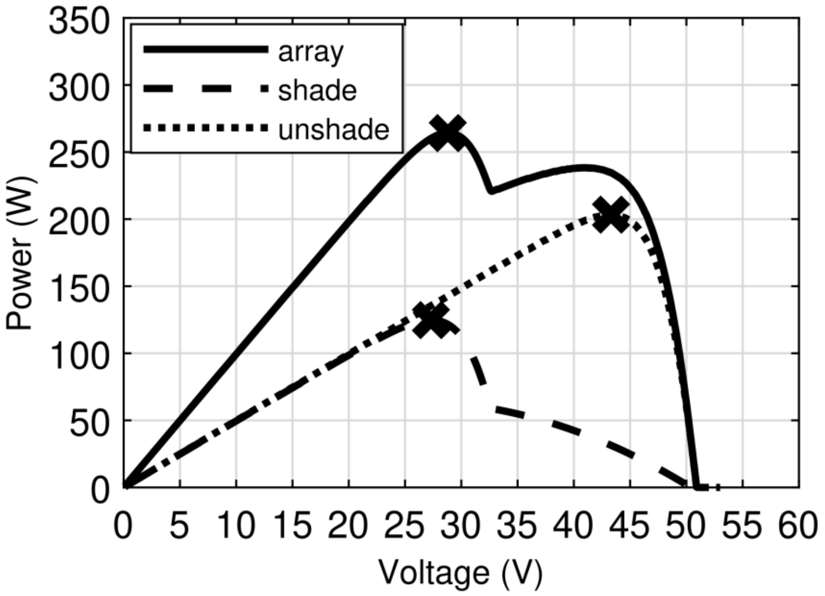


Combined P-V curve for array



Module Mismatch of Parallel Modules

MPP shaded: 203 W at 43V
MPP unshaded: 125 W at 27 V
MPP array: 265 W at 28 V



Parallel modules must operate at the same voltage.

MPP for array is different than MPP of each module individually

Array MPP of 265 W is less than 203 + 125 = 328 W. Difference is the mismatch loss (63 W)

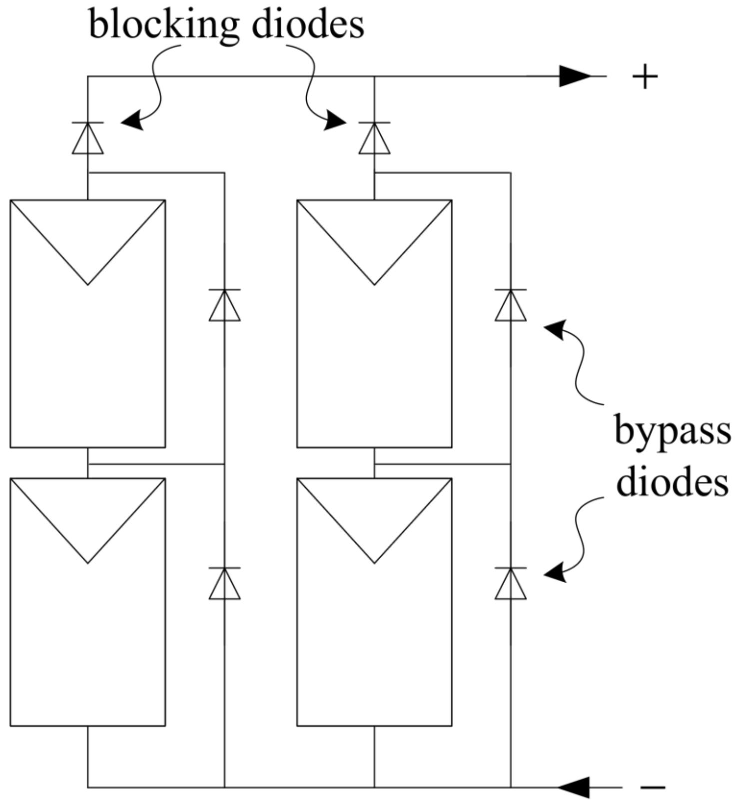
Module Mismatch Mitigation

Ways to minimize mismatch losses

- use identical PV modules in array
- avoid shading
- locate modules in an array near each other (with same orientation)
- connect fewer PV modules to each charge controller

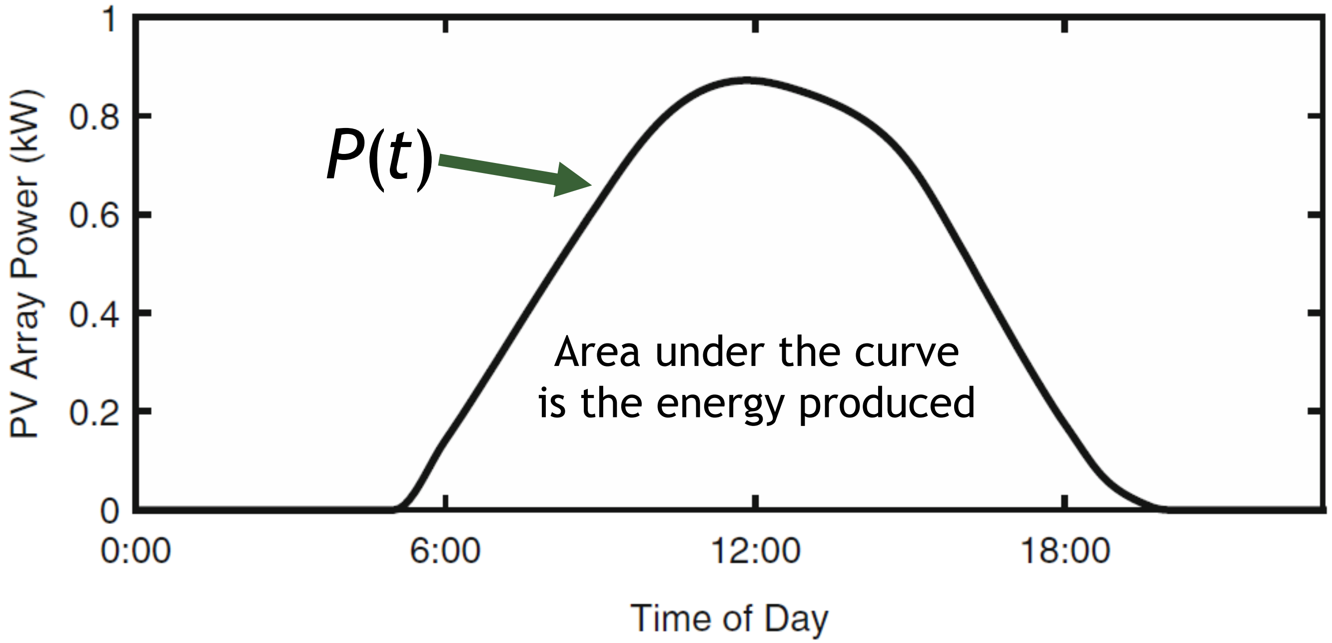
External Diodes

- Large PV arrays may use external bypass diodes in case an entire module is shaded while others are not
- Similar concept as when bypass diodes are used inside an individual PV module



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



Energy Production from PV Arrays

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

$$P(t) = P^{*}_{\text{STC}} \times \frac{G(t)}{1000} \times \left(1 + \alpha_{\text{p}} \times \left(T_{\text{C}}(t) - 25\right)\right)$$

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

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

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

Economic Considerations

- PV module costs have rapidly decreased (US$250-US$1000/kW)
  - require balance of systems components such as charge controllers and inverters
- No fuel cost, low operation and maintenance cost
- Energy cost US$0.35-US$0.60/kWh for mini-grids
- Potential to earn renewable energy credits

Environmental Considerations

- Solar resource is sufficient in most areas with low electricity access
- Zero emissions, low water use, no noise pollution
- Large amount of land can be needed
- Minimal impact to wildlife
- Manufacturing PV modules is energy intensive, and mining of silicon, aluminum, and other metals can cause environmental harm

Social Considerations

- PV modules can benefit most people in community, from small solar lanterns to large metro-grids
- Little health and safety concerns
- Can be a target for theft and vandalism
- External design expertise is likely needed for larger-capacity systems

Other Considerations

- PV modules and their associated components are now widely available with mature supply chains
- PV system design can be challenging due to the variable and uncertain nature of irradiance

Summary

- PV cells are p-n junctions
- PV modules produce maximum power at a single operating point
- Power produce depends on irradiance, temperature, and load
  - Osterwald's method and temperature coefficients are used to estimate power production
- Shading can dramatically reduce the power from a PV module (mismatch losses) and cause damage but is managed by bypass diodes
- New PV module technology
  - Bifacial: makes use of irradiance on front and rear of module
  - Half-cut cells: reduce losses and impact of shading
- PV arrays can increase the voltage and current from several PV modules connected together