09-Photovoltaics Part 3
PV Module Specifications and Operation

ECEGR 4530

Renewable Energy Systems

Overview

- PV Module Spec. Sheets
- Fill Factor
- Temperature Effects

PV Module Spec Sheets

SUNTECH

STP030S-12/Lb

Suntech's STPLb features total efficiency of 10.4% Which delivers the maximum power output at peak hours. Ideal for off-grid and remote power systems. With a 25 year warranty, the module has high efficiency and long-lasting operating time even in a variety of rigorous conditions. Unique textured cell surface and bypass diode design is critical for the module to fully utilize and absorb sunlight and offer maximum usable power per square foot of solar array.

Features and benefits

- High efficiency
- Nominal 12 V DC for standard output
- Outstanding low-light performance
- High transparent low-iron, tempered glass
- Unique techniques give the panel following features: esthetic appearance, with stands high wind-pressure and snow load, and easy installation
- Unique technology ensure that problems of water freezing and warping do not occur
- Design to meet unique demand of customer
- 25 year power output warranty

High Efficiency, High Quality PV Module

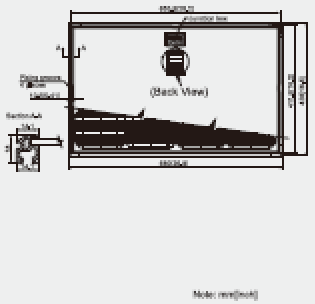
Electrical Characteristics

Model	STP030S-12/Lb
Open-circuit voltage (Voc)	21.8V
Optimum operating voltage (Vmp)	17.4V
Short-circuit current (Isc)	1.82A
Optimum operating current (Imp)	1.72A
Maximum power at STC (Pmax)	30Wp
Operating temperature	-40℃ to +85℃
Maximum system voltage	715V DC

STC: Irradiance 1000W/m², Module temperature 25℃, AM=1.5

SUNTECH

Module Diagram



Specifications

Cell	Monocrystalline silicon solar cells 156mm×30mm
No. of cells and connections	36(4×9)
Dimension of module	425mm×680mm×18mm
Weight	3.2kg

Temperature Coefficients

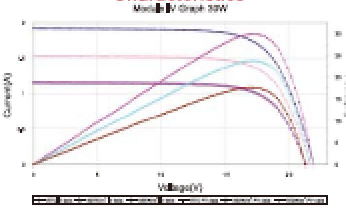
NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature (the data is only for reference)

Output

Cable	YUSHENG(18AWG×2C)
Lengths	3000mm

Characteristics



PV Module Spec Sheets

Electrical Characteristics

Model	STP030S-12/Lb
Open-circuit voltage (Voc)	21.8V
Optimum operating voltage (Vmp)	17.4V
Short-circuit current (Isc)	1.92A
Optimum operating current (Imp)	1.72A
Maximum power at STC (Pmax)	30Wp
Operating temperature	-40℃ to +85℃
Maximum system voltage	715V DC

STC: Irradiance 1000W/m^2, Module temperature 25℃, AM=1.5

Standard Test Conditions (STC)

- STC is defined as
  - Irradiance (G_{STC}): 1000 W/m^2
  - Spectral Distribution: AM 1.5
  - T_C: 25 ^{o}C
- STC rarely occur in actual PV systems
  - T_c > 25 ^{o}C (when G = 1000 W/m^2)
  - How have often does G = 1000 W/m^2 in Seattle?

Exercise

- Is it possible for a PV panel rated at 100 W to output more than 100 W?
  - Yes
  - No

Exercise

- Is it possible for a PV panel rated at 100 W to output more than 100 W?
  - Yes
  - No

If irradiance, temperature and load conditions are more favorable than STC, then 100 W can be exceeded

PV Module Spec Sheets

All values referenced to STC

Electrical Characteristics

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STC: Irradiance 1000W/m^2, Module temperature 25℃, AM=1.5

Notation

- P^*_{STC} : the maximum power output under STC
  - Sometimes units are written as Wp (Watts peak)
  - Also known as the rated power
  - Possible for power to exceed P^*_{STC}
- $V_{oc,STC}$: open circuit voltage of PV module under STC (V)
- $I_{sc,STC}$: short circuit current of PV module under STC (A)

Notation

- V^*_{STC} : voltage of PV module corresponding to P^*_{STC} under STC (V)

- I^*_{STC} : current of PV corresponding to P^*_{STC} under STC (A)

Fill Factor

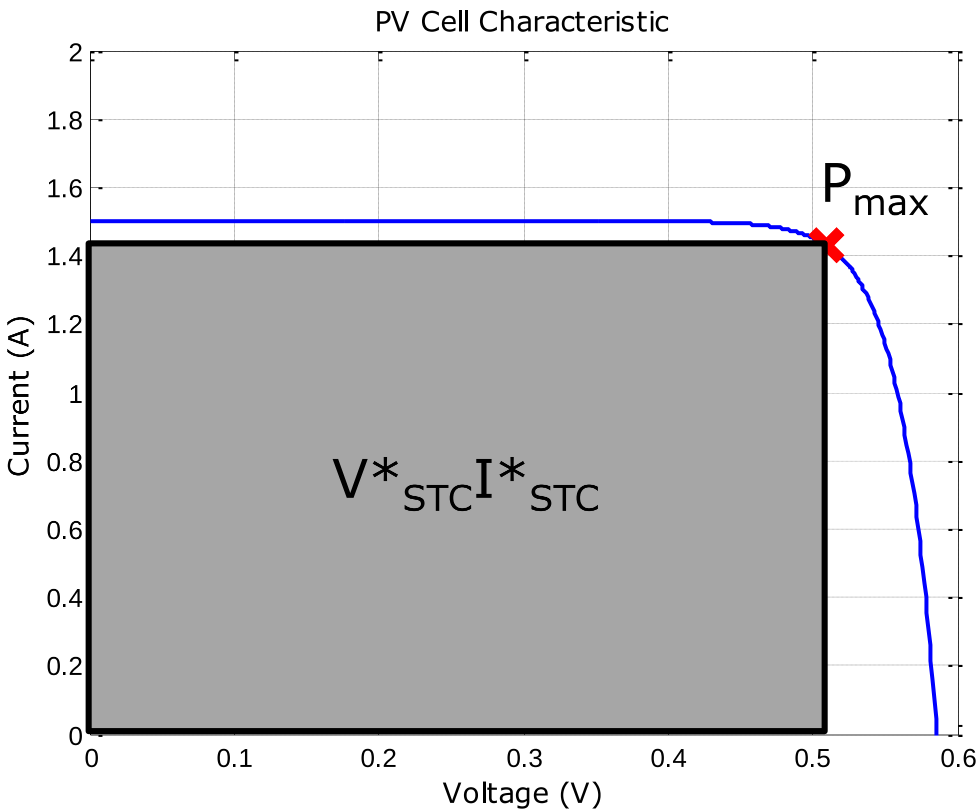
- Theoretical maximum power output of a PV cell is found by multiplying open circuit voltage with the short circuit current
- The ratio of actual maximum power to theoretical is known as the Fill Factor, and provides a metric to compare PV cell quality

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



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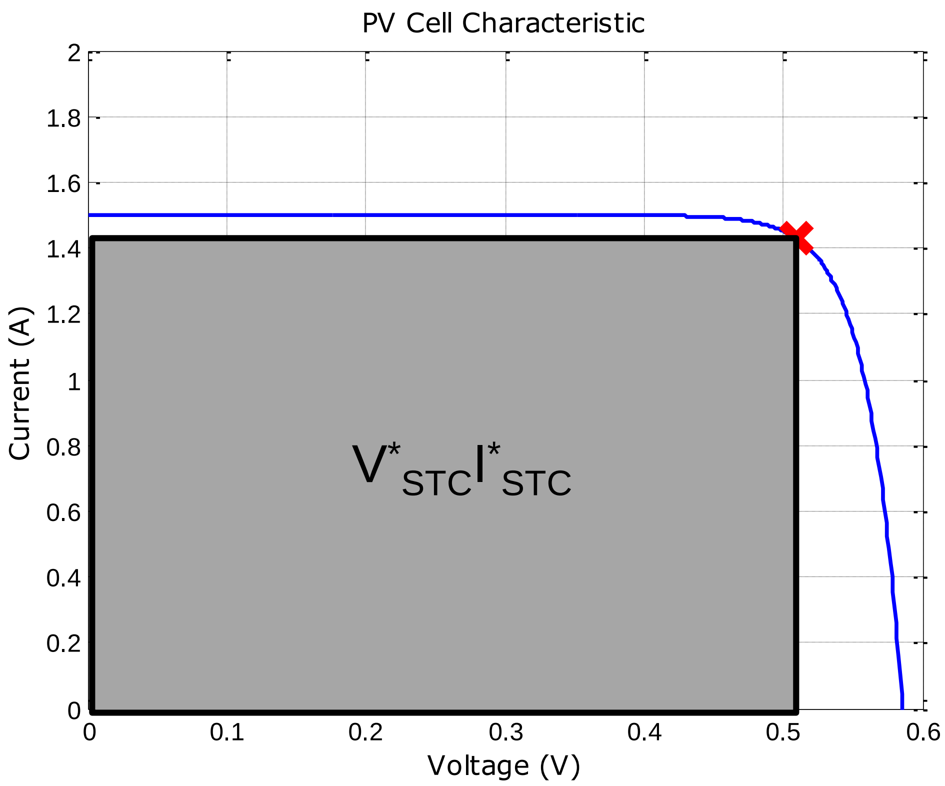
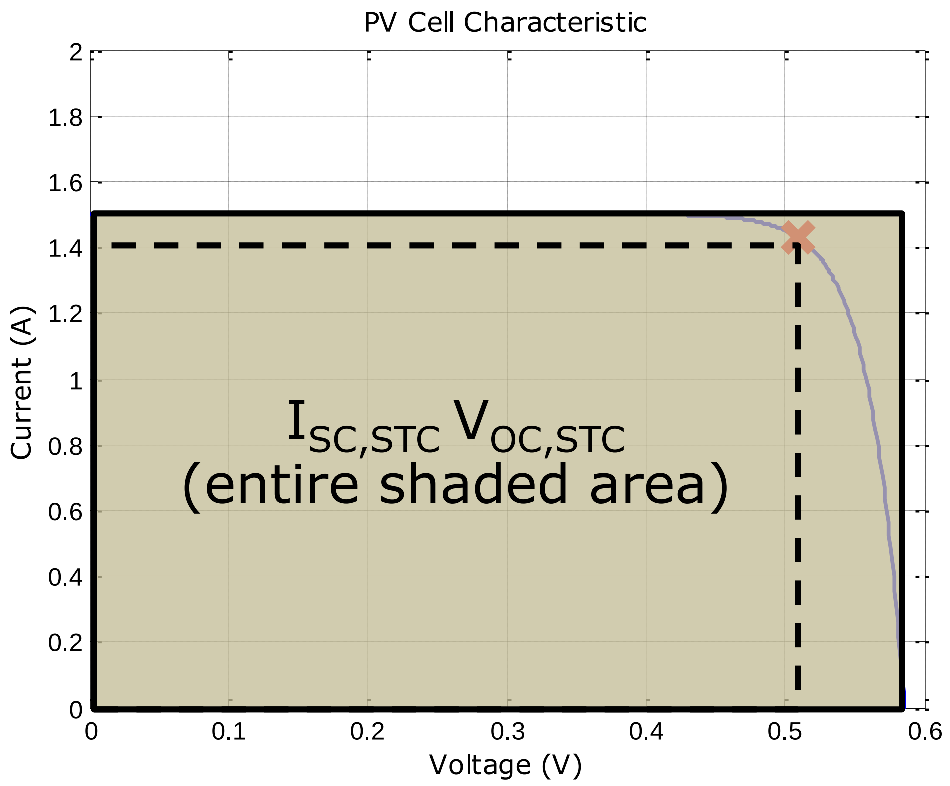
Fill Factor





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 Array Power Output

- Another method of estimating power:

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

- Where G_{STC} = 1000 W/m^2
- Assumes:
  - Operation at MPP
  - $I^* = I^*_{STC} \times (G/G_{STC})$
  - $V^* = V_{OC}(G) = V_{oc,STC}$
- Ignores:
  - Thermal effects

Exercise

- Find the fill factor and the maximum power output of the following cell if G = 600 W/m^2. Ignore thermal effects.

$V_{OC}(600)$ is measured to be 44.04V

Electrical Characteristics

STC	STP185S-24/Ad+
Optimum Operating Voltage (Vmp)	36.4 V
Optimum Operating Current (Imp)	5.09 A
Open - Circuit Voltage (Voc)	45.0 V
Short - Circuit Current (Isc)	5.43 A
Maximum Power at STC (Pmax)	185 W
Module Efficiency	14.5 %
Operating Temperature	-40 °C to +85 °C
Maximum System Voltage	600 V DC
Maximum Series Fuse Rating	15 A
Power Tolerance	0/+5 W

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

No. of Cells	72 (6 × 12)

Exercise

- Find the fill factor and the maximum power output of the following cell if G = 600 W/m². Ignore thermal effects.

$V_{OC}(600)$ is measured to be 44.04V

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STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

No. of Cells	72 (6 x 12)

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

$$F = \frac{P^*_{STC}}{I_{SC,STC} V_{OC,STC}} = \frac{185}{5.43 \times 45} = 0.757$$

Exercise

- Find the fill factor and the maximum power output of the following cell if G = 600 W/m². Ignore thermal effects.

$V_{OC}(600)$ is measured to be 44.04V

$$F = 0.757$$

$$I_{SC}(G) = 5.43x\left(\frac{600}{1000}\right) = 3.258A$$

$$P^*(G) = FI_{SC}(G)V_{OC}(G) = 108.6W$$

Electrical Characteristics

STC	STP185S-24/Ad+
Optimum Operating Voltage (Vmp)	36.4 V
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Open - Circuit Voltage (Voc)	45.0 V
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Power Tolerance	0/+5 W

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

No. of Cells	72 (6 x 12)

PV Array Power Output

- Alternatively, we could estimate P*(G) for G = 600 W/m² to be:

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

$$P^*(600) = 185\left(\frac{600}{1000}\right) = 111 \text{ W/m}^2$$

Electrical Characteristics

STC	STP185S-24/Ad+
Optimum Operating Voltage (Vmp)	36.4 V
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Open - Circuit Voltage (Voc)	45.0 V
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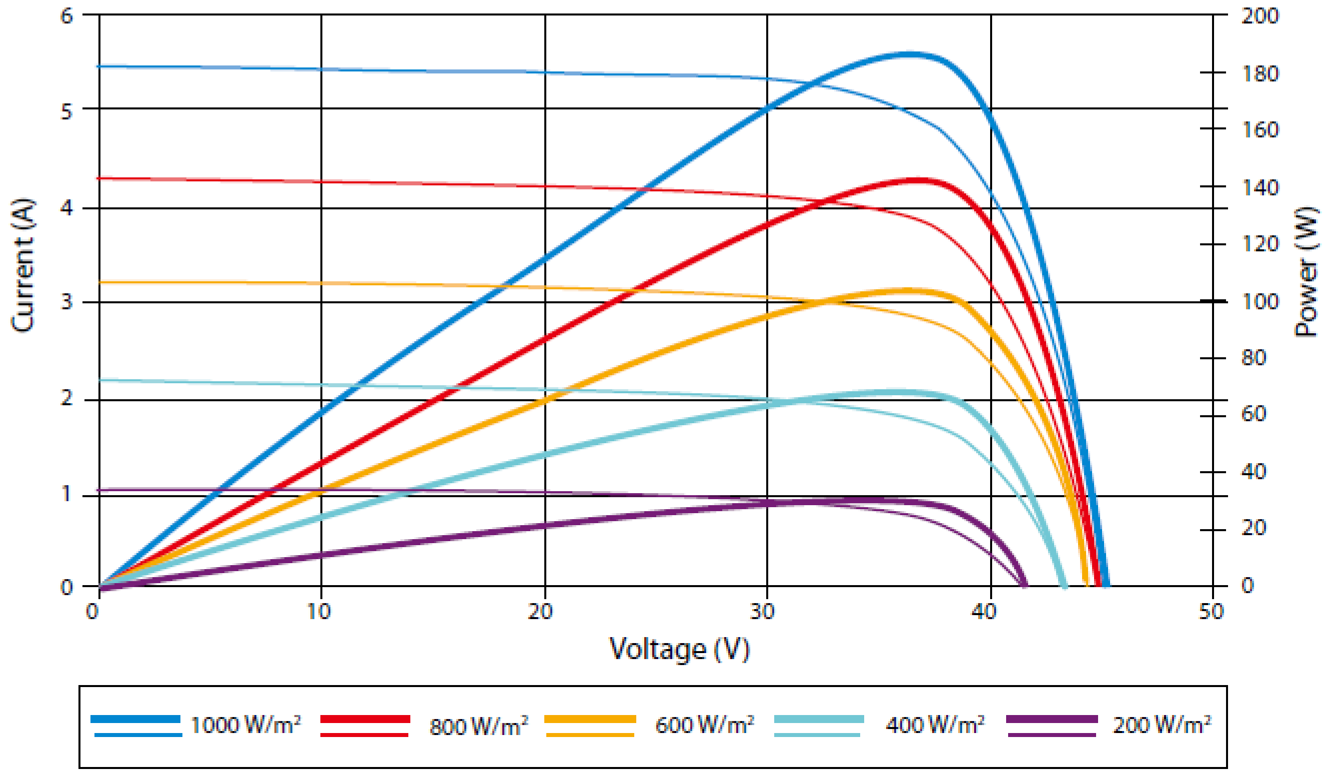
STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

PV Array Power Output



Temperature Effects

- PV cells often operate in areas of high solar irradiance and high ambient temperatures
- PV cells, like diodes, are temperature sensitive
- Effects of temperature:
  - <u>Increase</u> PV cell current
  - <u>Decrease</u> PV cell voltage

PV Module Spec Sheets

α_v: open circuit voltage temperature coefficient at STC (%/K, %/C, mV/K or mV/C)

- percent change in voltage for every degree difference in temperature from STC (25° C)

Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

PV Module Spec Sheets

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

- percent change in current for every degree difference in temperature from STC (25° C)

Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Temperature Effects

- A PV panel's rated open circuit voltage is 50 V. Let α_v = -0.37 %/K. If G = 1000 W/m^2 and the panel's temperature is 30^{o}C, then:
  - Open circuit voltage changes by:
    50(-0.0037 x (30 - 25)) = -0.925V
  - V_{oc} is then: 50 – 0.925 = 49.075 V

Temperature Effects

- A PV panel's rated short circuit current is 5 A. Let α_i = 0.04 %/K. If G = 1000 W/m^2 and the panel's temperature is 30^{o}C, then:
  - Short circuit current changes by:

    $5(0.0004 \times (30 - 25)) = 0.01A$
  - I_{sc} is then: $5 + 0.01 = 5.01$ A

Temperature Effects

- Mathematically:

$$V_{OC}(T_c) = V_{OC}(25^\circ \mathrm{C})[1 + \alpha_v \times (T_c - 25)]$$

  - $V_{OC}(T_c)$: temperature-corrected open circuit voltage (V)
  - $V_{OC}(25^oC)$: open circuit voltage at T_C = 25ºC (V)

- Important: if G = 1000 W/m^2, then
  - $V_{OC}(25^oC)$ = $V_{OC,STC}$, else
  - $V_{OC}(25^oC)$ must be adjusted for the irradiance

Temperature Effects

- Mathematically:

$$I_{SC}(T_c) = I_{SC}(25^{\circ}\text{C})[1 + \alpha_i \times (T_c - 25)]$$

  - $I_{SC}(T_c)$: temperature-corrected short circuit current (A)
  - $I_{SC}(25^{o}C)$: short circuit current at $T_C = 25^{o}C$ (A)

- Important: if G = 1000 W/m^2, then
  - $I_{SC}(25^{o}C) = I_{SC,STC}$, else
  - $I_{SC}(25^{o}C)$ must be adjusted for the irradiance

Temperature Effects

- A PV panel's rated short circuit current is 5 A. Let α_i = 0.04 %/K. If G = 600 W/m^2 and the panel's temperature is 27^{o}C, then:
  - Short circuit current at G = 600W/m^2, T_C = 25^{o}C:

    $I_{SC}(25^oC) = 5 \times (600/1000) = 3A$ (irradiance-adjusted current)

  - Short circuit current at G = 600W/m^2, T_C = 27^{o}C

    $I_{SC} = 3 \times [1 + 0.0004 \times (27-25)] = 3.0024$ A

    ↑

    irradiance-adjusted short circuit current

Temperature Effects

- A PV panel's rated open circuit voltage is 50V. Let α_V = -0.37 %/K. If G = 600 W/m^2 and the panel's temperature is 27^{o}C, then:
  - Open circuit voltage at G = 600W/m^2, T_C = 25^{o}C: recall from Lecture 9:

$$V_{OC} = N_{cells} \times V_T \ln\left(\frac{I_L}{I_{Sat}}\right)$$

$I_L = I_{SC}$ = 3A

Let: $I_{sat} = 9.4^{-10}$A

Let there be 80 series connected cells in this panel

V_T = 26mV

Temperature Effects

- A PV panel's rated open circuit voltage is 50V. Let α_V = -0.37 %/K. If G = 600 W/m^2 and the panel's temperature is 27^{o}C, then:
  - Open circuit voltage at G = 600W/m^2, T_C = 25^{o}C:

$$V_{OC}(25^oC) = 80 \times 0.026 \times \ln\left(\frac{3}{9.4^{-10}}\right) = 48.89V \text{ (irradiance-adjusted voltage)}$$

  - Open circuit voltage at G = 600W/m^2, T_C = 27^{o}C

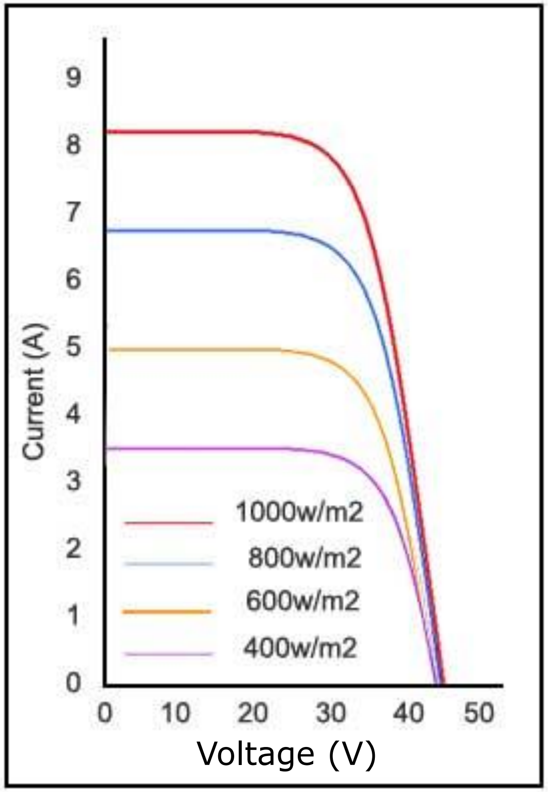
V_{OC} = 48.89 x [1 - 0.37x(27-25)] = 45.27 V

↑

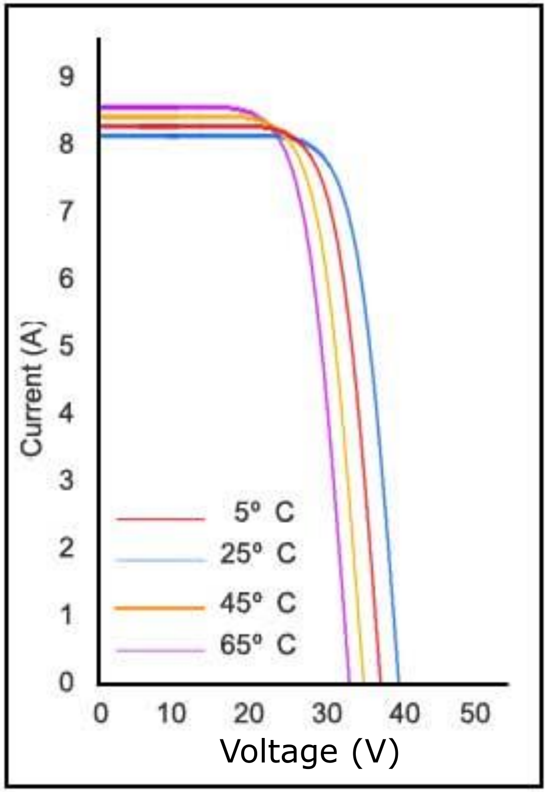
irradiance-adjusted
open circuit voltage

Irradiance/Temperature Effects

Irradiance



Temperature



Temperature Effects

- PV voltage decrease dominates current increase
- Result: percent decrease in power is approximately equal to percent decrease in voltage

PV Module Spec Sheets

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

- percent change in maximum power for every degree difference in temperature from STC (25^o C)

- Mathematically:

$$P^*(T_c) = P^*(25^\circ\text{C})[1 + \alpha_p \times (T_c - 25)]$$

- $P^*(T_c)$: temperature-corrected maximum power point (W)
- $P^*(25^oC)$: maximum power at T_C = 25^{o}C (W). Must be adjusted for irradiance if G is not 1000 W/m^2

Temperature Effects

- Conversion of mV/K to %/K
  - Divide mV/K by $V_{OC,STC}$
- For a cell with
  - α_v = -78 mV/K
- With $V_{oc,STC}$ = 21.8 V
  - α_v = -0.36 %/K (much larger than α_i)

Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Temperature Effects

- To compute the change in voltage and/or current with respect to temperature, we must know the temperature of the cell

Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Temperature Effects

- Normal Operating Cell Temperature (NOCT) is the temperature of the cell (T_C) under the following conditions:
  - G: $0.8G_{STC}$
  - Spectral Distribution: AM 1.5
  - T_{amb}: 20 ^oC
  - Wind speed: 1 m/s
  - No Load
- This is known as Standard Operating Conditions (SOC)

Temperature Effects

- Do NOT confuse SOC with STC
- STC is used to determine P^*_{STC}, etc
  - Note the difference in Temperature between NOCT and STC (20 ^oC vs 25 ^oC)
- Typical values of NOCT
  - 42 to 50 ^oC

Temperature Effects

- Cell temperature is computed by:

$$T_c - T_a = \frac{NOCT - 20}{800} G$$

- Where T_a is the ambient temperature

Temperature Effects

- Consider a PV module with the nameplate values:

Electrical Characteristics

STC	STP185S-24/Ad+
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Maximum System Voltage	600 V DC
Maximum Series Fuse Rating	15 A
Power Tolerance	0/+5 W

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

Temperature Characteristics

Nominal Operating Cell Temperature (**NOCT**)	45±2°C
Temperature Coefficient of Pmax	-0.48 %/°C
Temperature Coefficient of Voc	-0.34 %/°C
Temperature Coefficient of Isc	0.037 %/°C

No. of Cells	72 (6 x 12)

Temperature Effects

- Under the following conditions:
  - G = 700 W/m^2
  - T_a = 34 ^{o}C
- Compute the open circuit voltage and short circuit current

Temperature Effects

- First compute T_c
  - NOCT = 45 ^oC
  - G = 700 W/m^2
  - T_a = 34 ^oC

$$T_c - T_a = \frac{NOCT - 20}{800} G = \frac{NOCT - 20}{800} G + T_a$$

$$T_c = \frac{45 - 20}{800} 700 + 34 = 55.9\ ^\circ C$$

Temperature Effects

- Now compute I_{sc}
  - $T_c = 55.9\ ^oC$
  - α_i: 0.037 %/K
  - $I_{sc,STC} = 5.43$ A

- $I_{SC} = 3.801 \times [1 + 0.00037 \times (55.9-25)] = 3.84$ A

  ↑ 3.801 = 5.43 x 0.7

Temperature Effects

- Now compute V_{oc}
  - T_c = 55.9 °C
  - α_v: -0.34 %/K
  - $V_{oc,STC}$ = 45 V
  - N_{cells} = 72
  - Assume V_t = 25 mV, I_{sat} = 10.2^{-10} A
- V_{OC} = 44.4 x [1 -0.0034x(55.9-25)] = 39.32 V

↑

$$N_{cells} \times V_T \ln\left(\frac{I_L}{I_{Sat}}\right)$$

PV Array Power Output

- Power output of PV array is:
  - T_c = 55.9 °C
  - α_p: -0.48 %/K
  - P^*_{STC} = 185W

$$P^* = 129.5[1 - 0.0048(55.9 - 25)] = 110.3 \text{ W}$$

↑

$$185\left(\frac{700}{1000}\right)$$

or could use Fill Factor method to adjust for irradiance (slide 48)

Temperature Effects

- Sometimes α_p is not known, so this approximation can be used

$$\alpha_p \approx \alpha_v \frac{V_{OC,STC}}{V^*\left(G_{STC}\right)}$$

- In the previous example:

$$\alpha_p \approx -0.0034 \frac{45}{36.4} = -0.0042$$ nameplate value: -0.0048

Comparison of Power Output

- Power as computed by various methods:

1. $P_{STC}^{*} = 185 \text{ W}$
2. $P^{*} = P_{STC}^{*}\left(\frac{700}{1000}\right) = 129.5 \text{ W}$ Ignoring temperature
3. $P^{*} = FV_{OC}(700)I_{SC}(700) = 118.9 \text{ W}$ Using Fill factor, ignoring temp
4. $P^{*} = P_{STC}^{*}\left(\frac{700}{1000}\right)\left(1 + \alpha_{v}\frac{V_{OC,STC}}{V_{mp}^{*}}(T_{c} - 25)\right) = 112.7 \text{ W}$ Estimated α_p
5. $P^{*} = P_{STC}^{*}\left(\frac{700}{1000}\right)\left(1 + \alpha_{p}(T_{c} - 25)\right) = 110.3 \text{ W}$ Actual α_p, most accurate

Or use irradiance-adjusted short circuit current and open circuit voltage and multiply by fill factor

Exercise

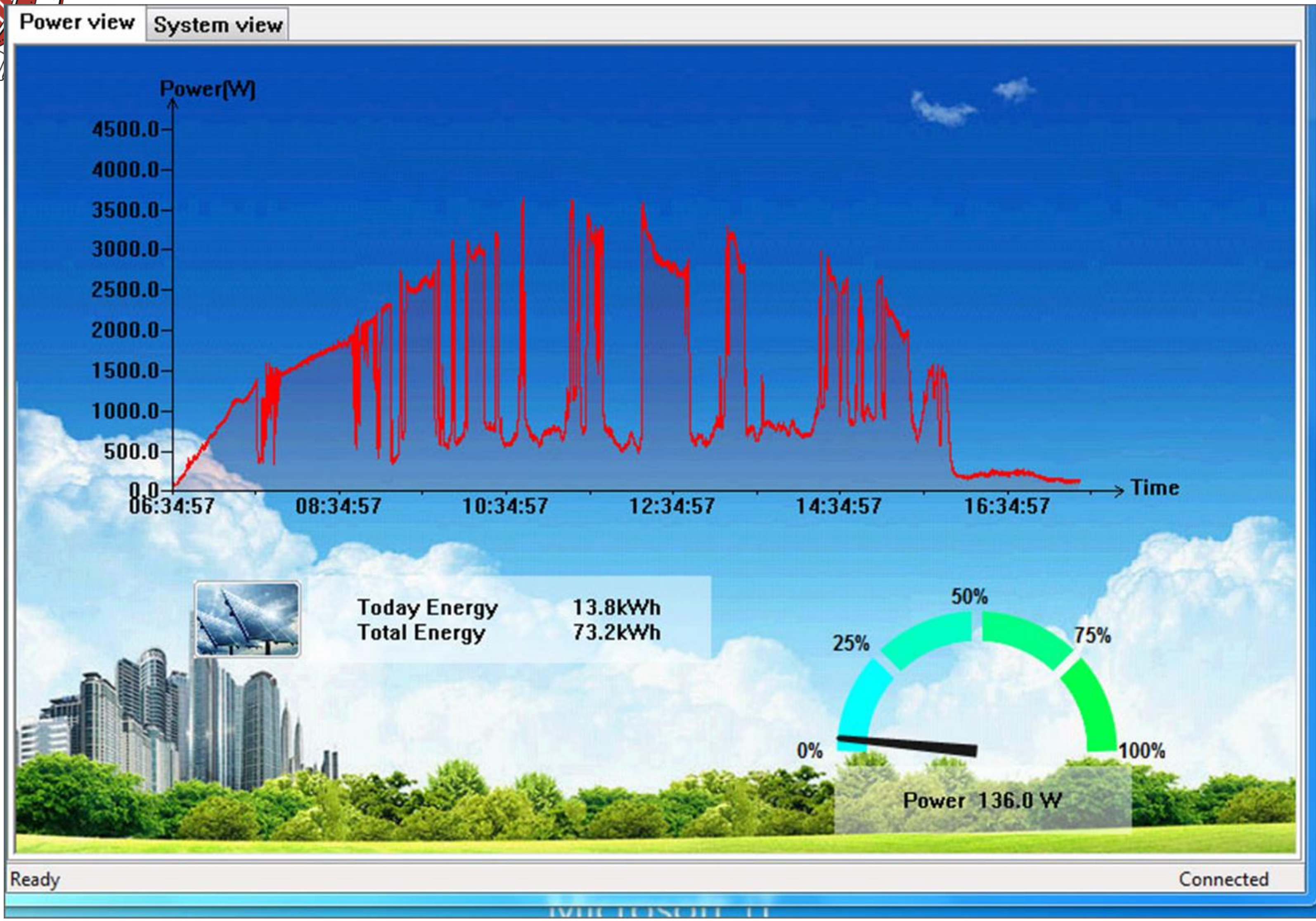
Which condition is the most favorable for PV power generation?

- Cold with high irradiance
- Hot with high irradiance
- Cold with low irradiance
- Hot with low irradiance

Exercise

Which condition is the most favorable for PV power generation?

- Cold with high irradiance
- Hot with high irradiance
- Cold with low irradiance
- Hot with low irradiance


Power view
System view
Power(W)
4500.0
4000.0
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
06:34:57
08:34:57
10:34:57
12:34:57
14:34:57
16:34:57
Time
Today Energy 13.8kWh
Total Energy 73.2kWh
0%
25%
50%
75%
100%
Power 136.0 W
Ready
Connected