Characteristics of PV Power Systems

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Overview

- Solar resource characteristics
- Sun position
- Decomposition of solar flux
- TMY data
- Band gap energy and cell efficiency
- I-V and P-V Curves
- Panel specs.
- Impact of shading
- PV inverters
- Characteristics of PV Power variability
- Challenges in sunlight forecasting

Extraterrestrial Solar Spectrum

Sunlight: continuous number of electromagnetic waves with different wavelengths and power densities. The total area under the curve is nearly 1,375 W/m²
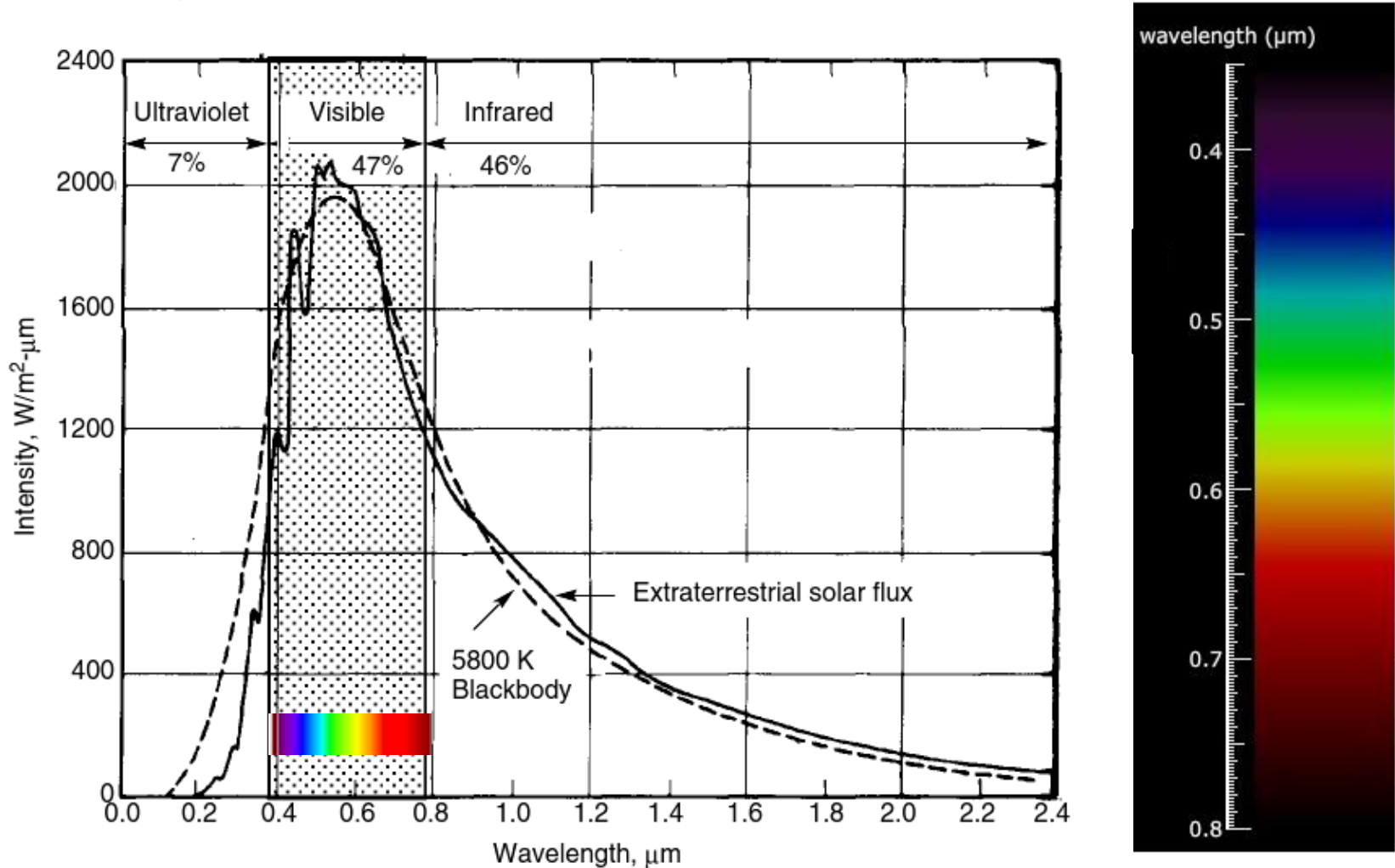
Electromagnetic Spectrum

- sunlight is viewed as a small subset of the electromagnetic spectrum.

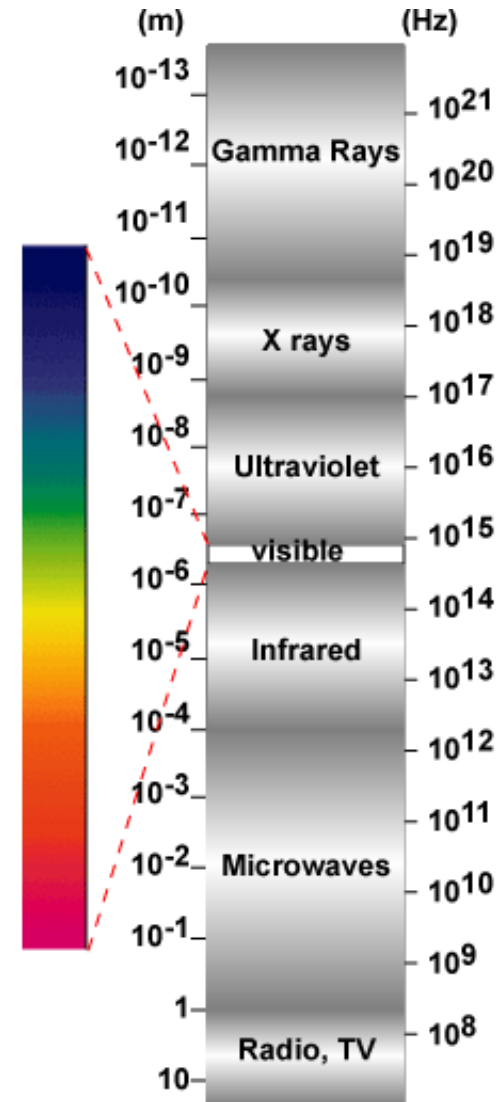- Relation between wavelength λ (m), and frequency f (Hz) :

$$f = \frac{c}{\lambda}$$

  where c is the speed of light: c = 3 x 10^8 m/sec.

- Note that photons can be described by either their wavelength, their frequency, or their energy

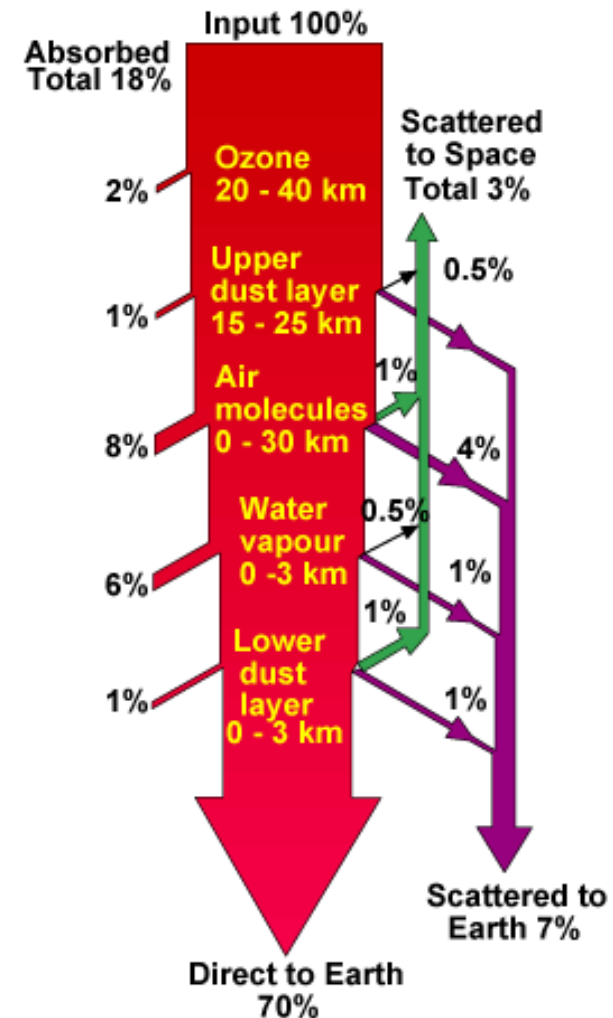$$E = hf = hc / \lambda$$

  Where h is Planck's constant (= 6.626×10^{-34} J-s).

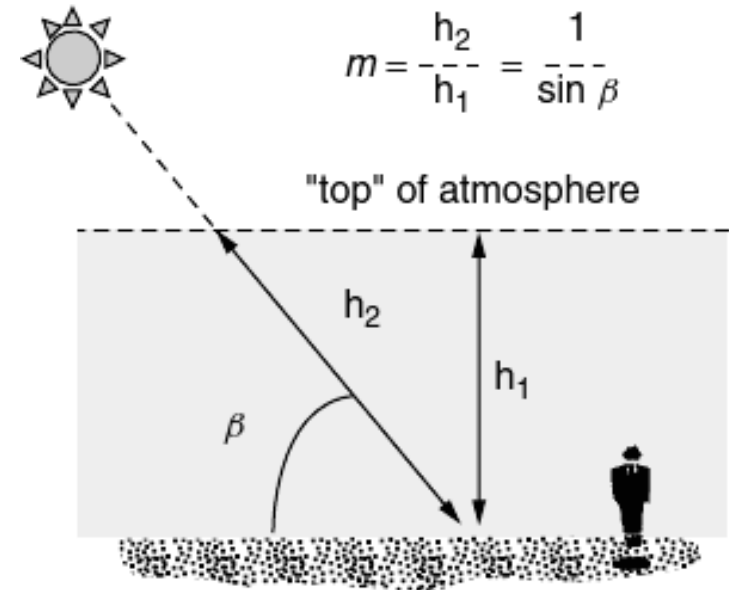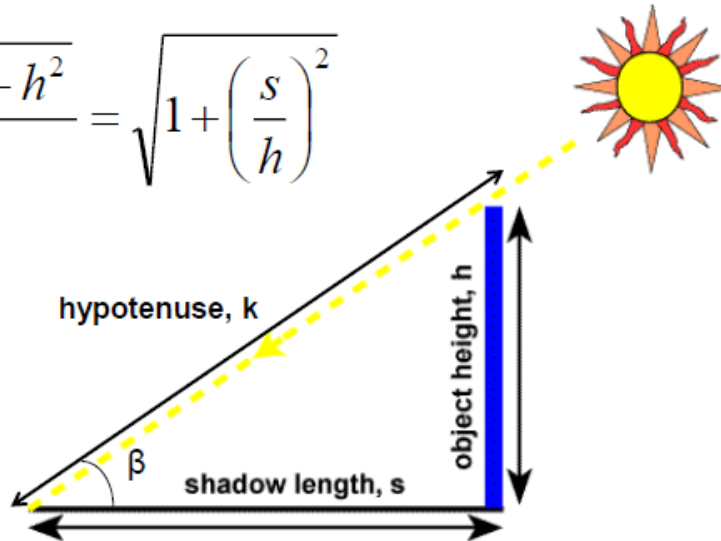| (m)		(Hz)
10^{-13}		
10^{-12}	Gamma Rays	10^{21}
10^{-11}		10^{20}
10^{-10}		10^{19}
10^{-9}	X rays	10^{18}
10^{-8}		10^{17}
10^{-7}	Ultraviolet	10^{16}
10^{-6}	visible	10^{15}
10^{-5}	Infrared	10^{14}
10^{-4}		10^{13}
10^{-3}		10^{12}
10^{-2}	Microwaves	10^{11}
10^{-1}		10^{10}
1		10^9
10	Radio, TV	10^8

Effect of Atmosphere on Direct Sunlight

- As sunlight enters the earth's atmosphere, some of it gets absorbed, some is scattered and some passes through and reaches the earth's surface.

- Different molecules in the atmosphere absorb significant amounts of sunlight at certain wavelengths
  - Water vapor and carbon dioxide absorb sunlight in the visible and infrared region
  - Ozone absorbs sunlight in the UV region

Input 100%

Absorbed Total 18%

Scattered to Space Total 3%

2% — Ozone 20 - 40 km

0.5%

1% — Upper dust layer 15 - 25 km

1%

8% — Air molecules 0 - 30 km

4%

0.5%

6% — Water vapour 0 -3 km

1%

1%

1% — Lower dust layer 0 - 3 km

1%

Scattered to Earth 7%
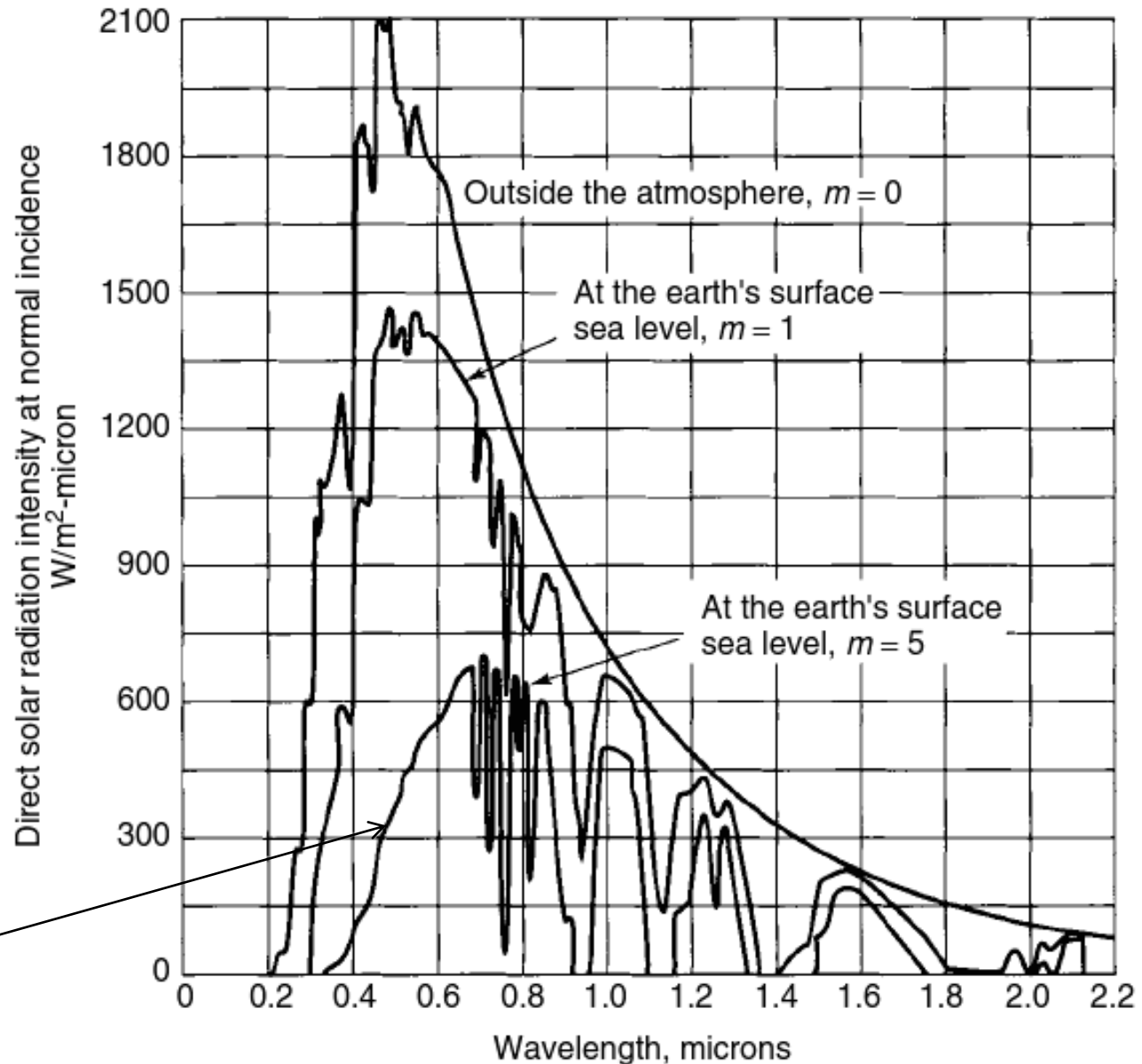
Direct to Earth 70%

Air Mass Ratio

- The terrestrial spectrum depends on how much atmosphere the radiation has to pass through to reach the surface.
- Air Mass (AM) ratio is the optical path length through earth's atmosphere relative to the minimum path. This ratio is approximately equal to the inverse of the sine of the sun's altitude angle β.
  - AM1.5 (an air mass ratio of 1.5) is often assumed as the average spectrum at the earth's surface. AM1.5 is chosen as the standard calibration spectrum for PV Cells.

$$AM \approx \frac{\sqrt{s^2 + h^2}}{h} = \sqrt{1 + \left(\frac{s}{h}\right)^2}$$

hypotenuse, k

object height, h

β   shadow length, s

$$m = \frac{h_2}{h_1} = \frac{1}{\sin \beta}$$

"top" of atmosphere

h_2

h_1

β

Solar Spectrum for Various Air Mass Ratios

Spectrum shifts towards longer wavelengths
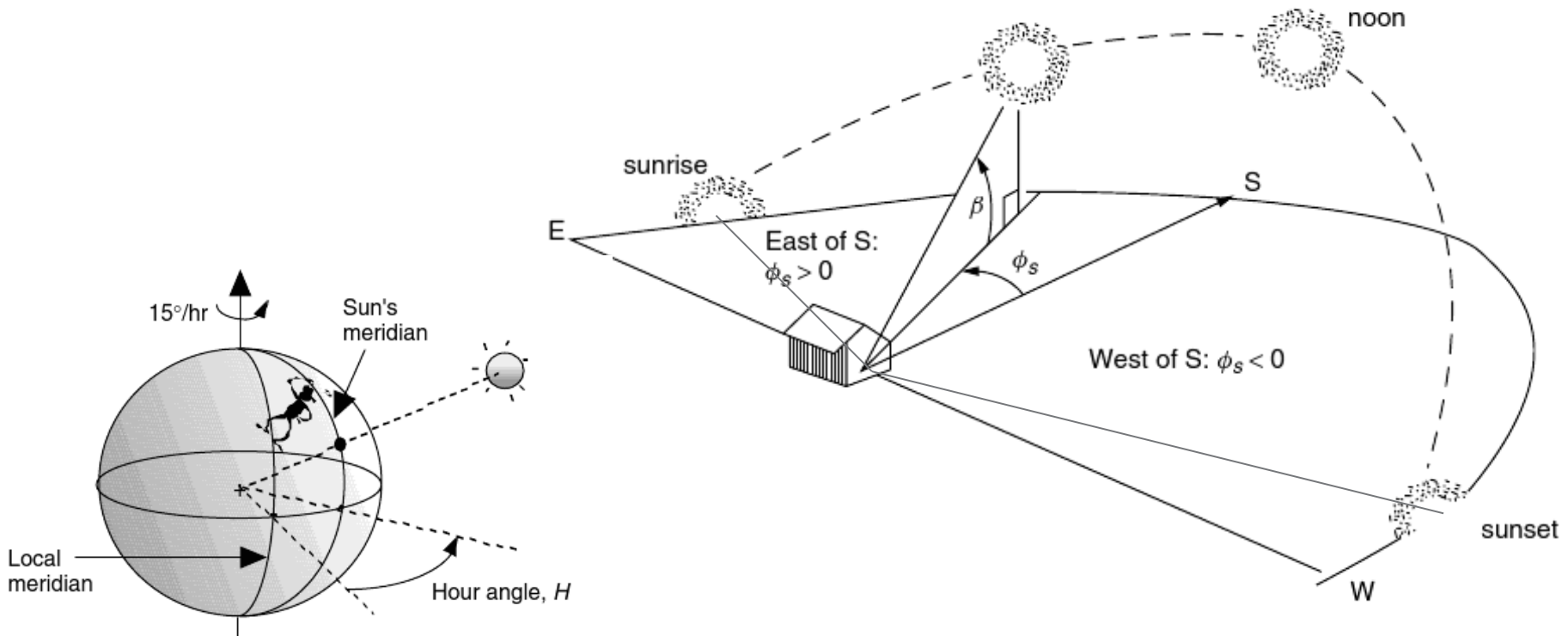
Sun declination angle δ

- On summer solstice, the sun appears vertically above the Tropic of Cancer (which is at 23.45° latitude above the equator)
- On winter solstice, the sun appears vertically above the Tropic of Capricorn (which is at 23.45° latitude below the equator)
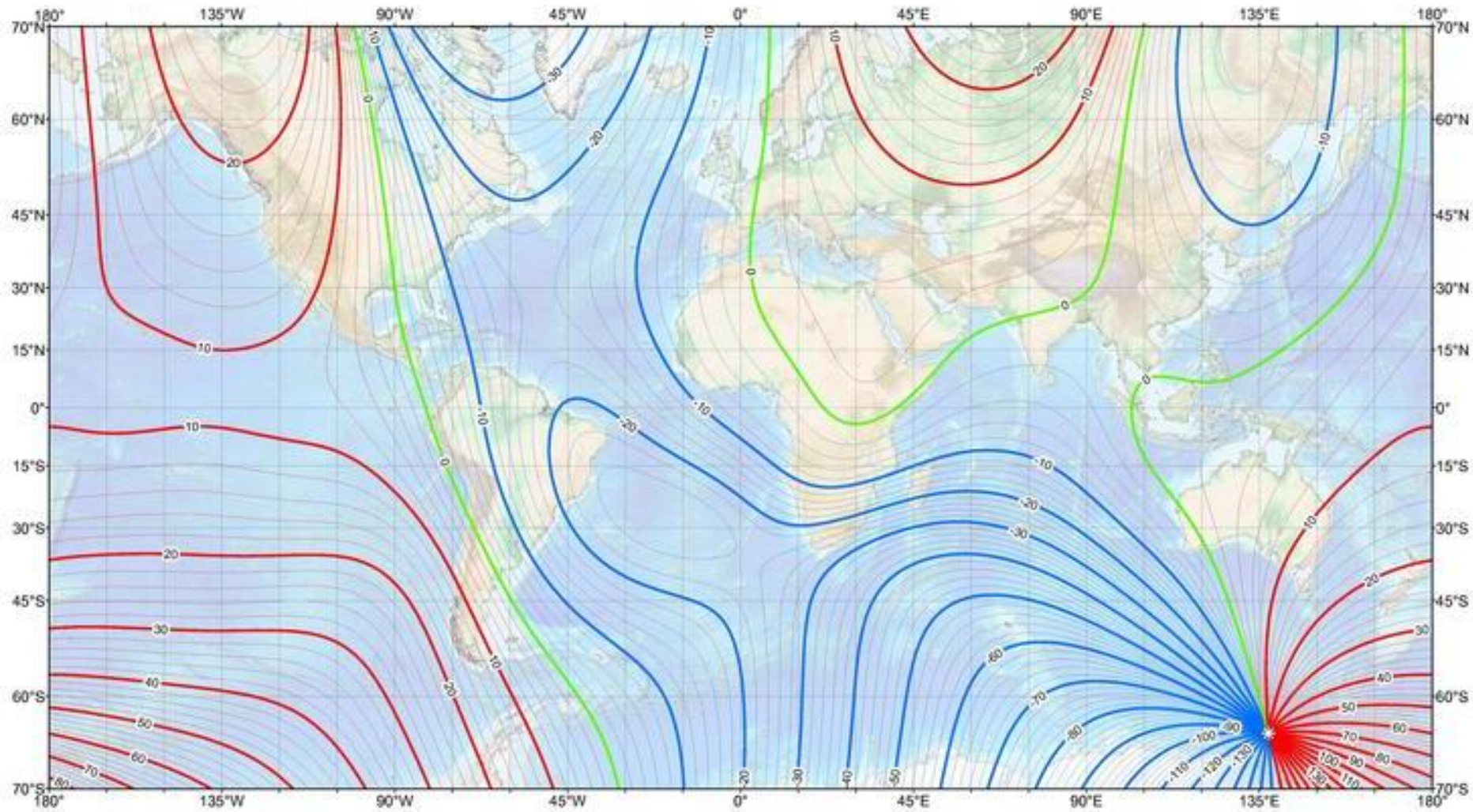- At the two equinoxes, the sun appears vertically above the equator (which is at 0° latitude)
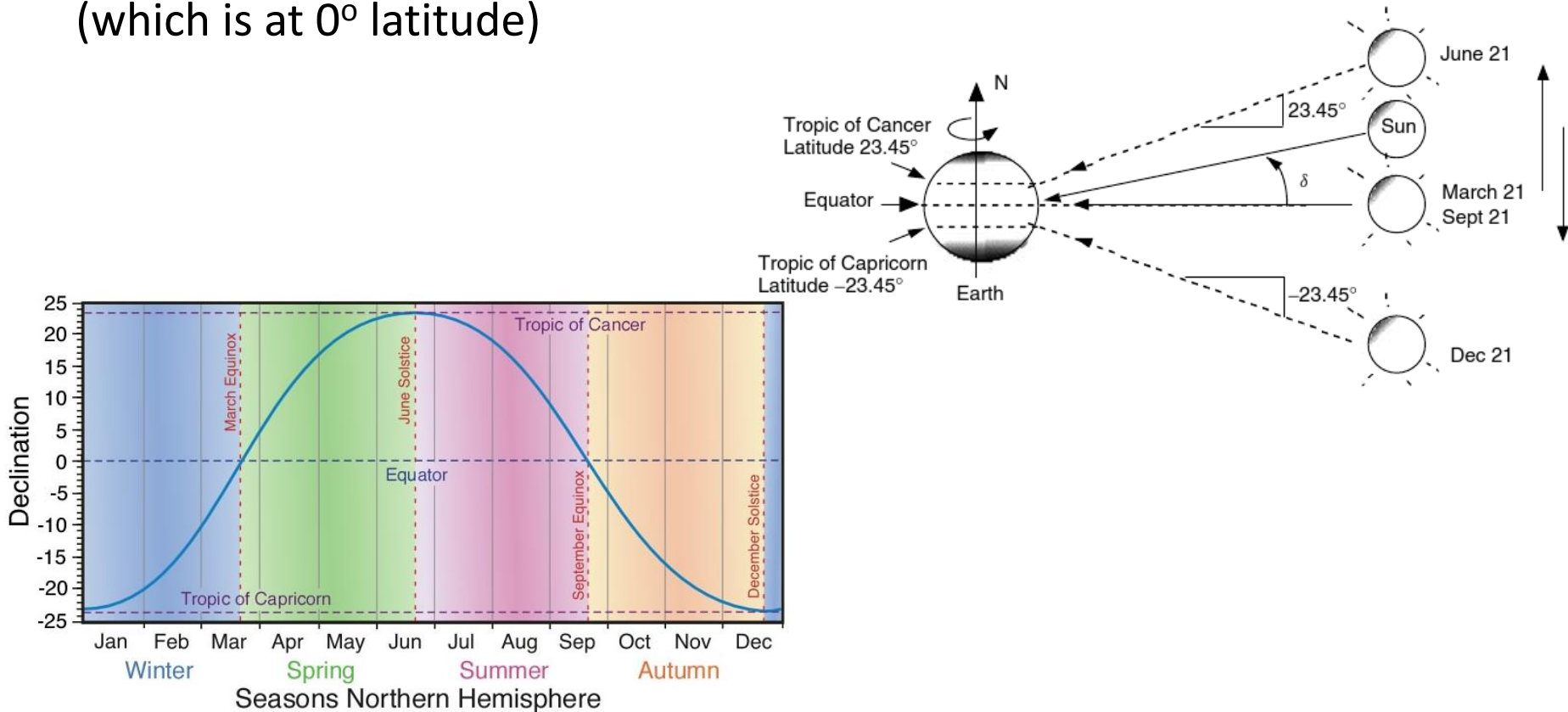
Sun Position

Sun altitude and azimuth angles can be computed at any hour angle H (difference between the local meridian and the sun's Meridian), and latitude angle L:

$$\sin \beta = \sin \delta \sin L + \cos \delta \cos L \cos H \qquad \sin \phi = \frac{\cos \delta \sin H}{\cos \beta}$$
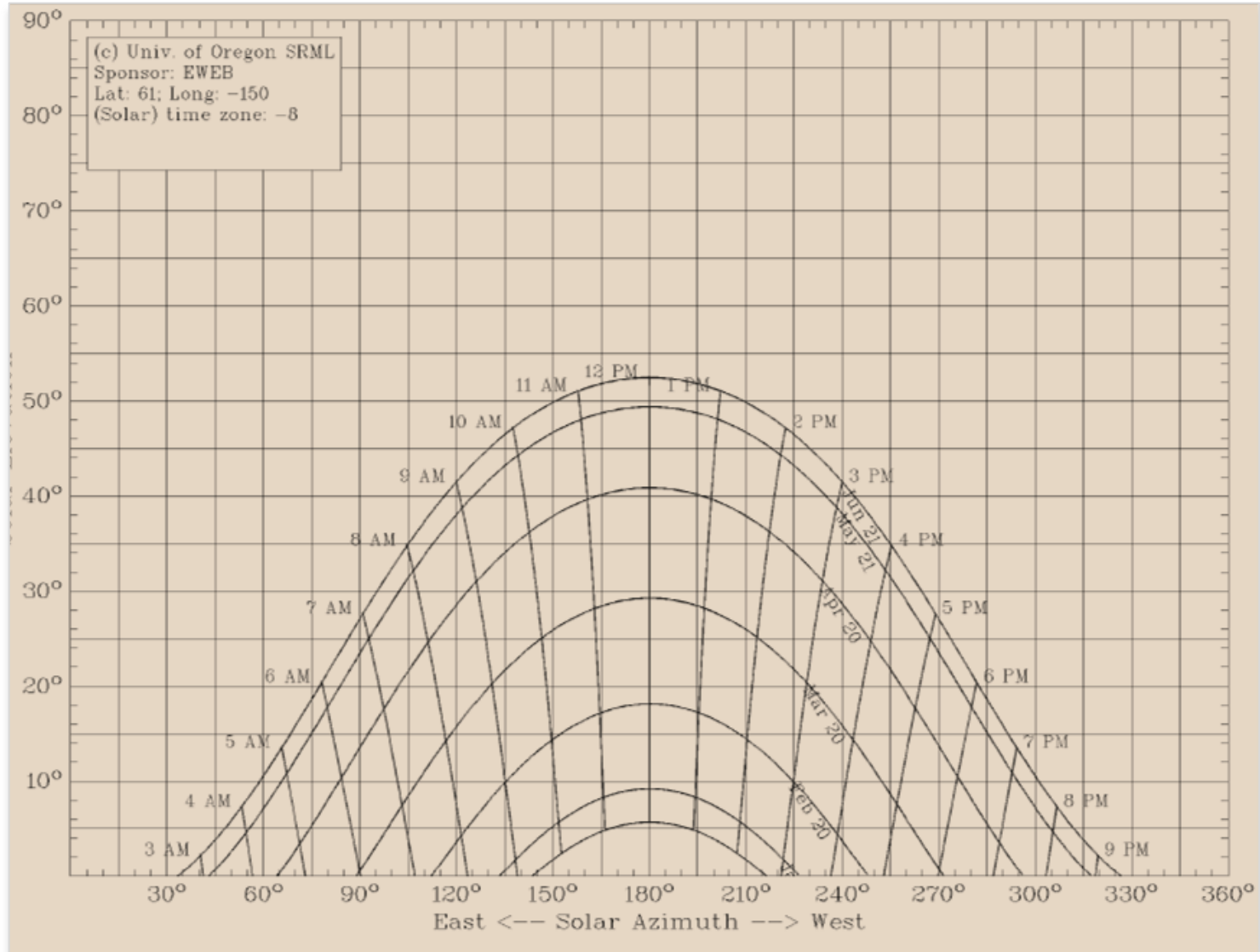
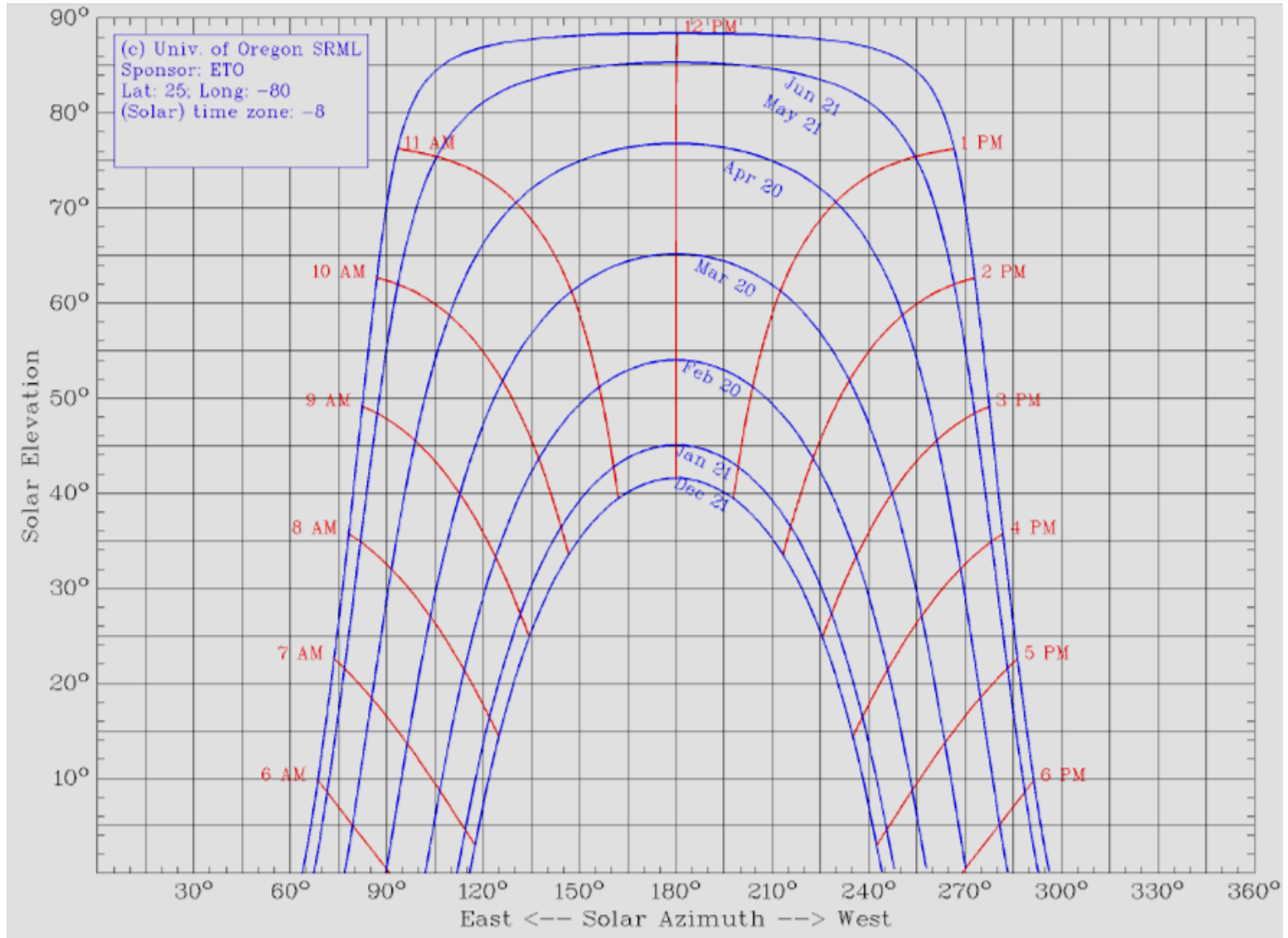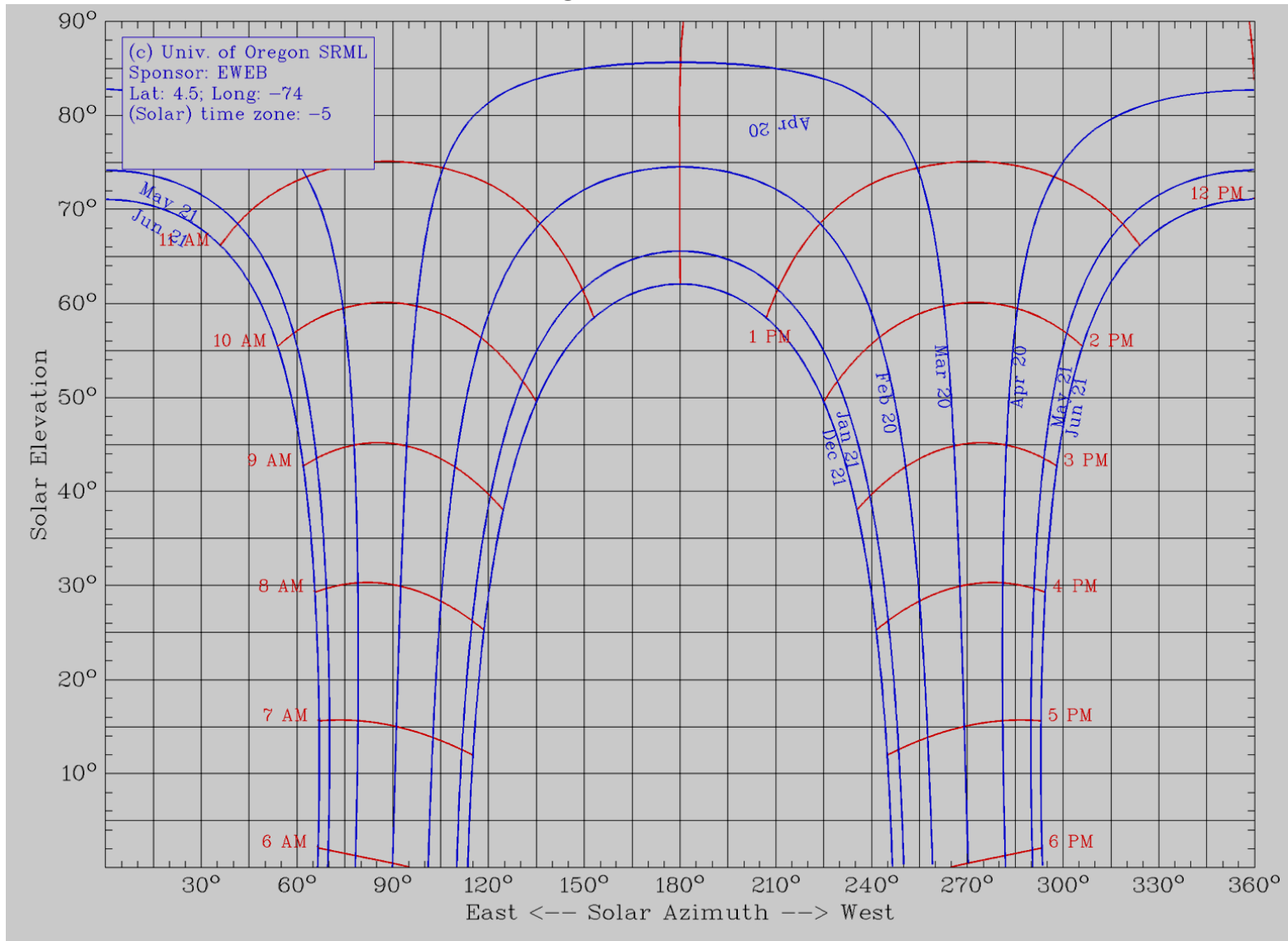# World Magnetic Field Declination Angles (2010)

Sun Path Diagram (plot of sun altitude versus azimuth for specific latitude and days of the year)

Sun path diagram: http://solardat.uoregon.edu/

Anchorage, Alaska

Sun path diagram: http://solardat.uoregon.edu/

Miami, FL

Sun path diagram: http://solardat.uoregon.edu/

Bogota, Columbia

Decomposition of solar flux striking a collector

- **Direct-beam radiation** is sunlight that reaches the earth's surface without scattering.

- **Diffuse radiation**: scattered sunlight (i.e., what makes the sky blue) responsible for the light entering the north-facing windows.

- **Reflected radiation (albedo):** sunlight that is reflected from the ground and other nearby structures.

- **Global radiation** : the sum of the all three components above.
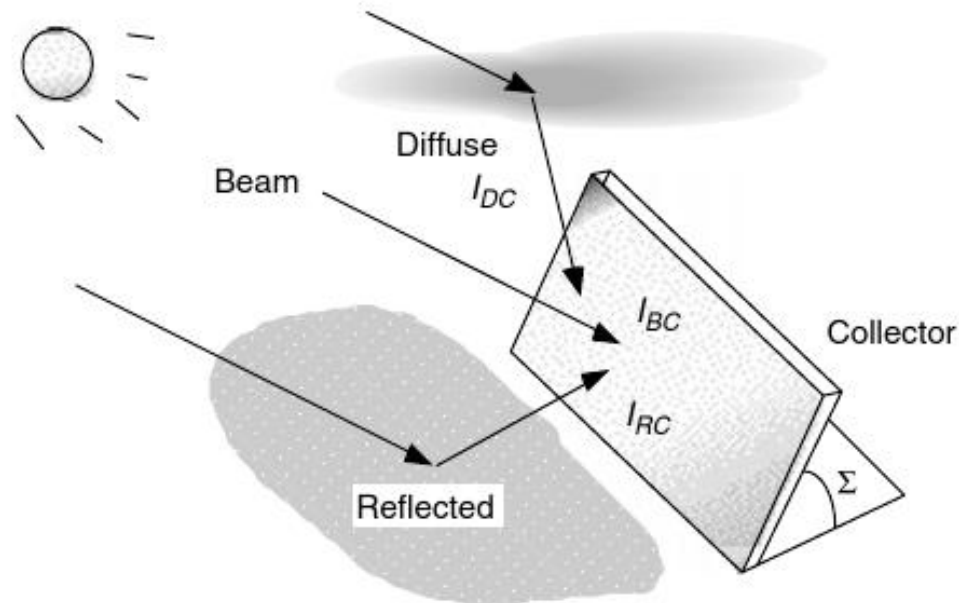
Direct beam radiation

- The attenuation of incoming radiation is a function of distance travelled through the atmosphere. An exponential model is often used for this

$$I_B = Ae^{-km}$$

Where
$$A = 1160 + 75\sin\left[\frac{360}{365}(n - 275)\right] \qquad (\text{W/m}^2)$$

and
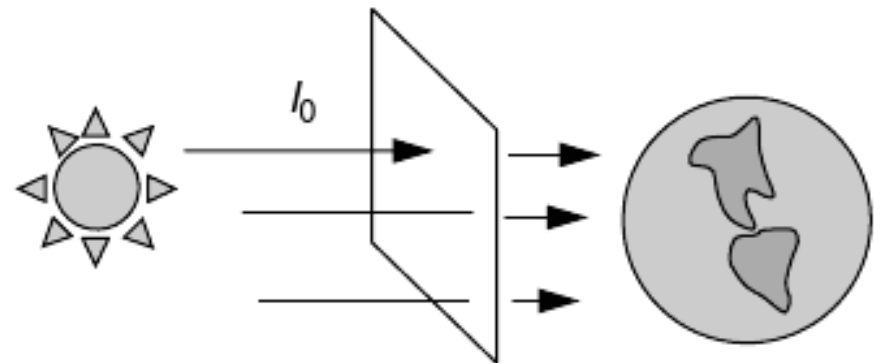$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n - 100)\right]$$

Herein,
I_B: beam portion reaching the earth surface
A: apparent extra-terrestrial flux
k: optical depth
m: air mass ratio
n: day number

Beam striking a collector surface

- **Incidence angle θ:** angle between a normal to the collector face and the incoming solar beam.
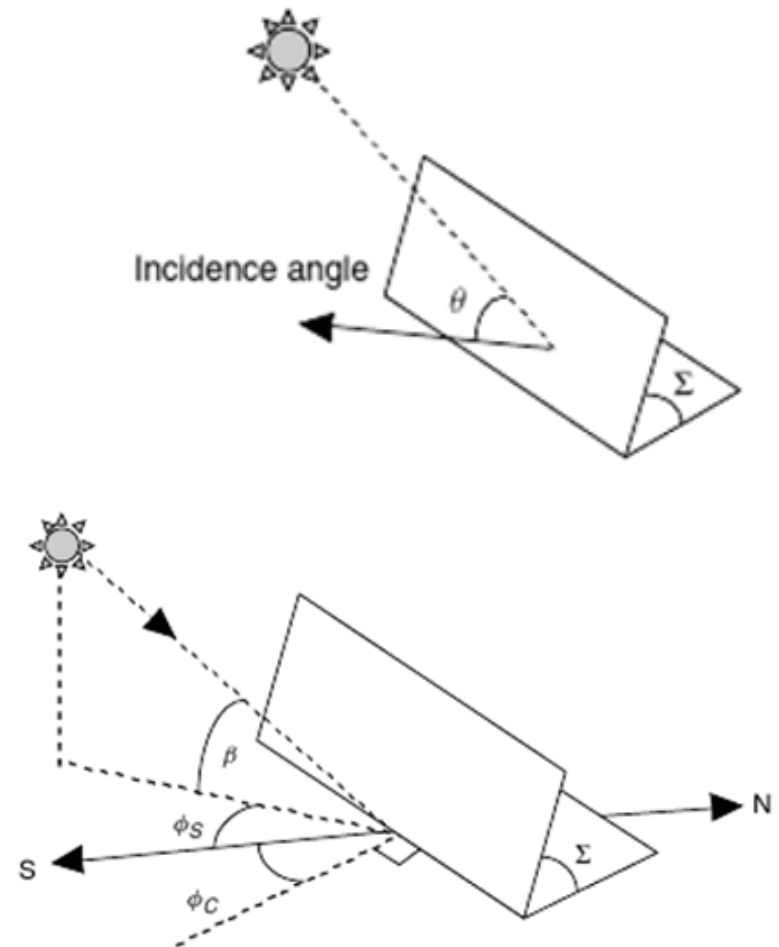
$$I_{BC} = I_B \cos \theta$$

- The incidence angle depends on the sun angles (altitude and azimuth) and collector angles (azimuth and tilt)

$$\cos \theta = \cos \beta \cos(\phi_S - \phi_C) \sin \Sigma + \sin \beta \cos \Sigma$$

- Special case of horizontal surface:

$$I_{BH} = I_B \cos(90^\circ - \beta) = I_B \sin \beta$$

Incidence angle

Diffuse Radiation

- This is difficult to estimate accurately.

- Model that is often used: diffuse radiation on a horizontal surface is proportional to the direct beam radiation all day.
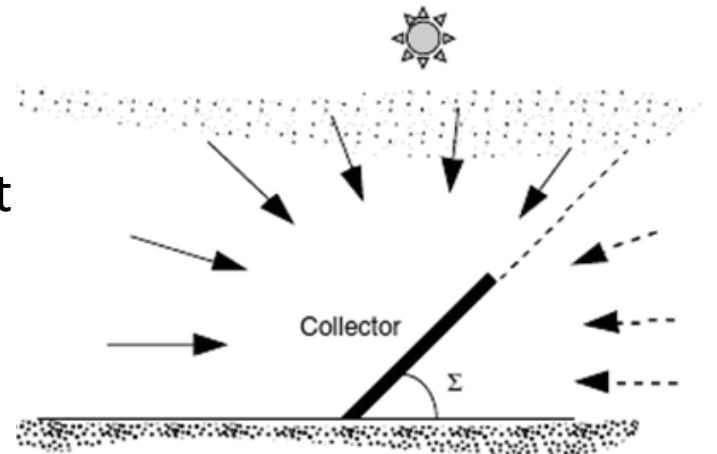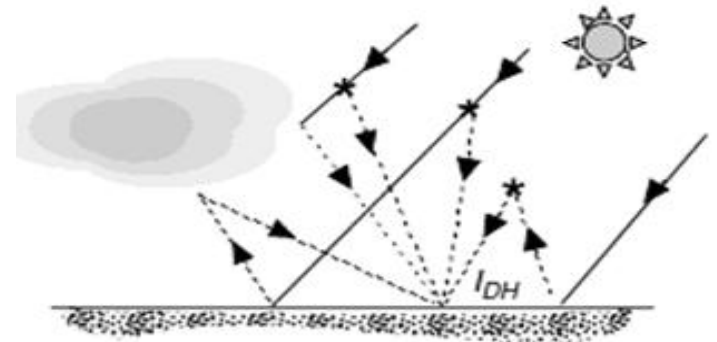
$$I_{DH} = C\,I_B$$

where C is the sky diffuse factor that

varies daily as follows:

$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right]$$

- The diffuse light received by a collector that is tilted at an angle is approximated by

$$I_{DC} = I_{DH}\left(\frac{1 + \cos\Sigma}{2}\right) = C\,I_B\left(\frac{1 + \cos\Sigma}{2}\right)$$

Reflected Radiation

- This is also hard to estimate accurately.

- Estimates of ground reflectance ρ range from 0.8 for fresh snow to 0.1 for gravel. Ordinary ground or grass assume a reflectance of 0.2.

- The reflected radiation received by a collector can be estimated by

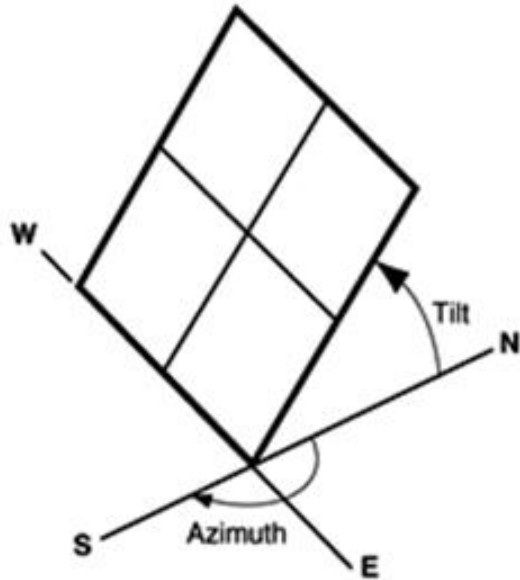$$I_{RC} = \rho I_B (\sin \beta + C) \left(\frac{1 - \cos \Sigma}{2} \right)$$
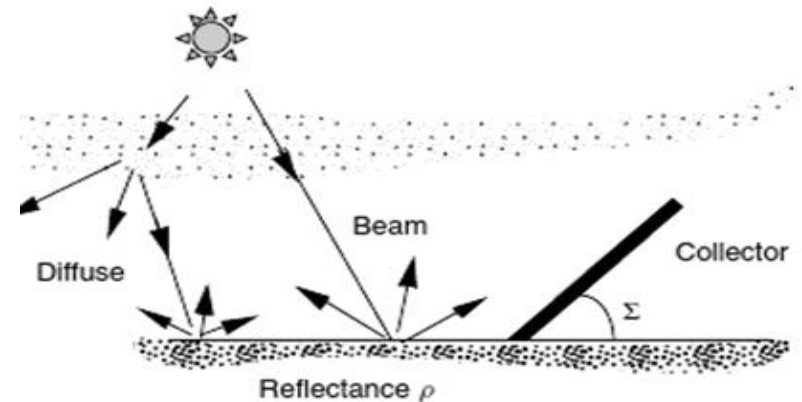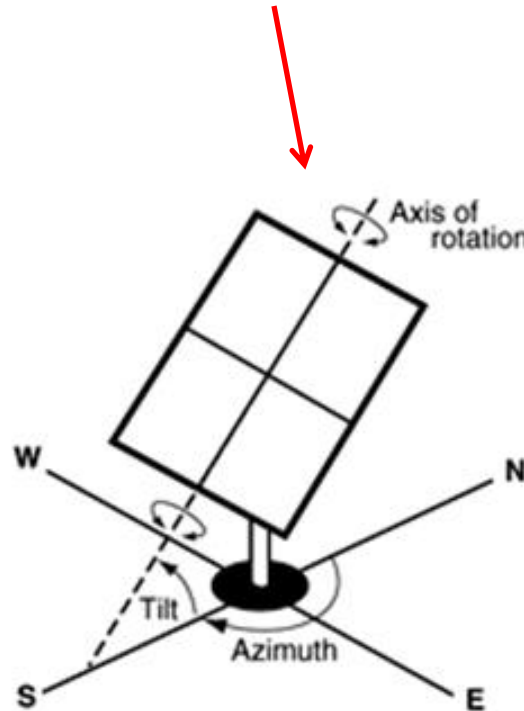
Capturing Direct Sunlight - Types of PV Arrays

$$I_{BC} = I_B \cos\theta$$
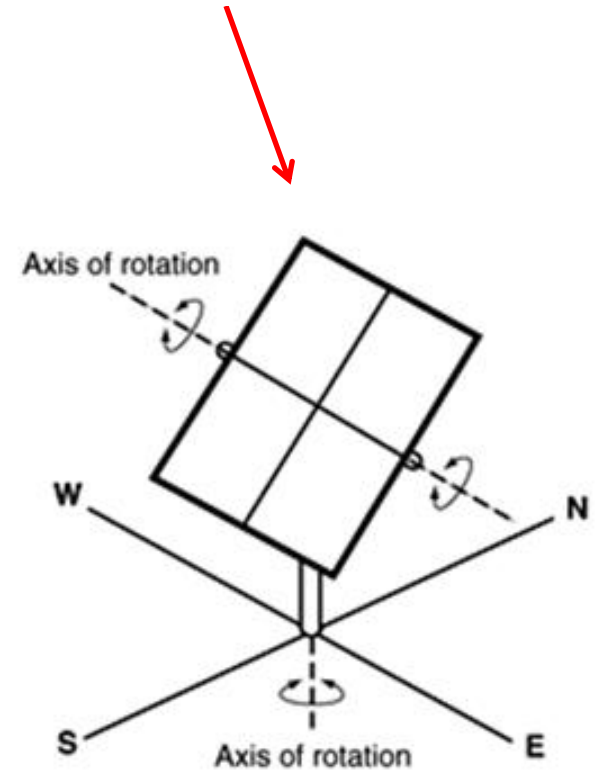
$$I_{BC} = I_B \cos\delta$$

$$I_{BC} = I_B$$

PV array facing south at fixed tilt.

One axis tracking PV array with axis oriented south.

Two-axis tracking PV array

Typical Metrological Data (TMY)

Previous equations apply only to clear skies – that is not the case in real life!

- The most common data for describing the local solar climate is through Typical Meteorological Year data (TMY).
  - Various meteorological measurements are made at hourly intervals over a number of years to build up a picture of the local climate.
  - Of the parameters given, usually only the time and irradiation figures are used. However, more advanced models also use the temperature and wind speed.
  - TMY2 – average over 30 years (1961-1990)
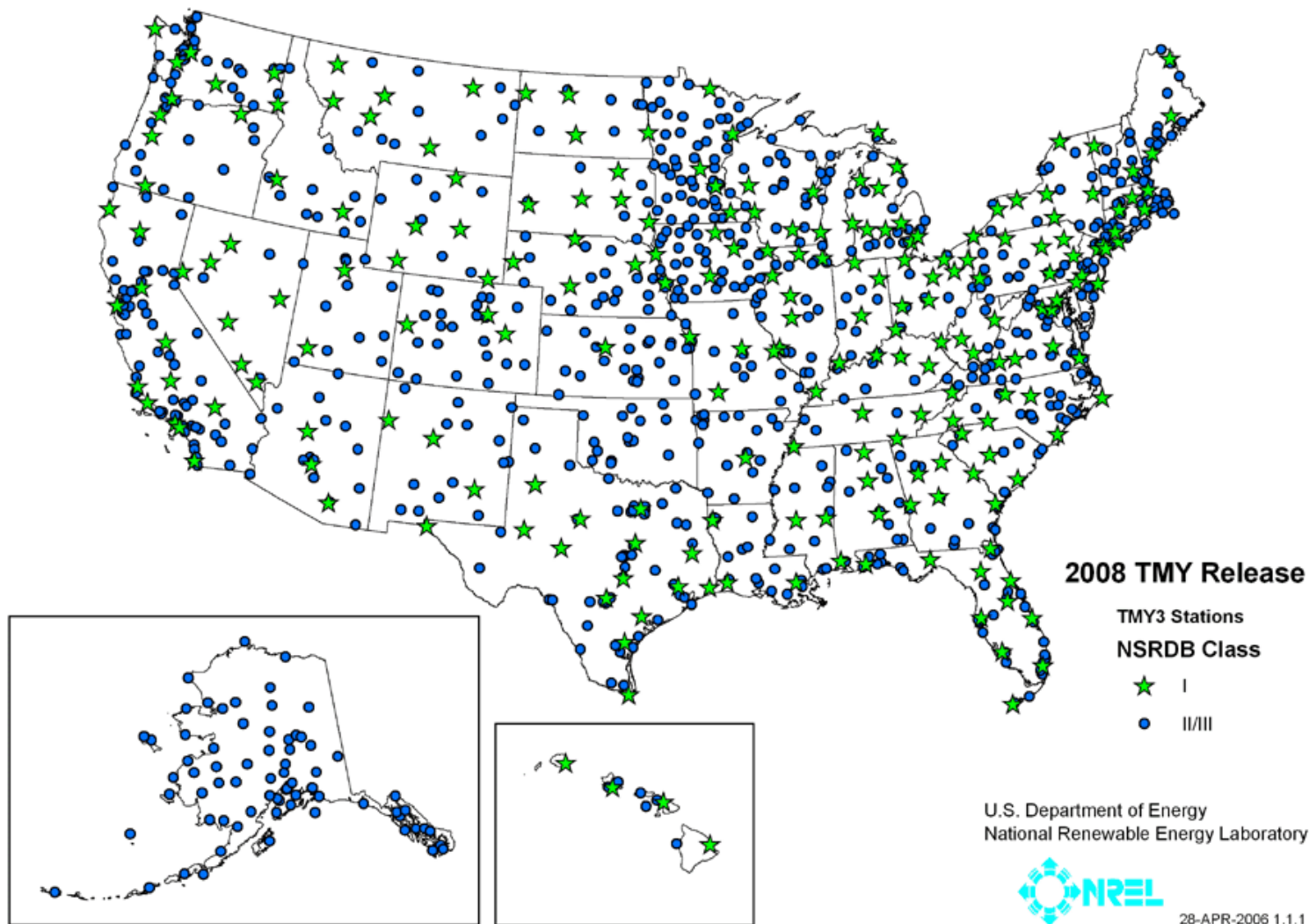 - TMY3 – average over 15 years (1991-2005)

Measuring Sunlight

- **Pyranometers** are designed to accurately measure the global solar irradiance (they respond to all wavelengths).
  - By a placing a shade ring to block the direct beam, a pyranometer can be used to measure diffuse radiation.
- **Pyrheliometers** - shaped like long narrow tubes - are designed to measure the direct (or normal incident) irradiance.
- Both Pyranometers and pyrheliometers use a stack of thermocouples (thermopile) to detect how much hotter a black surface becomes when exposed to sunlight – then produces a voltage that is proportional to insolation.
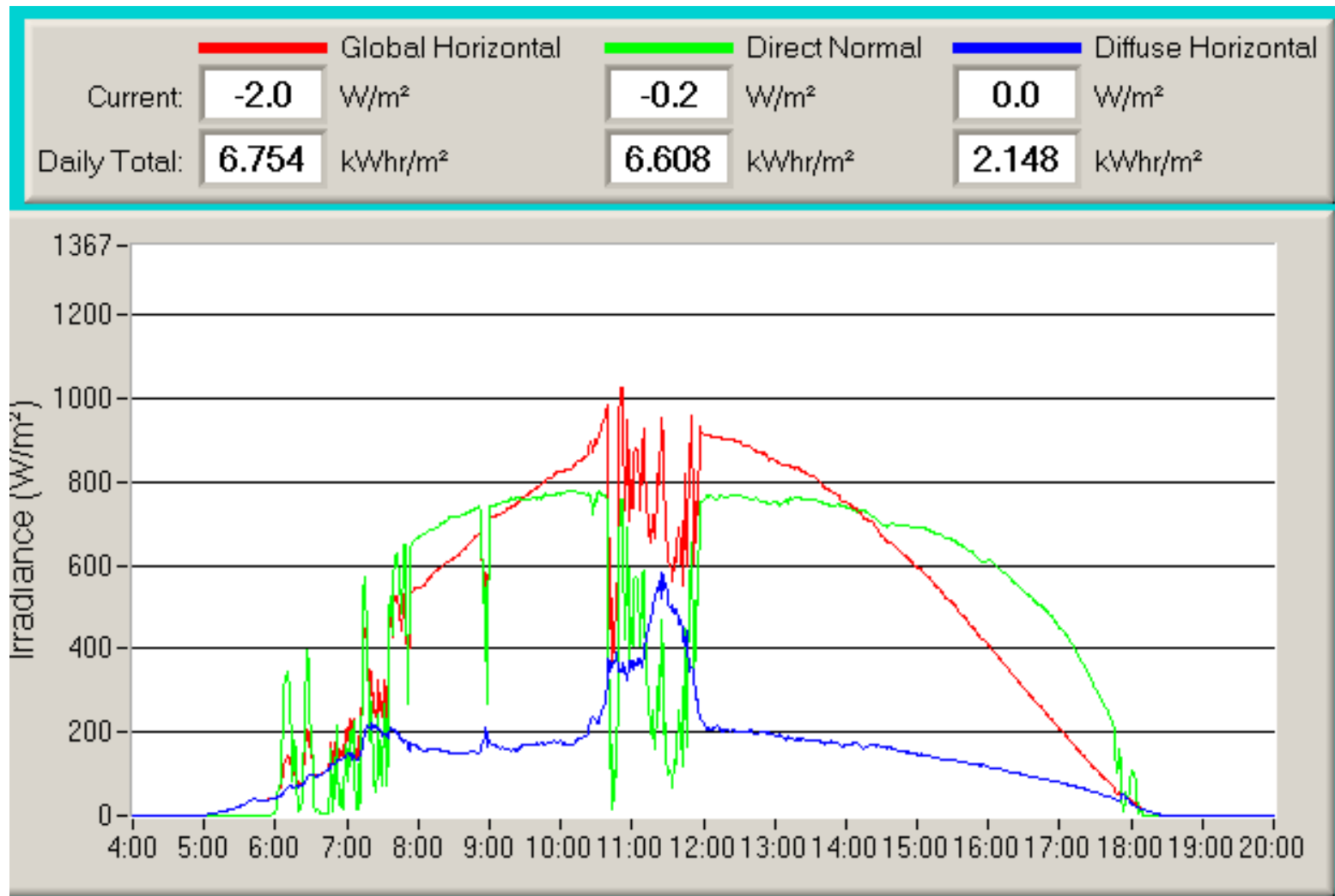
2008 TMY Release

TMY3 Stations
NSRDB Class

★ I
● II/III

U.S. Department of Energy
National Renewable Energy Laboratory

NREL

28-APR-2006 1.1.1

Live Local Data: http://www.nrel.gov/midc/unlv/

## August 17, 2012

Band gap energy

- The band-gap Eg for silicon is 1.12 eV (where 1 eV = 1.6 x 10^{-19} J). Hence, an electron needs to acquire that much energy to free itself from the electrostatic force that ties it to its own nucleus.

- For photovoltaics, the energy source is photons of electromagnetic energy from the sun. For silicon cells,

  - photons with λ > 1.11 µm have energy less than the 1.12 eV needed to excite an electron. Hence, their energy is wasted and just heats the cell.

  - photons with λ < 1.11 µm have more than enough energy to excite an electron. Any extra energy above the 1.12 eV needed is also dissipated as waste heat in the cell.

Cut-off wavelength and band gap
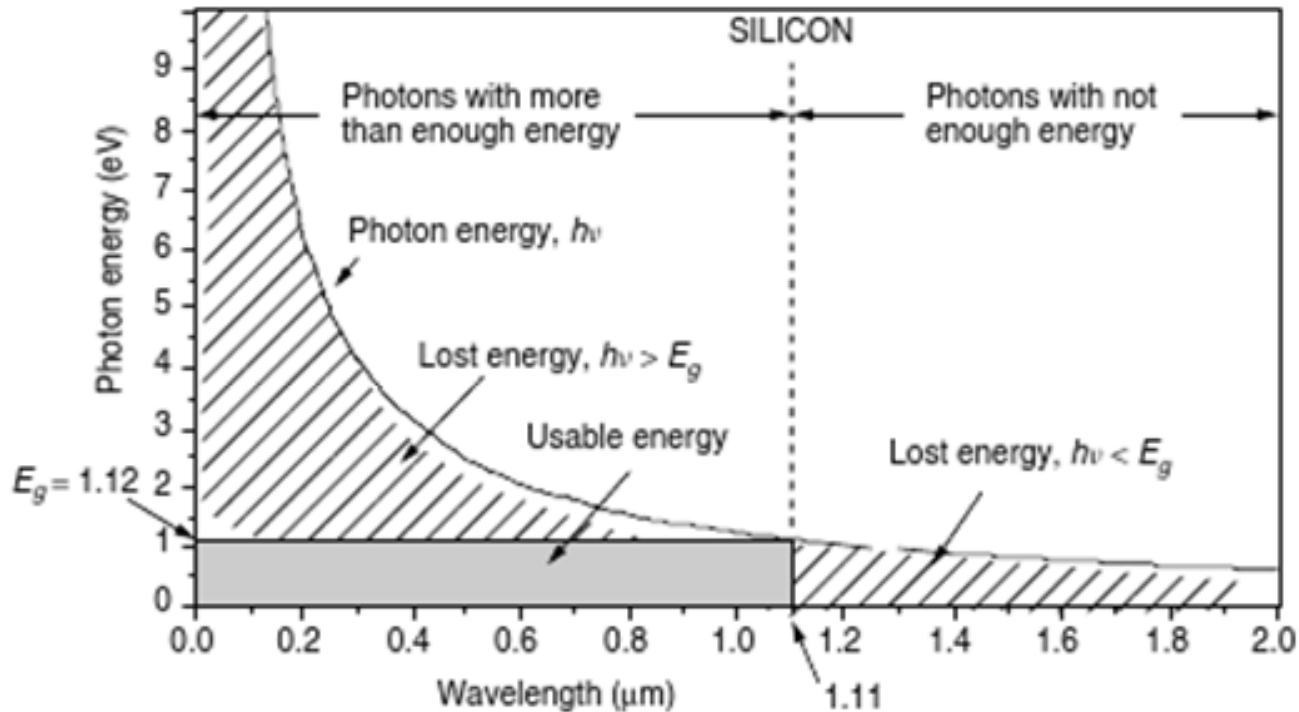
- Band gap and cut-off wavelength of common photovoltaic materials: Silicon (Si), gallium arsenide(GaAs), cadmium telluride (CdTe), indium phosphide (InP).

Quantity	Si	GaAs	CdTe	InP
Band gap (eV)	1.12	1.42	1.5	1.35
Cut-off wavelength (μm)	1.11	0.87	0.83	0.92

Maximum cell efficiency

- Note that the maximum possible fraction of the sun's energy that could be collected with a silicon solar cell is 49.5%. That is, the constraints imposed by silicon's band gap limit the efficiency of silicon to just under 50%.
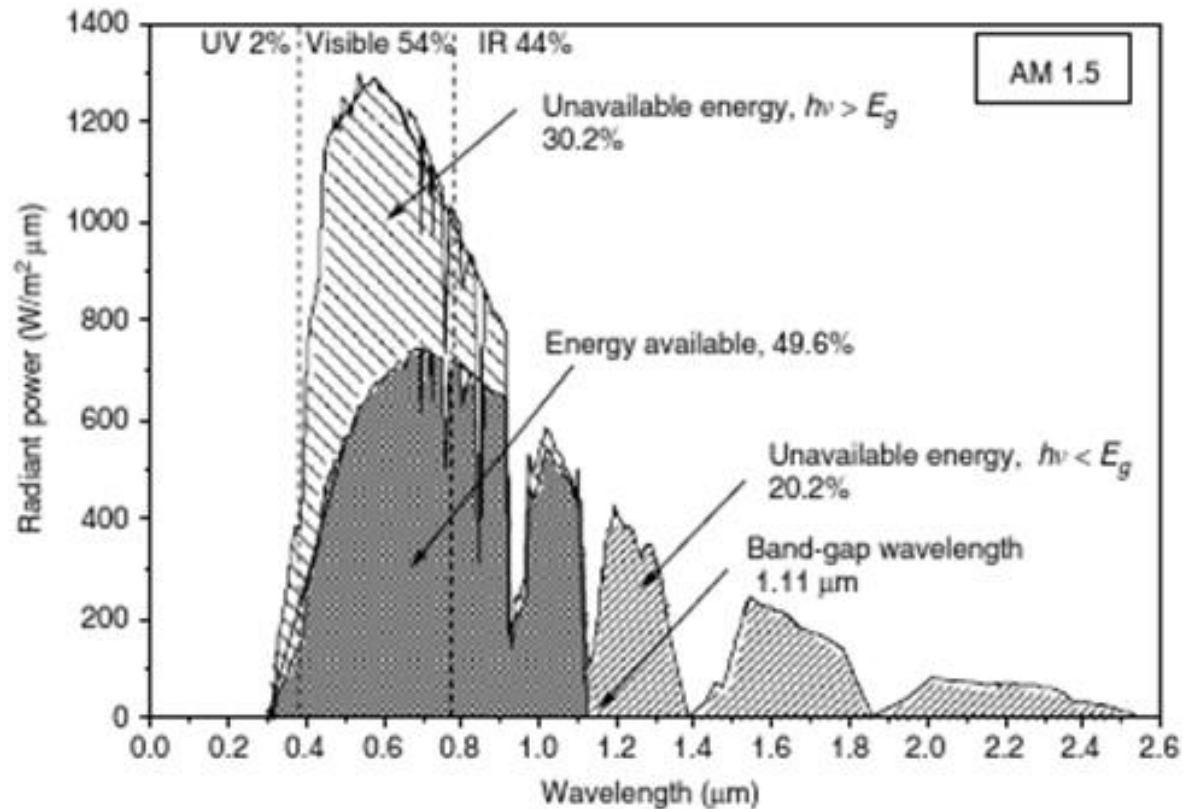
# Trade-off between material with small band gap versus one with large band gap

- – Low band gap gives more current with less voltage while high band gap results in less current and higher voltage.
- – Since power is the product current and voltage, there must be some middle-ground band gap, usually estimated to be between 1.2 eV and 1.8 eV, which will result in the highest power and efficiency.

PV cell equivalent circuit

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left(\frac{V + I \cdot R_S}{R_P} \right)$$

- At 25ºC,

$$I = I_{SC} - I_0 \left[e^{38.9(V + IR_S)} - 1 \right] - \frac{1}{R_P}(V + IR_S)$$
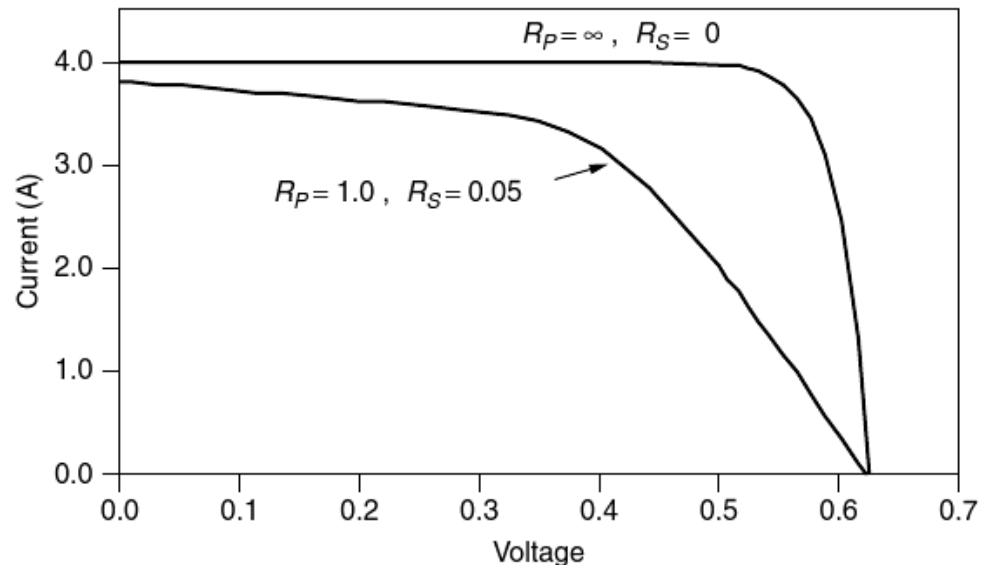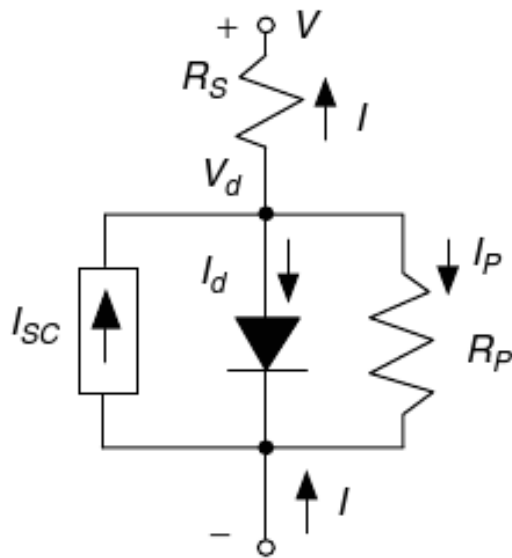
Cell to module to array

- A single cell produces only a voltage of 0.5 - 0.6 V and few watts of power – little use.

- To produce a larger voltage, a number of pre-wired cells in series, all encased in tough, weather-resistant package, to form a module.

- A typical module may have 36, 54, 72, 96 cells in series.

- Multiple modules can be wired in series to increase voltage and in parallel to increase current. Such combinations of modules are referred to as an array.
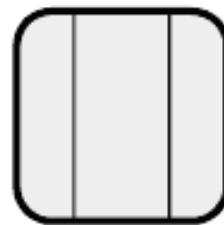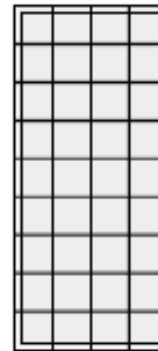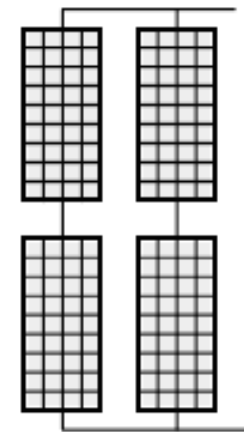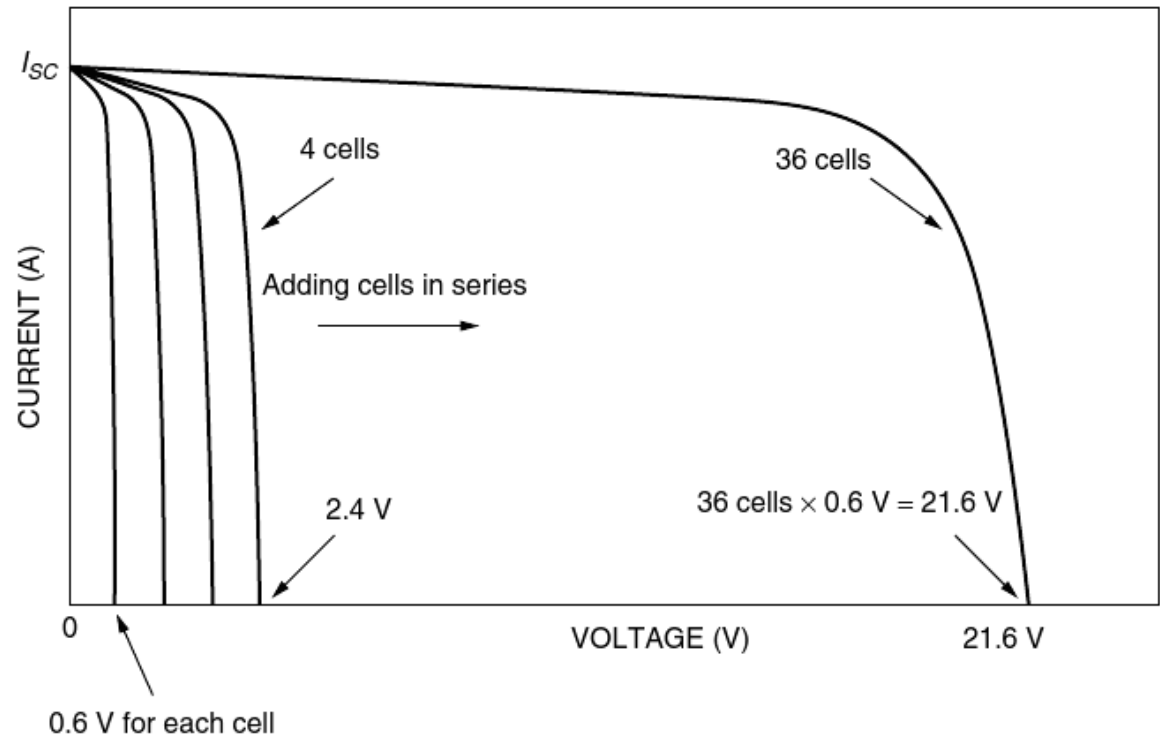
Cell   Module   Array

Cells connected in series

- When photovoltaics are wired in series, they all carry the same current, and their voltages add. The overall module voltage V_{module} is found by.
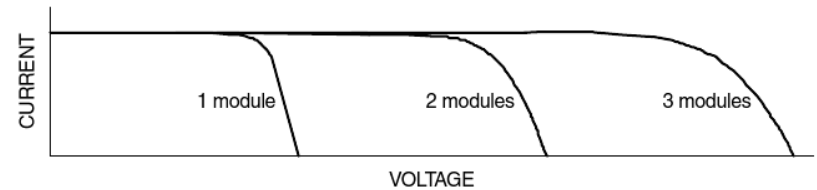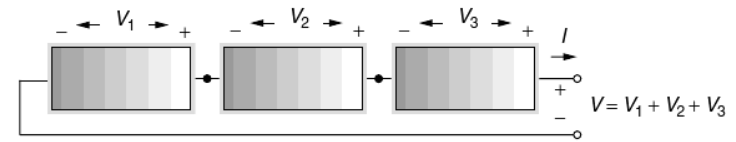
$$V_{module} = n(V_d - I R_S)$$

where *n* is the number of cells in series.

I_{SC}

4 cells

36 cells

Adding cells in series

CURRENT (A)

2.4 V

36 cells × 0.6 V = 21.6 V
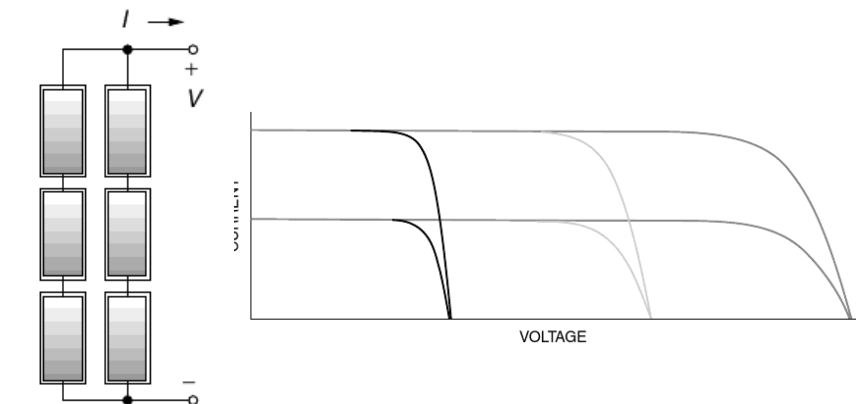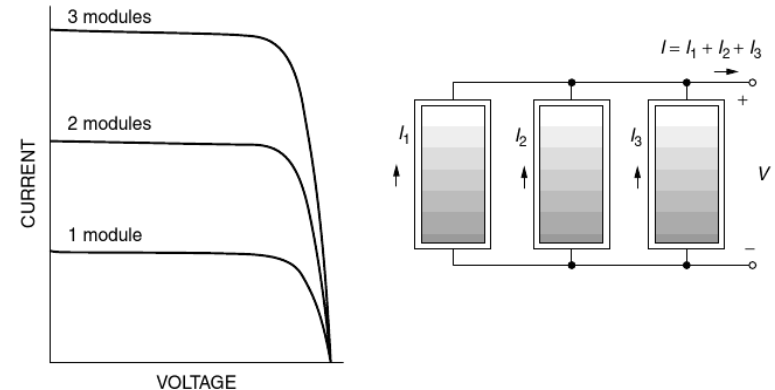
0

VOLTAGE (V)

21.6 V

0.6 V for each cell

Series- and parallel-connected modules

- For modules in series, the I –V curves are simply added along the voltage axis.

- For modules in parallel, the same voltage is across each module and the total current is the sum of the currents.

- In high power applications, the array usually consists of a combination of series and parallel modules for which the total I –V curve is the sum of the individual module I –V curves.
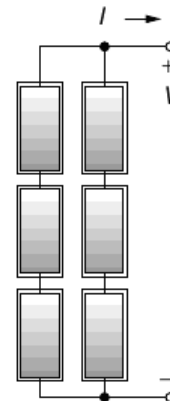
I-V and P-V Curves

- The figure below shows a generic I –V curve for a PV module, and the product of voltage and current, i.e., power curve of the module.
  - At the two ends of the I –V curve, the output power is zero.
  - The maximum power point (MPP) is the spot near the knee of the I –V curve at which the product of current and voltage reaches its maximum.
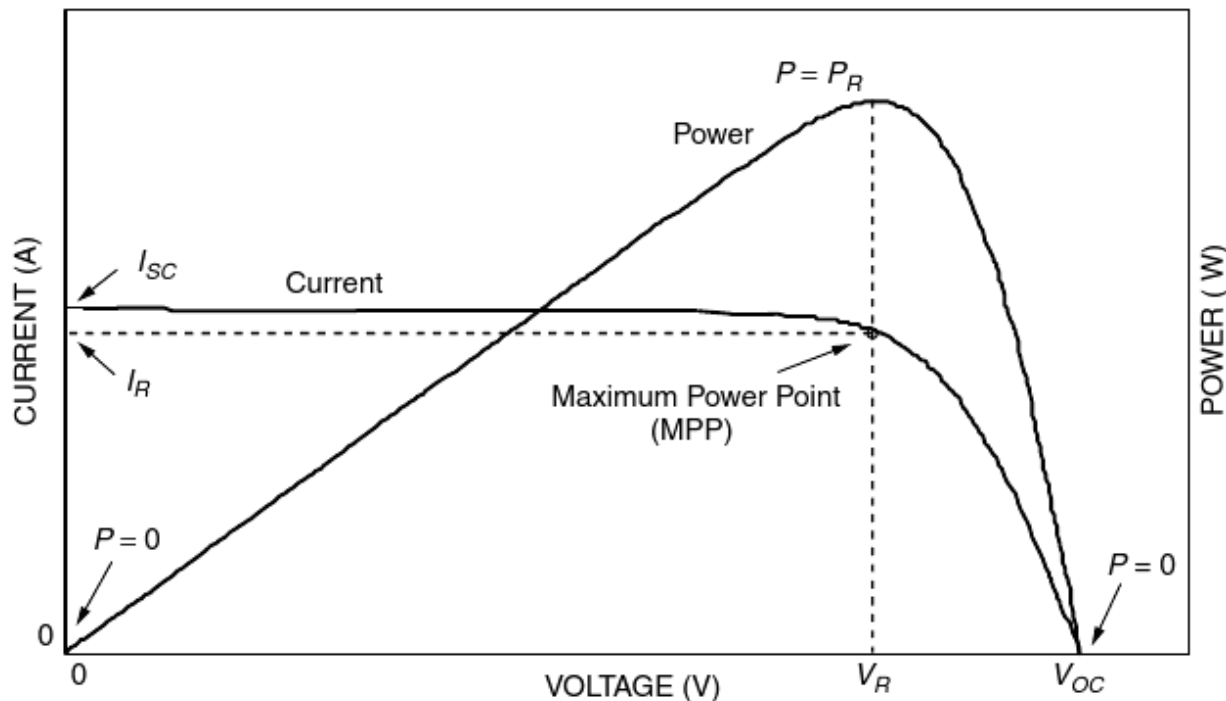
PV Panel Specs.

- Standard test conditions (STC) for PV have been established to enable fair comparisons of one module to another. These test conditions include a solar irradiance of 1 kW/m² with spectral distribution shown earlier, corresponding to an air mass ratio of 1.5, and the <u>cell</u> temperature is 25° C.

Standard Test Conditions (STC)
STC = 1000 W/M² irradiance, 25°C module temperature, AM 1.5 spectrum*

|	KD230GX-LPB	KD235GX-LPB	KD240GX-LPB	KD245GX-LPB	
P_{mp}	230	235	240	245	W
V_{mp}	29.8	29.8	29.8	29.8	V
I_{mp}	7.72	7.89	8.06	8.23	A
V_{oc}	36.9	36.9	36.9	36.9	V
I_{sc}	8.36	8.55	8.59	8.91	A
$P_{tolerance}$	+5/-3	+5/-3	+5/-3	+5/-3	%

Impact of irradiance

- Manufacturers often provide I –V curves that show how the curves shift as insolation and cell temperature changes. Notice as insolation drops, short-circuit current drops in direct proportion. Decreasing insolation also reduces the open circuit voltage , but it does so following a logarithmic relationship that results in relatively modest changes.
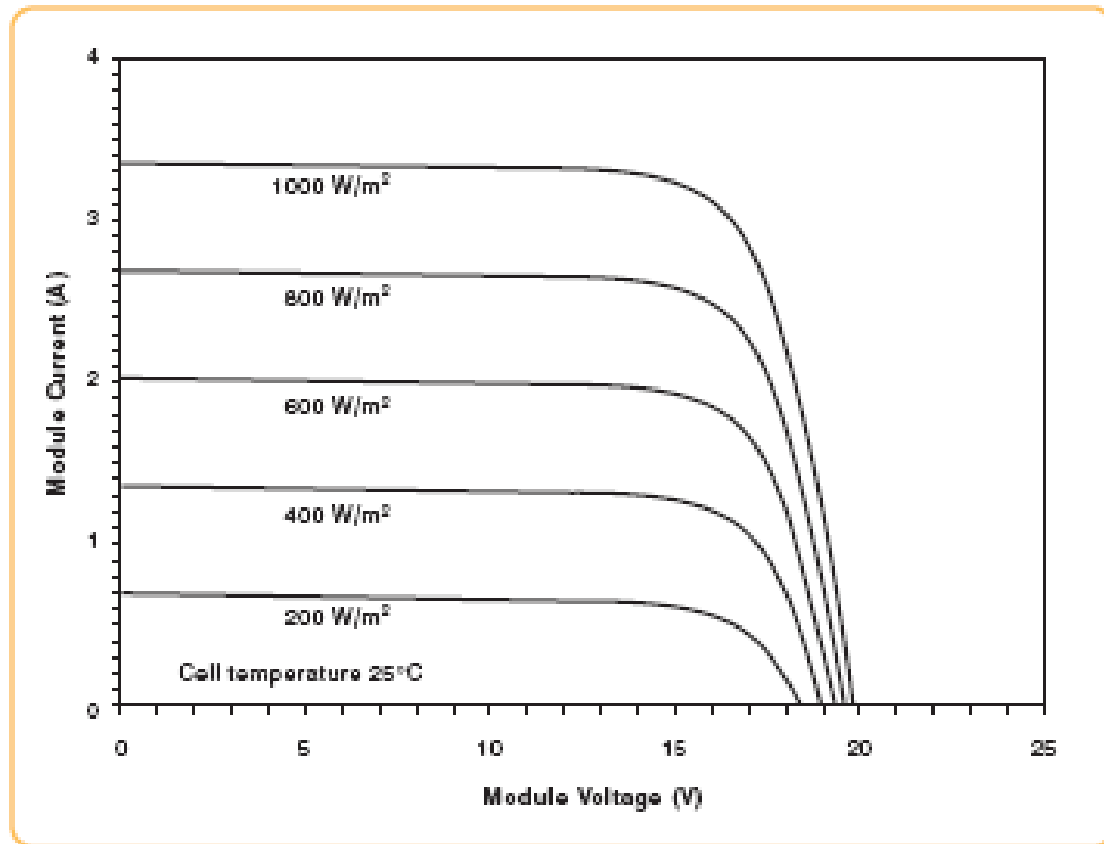
Impact of temperature

- As the cell temperature increases, the open-circuit voltage decreases substantially while the short-circuit current increases only slightly → Photovoltaics perform better on cold than hot days.
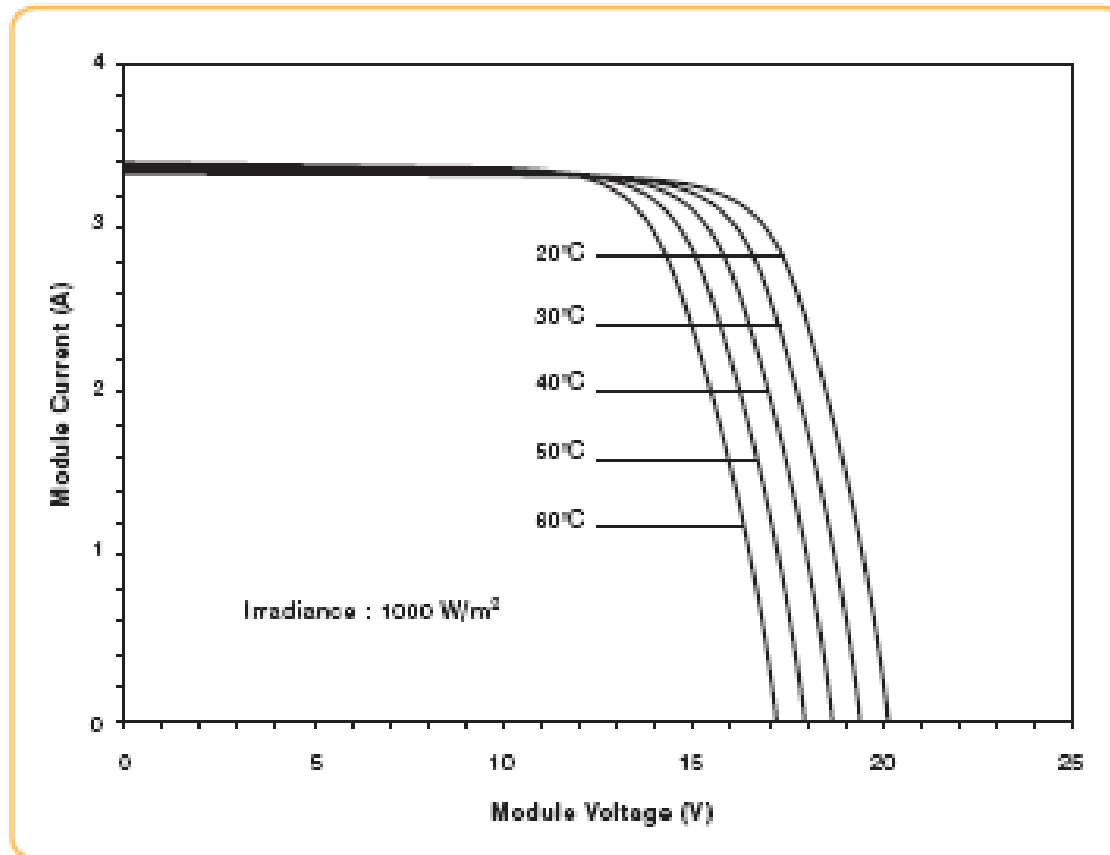
Nominal Operating Cell Temperature (NOCT)

- The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the following conditions: solar irradiance = 800 W/m^2 , air temp. = 20°C ,wind speed = 1 m/s, mounting = open back side.
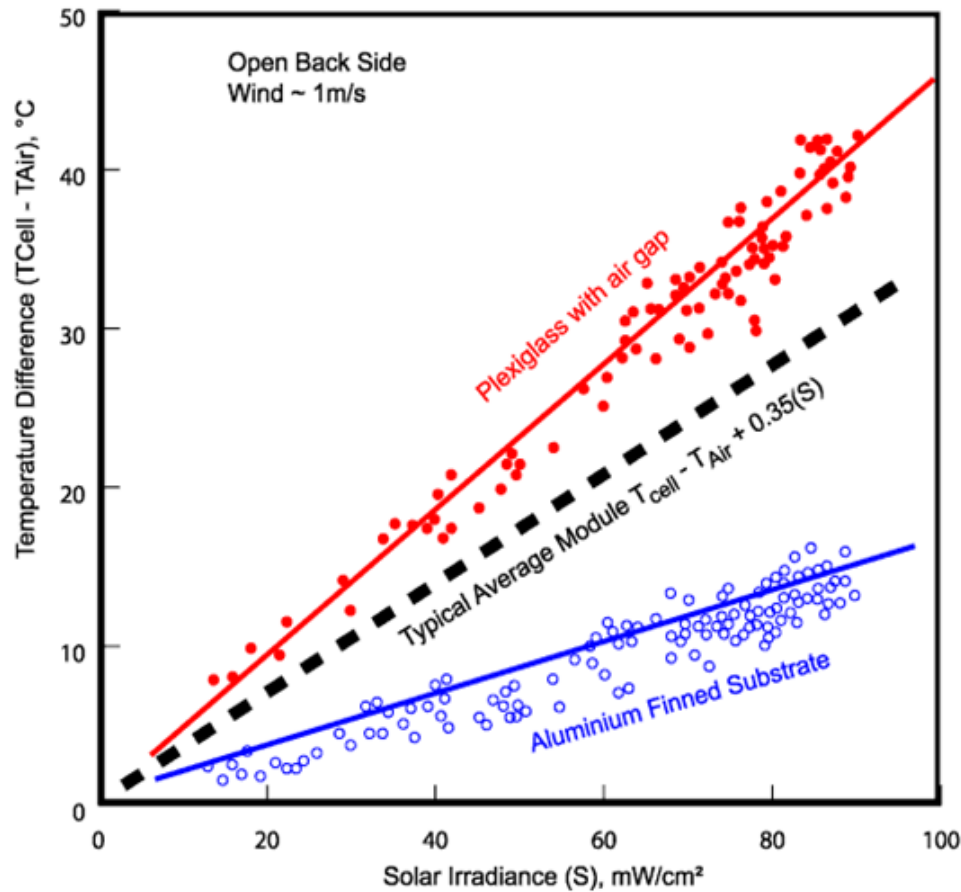
Power rating under NOCT (PVUSA)

- Approximate formula for calculating cell temperature:

$$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8} \right) \cdot S$$

- PV panels sold in the USA are required to post the panel rating under NOTC.

|	KD230GX-LPB	KD235GX-LPB	KD240GX-LPB	KD245GX-LPB	
Nominal Operating Cell Temperature Conditions (NOCT) *NOCT = 800 W/M² irradiance, 20°C ambient temperature, AM 1.5 spectrum**					
T_{NOCT}	45	45	45	45	°C
P_{max}	165	169	172	176	W
V_{mp}	26.8	26.8	26.7	26.8	V
I_{mp}	6.18	6.31	6.45	6.58	A
V_{oc}	33.7	33.7	33.7	33.7	V
I_{sc}	6.77	6.92	6.95	7.21	A
PTC	208.0	212.6	217.3	219.1	W

Temperature coefficients

- Manufacturers often provide temperature coefficients for maximum power, open circuit voltage and short circuit current.

	KD230GX-LPB	KD235GX-LPB	KD240GX-LPB	KD245GX-LPB	
Temperature Coefficients					
P_{max}	-0.45	-0.46	-0.46	-0.46	%/°C
V_{mp}	-0.51	-0.52	-0.52	-0.52	%/°C
I_{mp}	0.0065	0.0065	0.0064	0.0065	%/°C
V_{oc}	-0.36	-0.36	-0.36	-0.36	%/°C
I_{sc}	0.060	0.060	0.060	0.060	%/°C
Operating Temp	-40 to +90	-40 to +90	-40 to +90	-40 to +90	°C

Bypass diodes

- External bypass diodes are purposely added by the PV manufacturer to help preserve the performance of PV modules.
  - In a sunny cell, there is a voltage rise across the cell so the bypass diode is reverse biased— as if it is not there.
  - In a shaded, however, the negative voltage will forward bias (i.e., turn on) the bypass diode, thus diverting the current flow.
  - When conducting, the bypass diode drops about 0.6 V, thus placing a cap on the negative voltage across the cell.

$V_c \approx 0.5$ V

$V \approx -0.6$ V

0 A

Bypass diode is cutoff

Bypass diode conducts

Sunny cell

Shaded cell
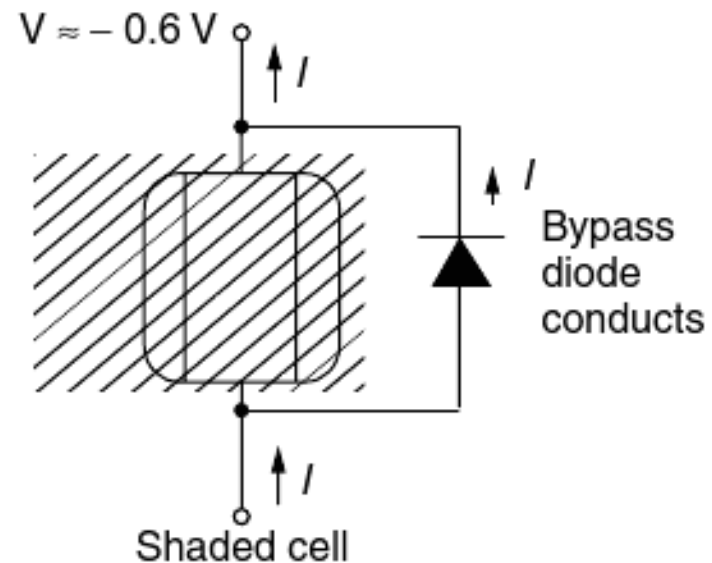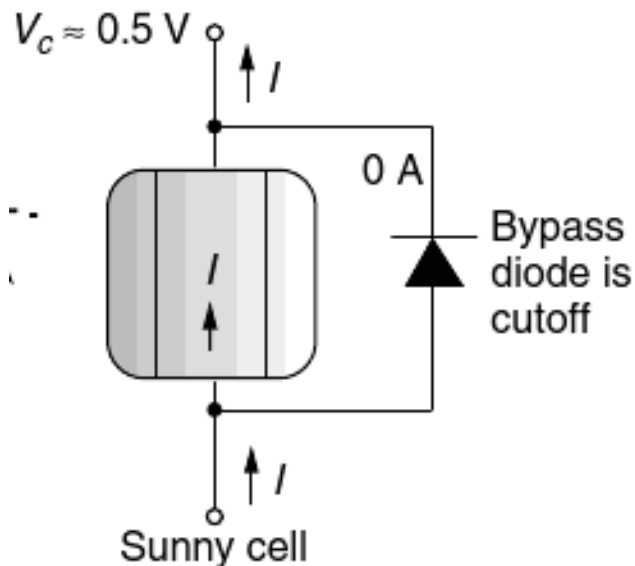
Bypass diode placement (real world)

- In practice, placing one bypass diode across each solar cell is too expensive and not easy to install. Instead, bypass diodes are conveniently placed across a group (or a string) of cells in the back of the panel. Normally one diode is placed across each pair of strings.
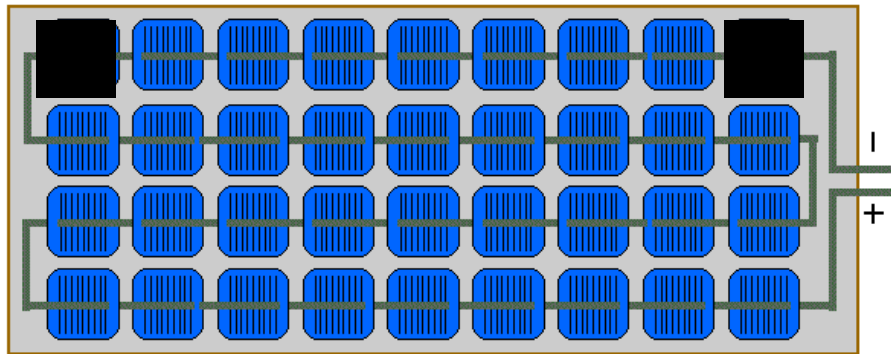
Hidden bypass diodes
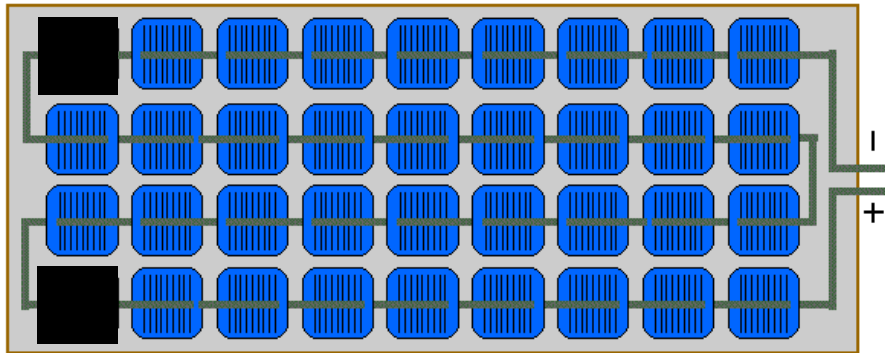

Visible bypass diodes

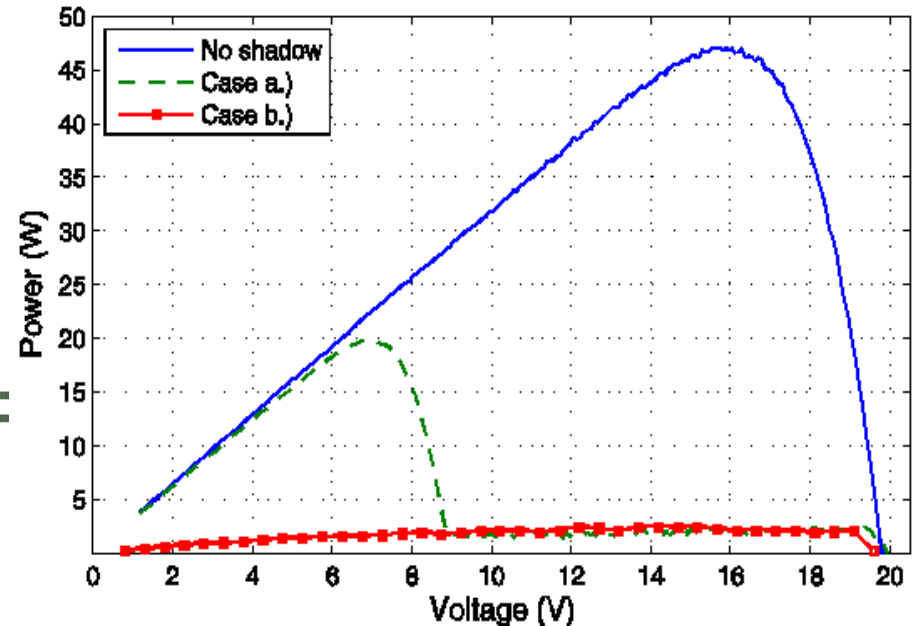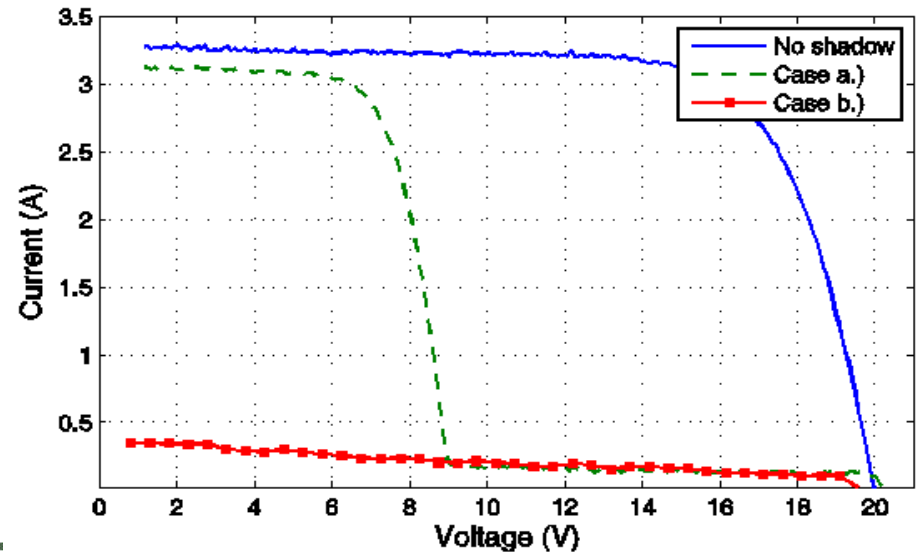# Impact of Partial Shading on a series of strings (module)

- Panel Model: Kyocera KC70
- Panel Layout: 2 series-connected strings (18 cells each) – one bypass diode per string.
- Two shaded cells belonging to (a) same string (b) different strings.
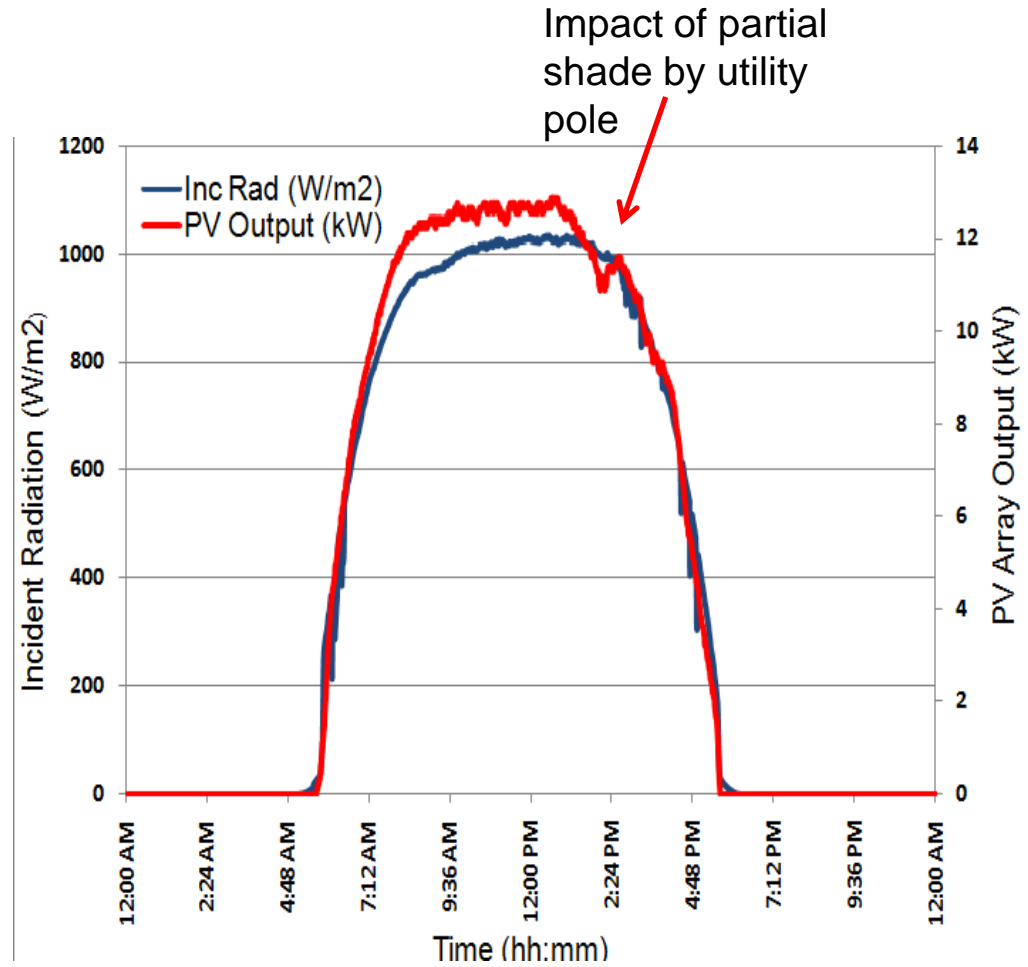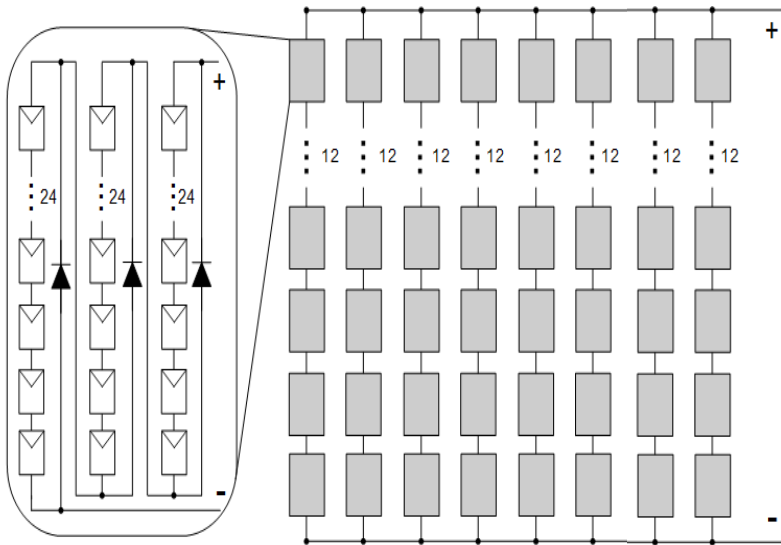

Case (a)
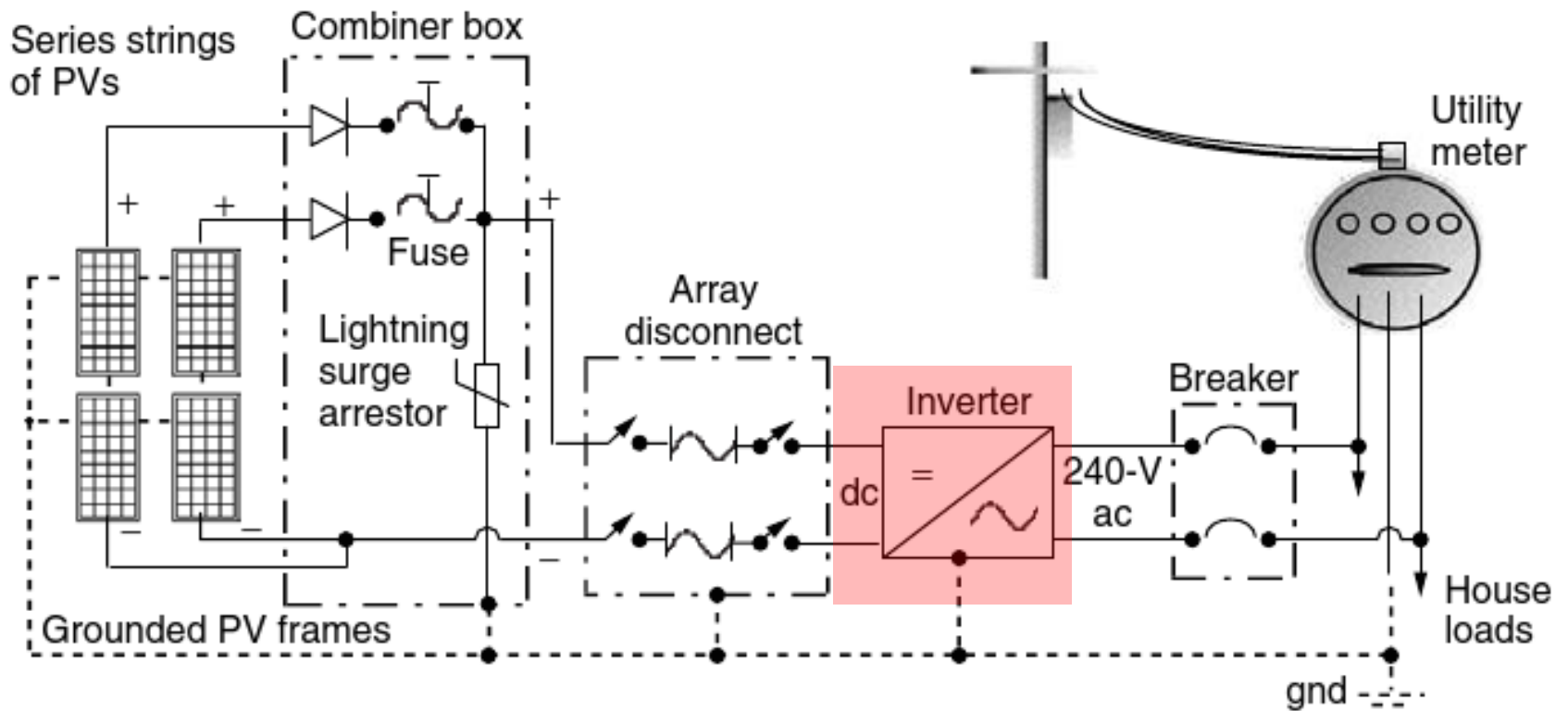

Case (b)

Impact of Partial Shading on PV system Power

Note shadow of power pole at the bottom left

Array Power Rating: 0.150x12x8 = 14.4 kW

Impact of partial shade by utility pole

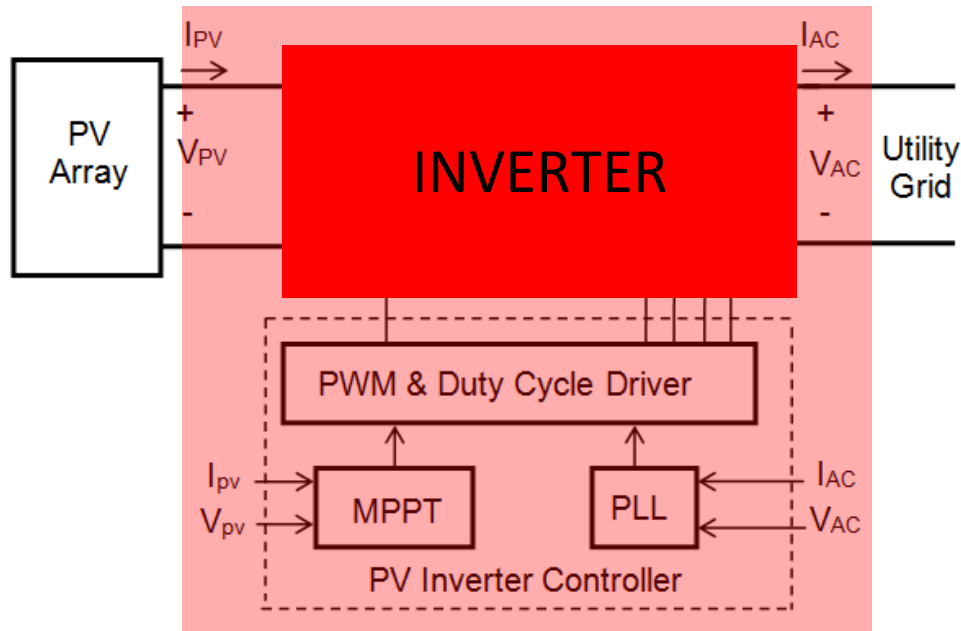# Components of a residential grid-connected PV system
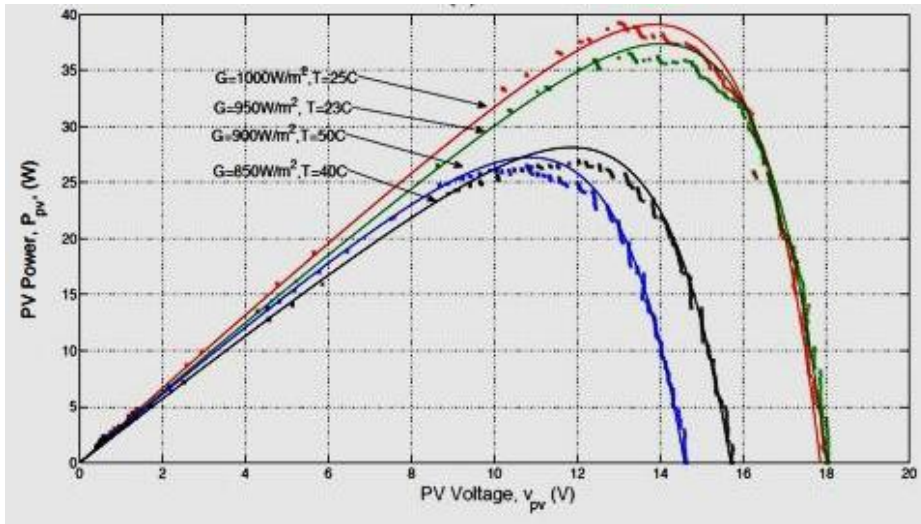
Grid-Tied PV Inverters

Grid-tied inverters

- monitor the PV array and track the maximum power and operate at that point,
- sense the presence of the grid, synchronize to it, and inject a current in phase with the voltage,
- monitor the grid and disconnect in case of trouble (e.g., large swings in voltage or frequency).
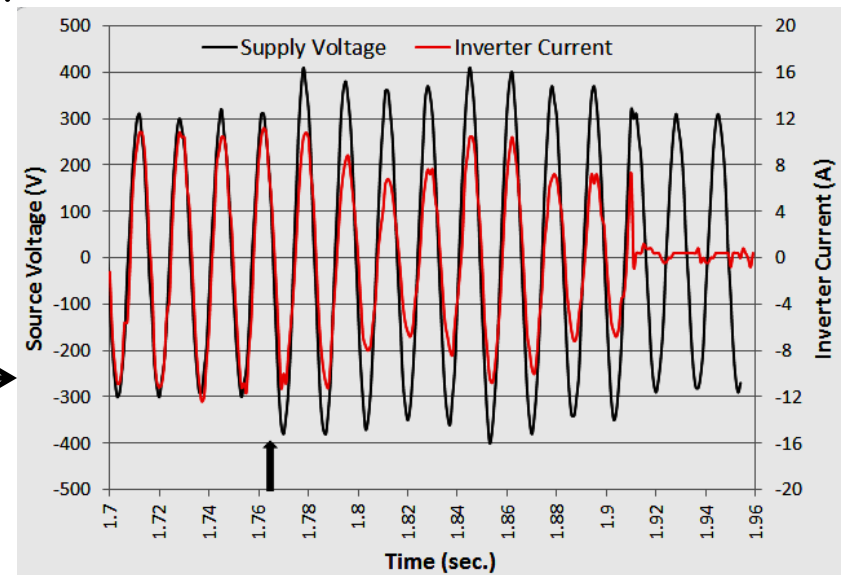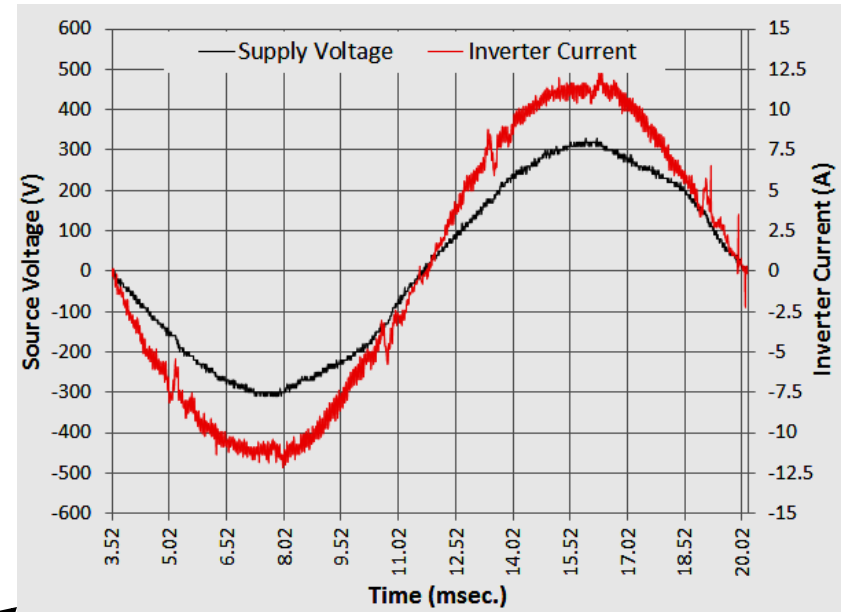
Functions of Grid-Tied PV Inverters

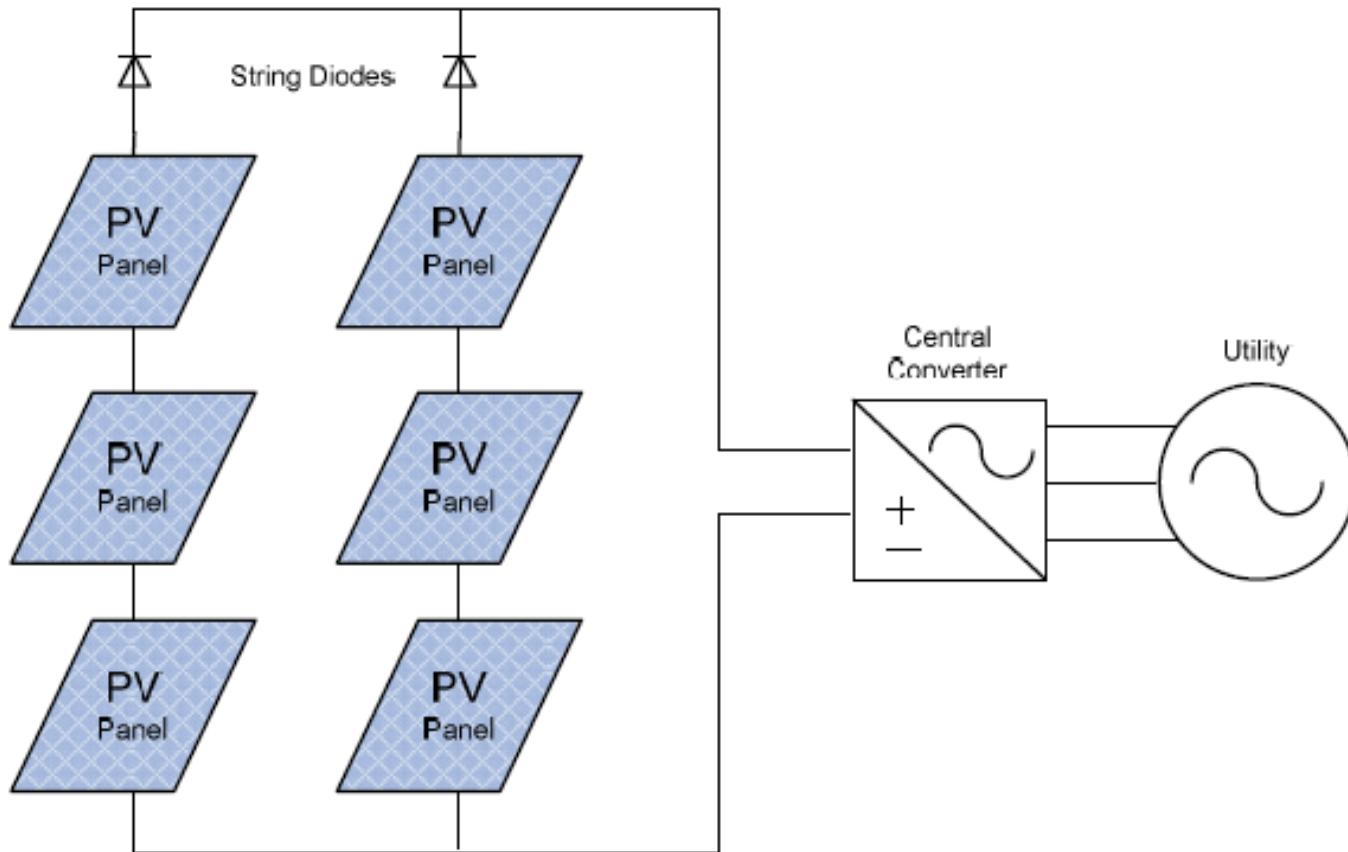

Maximum Power Tracking

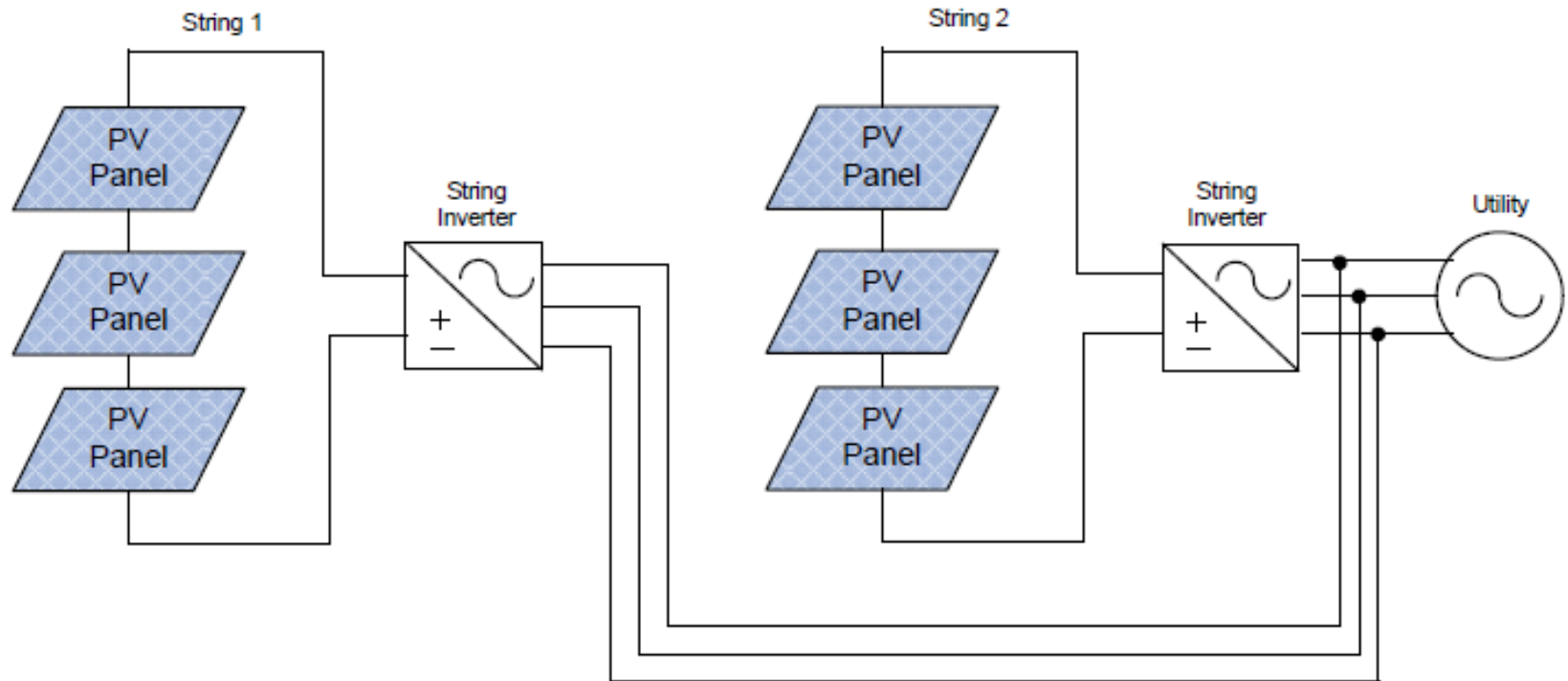Grid synchronization

Grid Monitoring - Disconnect

Centralized PV inverter configuration

- Lower cost, less reliable (single point of failure), more losses due to string diodes.
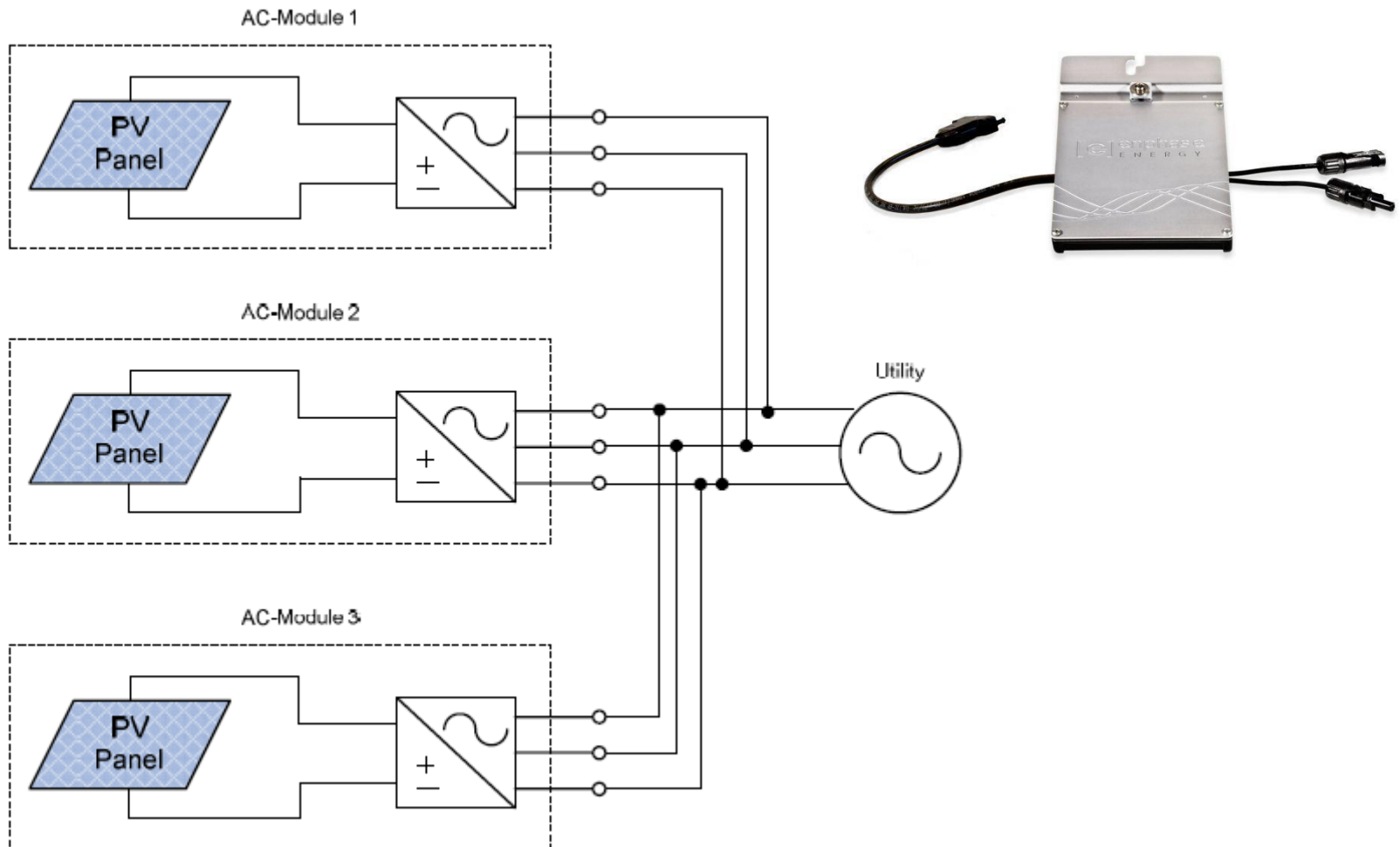
PV panels in strings with individual inverters

- Increased cost, higher reliability, no additional losses from string diodes.

Panels with individual inverters

- Most costly, highest reliability, easy expansion.

Single-phase single-stage inverter

- The capacitor on the DC side is used as a buffer and to limit current distortion.
- The full-bridge converter converts the DC voltage to AC by PWM. A PLL is used to synchronize with the utility voltage.
- The LC filter reduces the harmonic content of the inverter output signals
- The PV array is connected to the utility grid through an electrical isolation transformer. A bulky low frequency transformer is required in this situation.
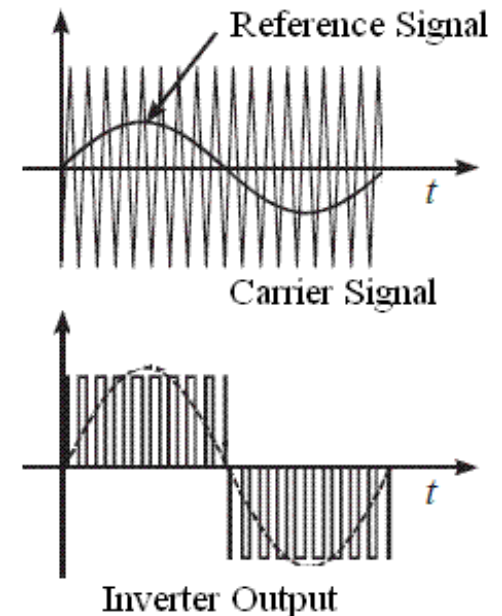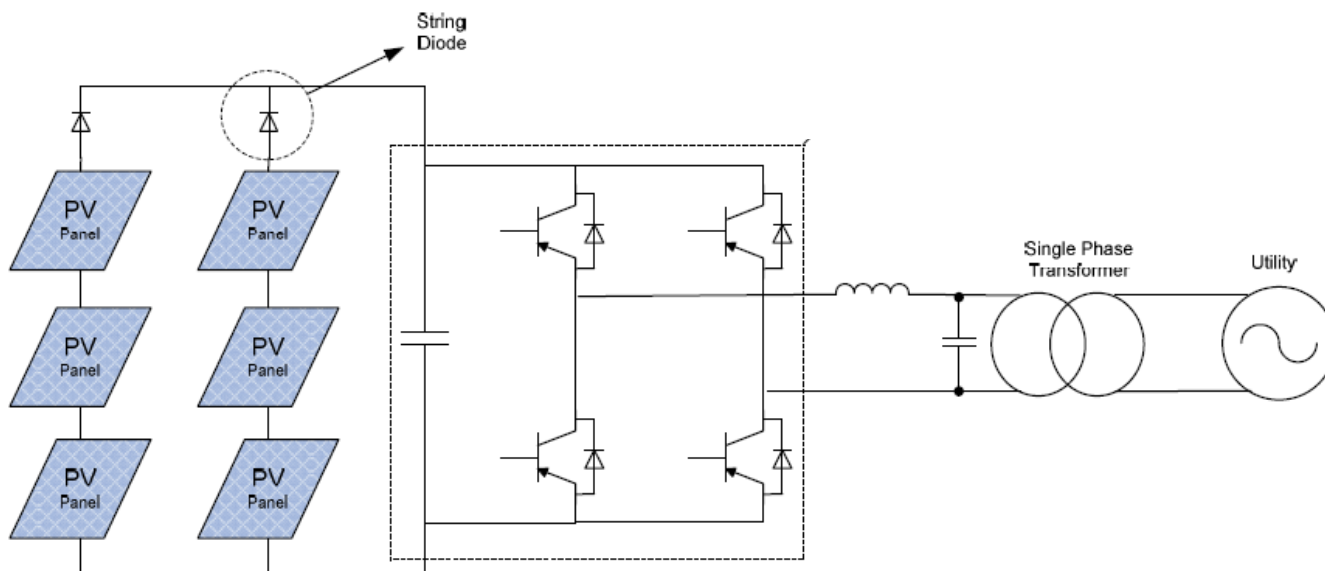
Three-phase single-stage inverter

- For larger systems over 10 kW, three-phase inverters are most often used.
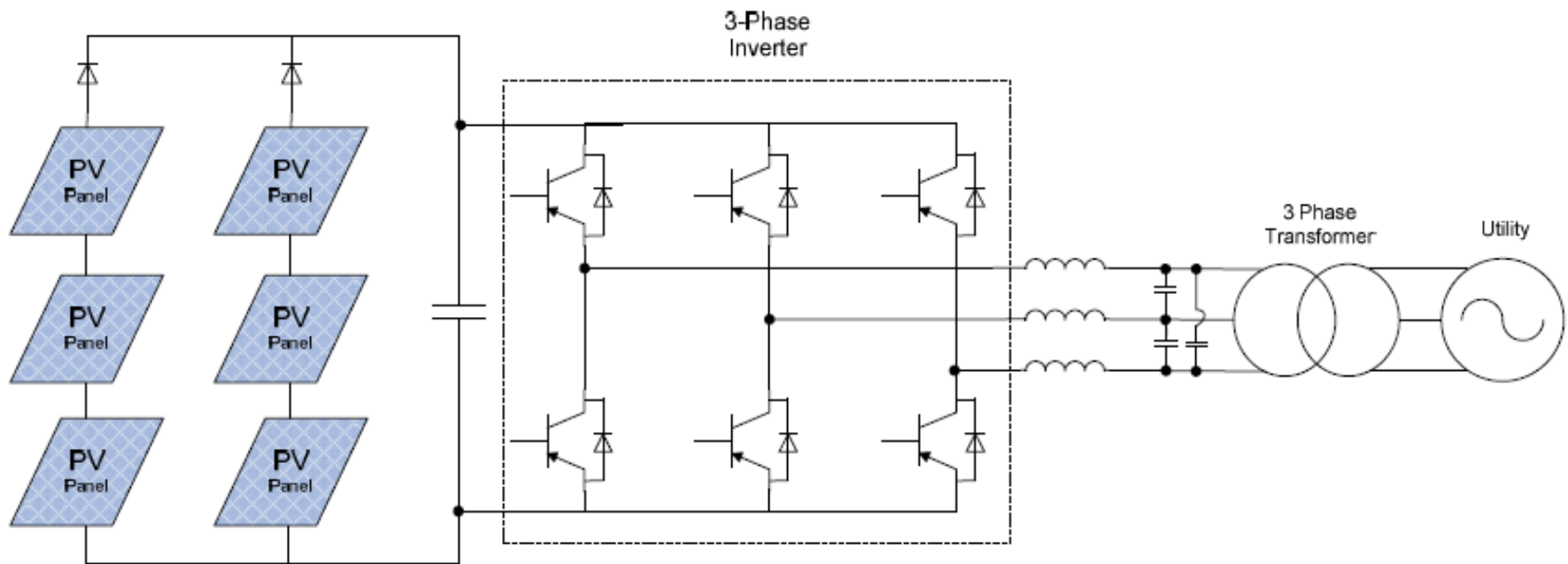
Single-phase multi-stage inverter

- The inverter converts DC to high-frequency AC, then back to low-frequency AC.
- The high-frequency transformer is more efficient and much lighter that the low-frequency transformer.
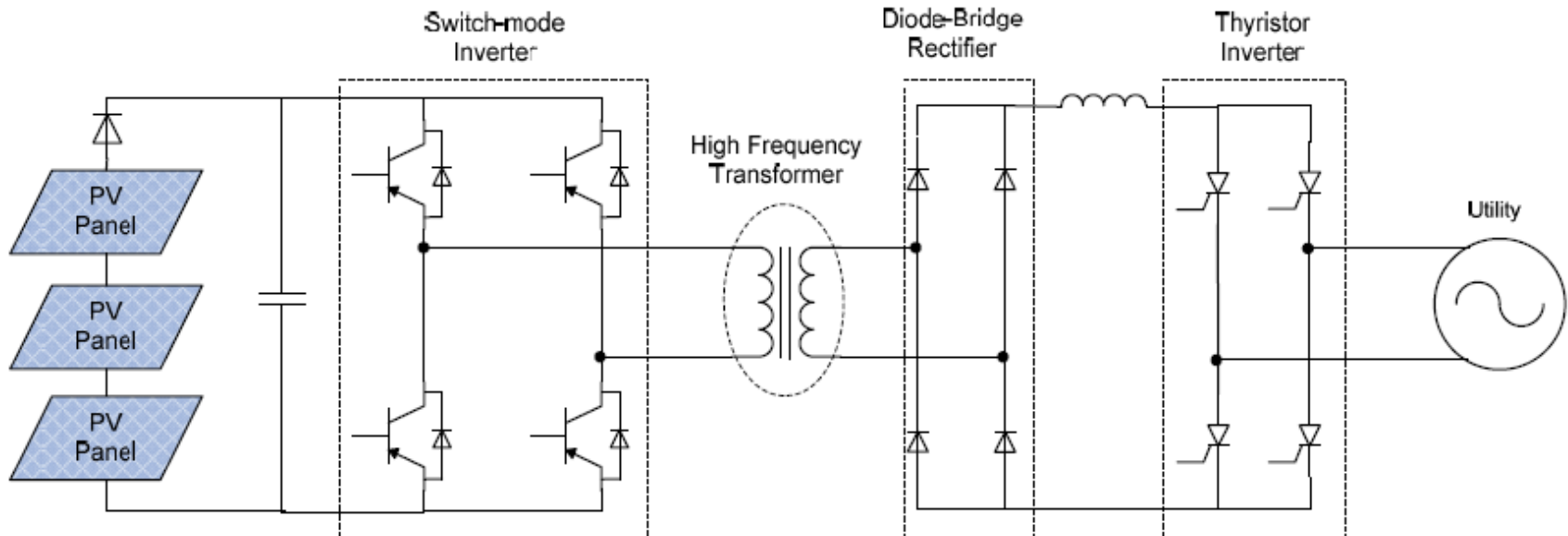
Transformless inverters

- Configurations without transformers can be used for the PV system. However, such topologies are more for European countries and Japan where system grounding is not mandatory for the PV inverters.

- In the United States, the National Electrical Code (NEC) - Article 690 - requires that the PV modules be grounded (for VDC > 50 V).

Typical Inverter specifications

Technical data	Sunny Boy 2000HF-US	
	208 V AC	240 V AC
Input (DC)		
Max. recommended PV power (@ module STC)	2500 W	
Max. DC power (@ cos φ = 1)	2200 W	
Max. DC voltage	600 V	
DC nominal voltage	480 V	
MPP voltage range	175 – 480 V	
Min. DC voltage / start voltage	175 V / 220 V	
Max. input current / per string	15 A / 15 A	
Number of MPP trackers / fused strings per MPP tracker		
Output (AC)		
AC nominal power	2000 W	
Max. AC apparent power	2000 VA	
Nominal AC voltage / adjustable	208 V / ●	240 V / ●
AC voltage range	183 – 229 V	211 – 264 V
AC grid frequency; range	60 Hz; 59.3 – 60.5 Hz	
Max. output current	9.6 A	8.3 A
Power factor (cos φ)	1	
Phase conductors / connection phases	1 / 2	
Harmonics	< 4%	
Efficiency		
Max. efficiency	97.3%	

Inverter Efficiency

- The efficiency of the inverter depends on the output power


Efficiency curve SUNNY BOY 3000HF-US
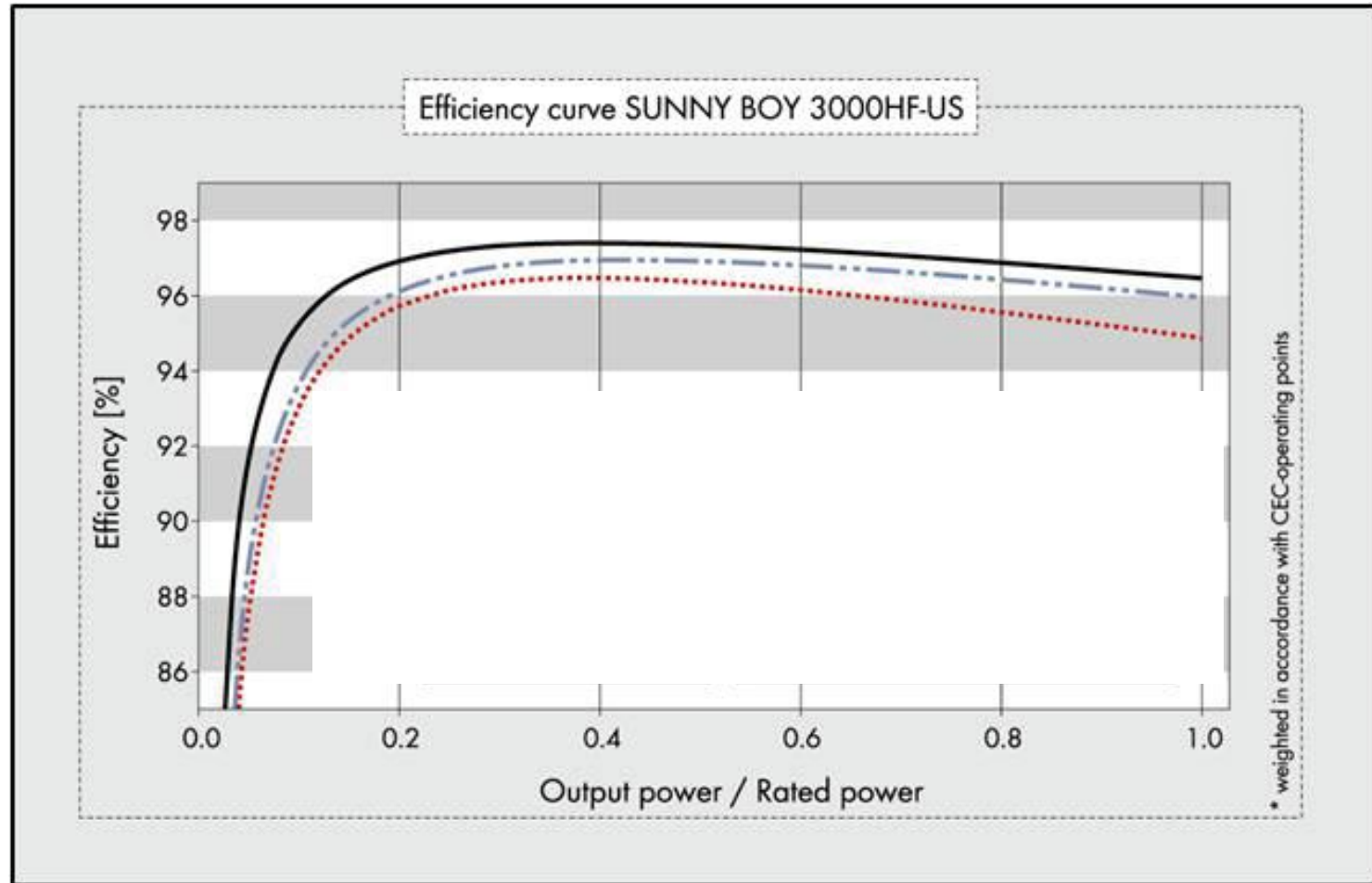
Maximum Power Point Tracking (MPPT)

- Tracking the maximum power point of a PV array is an essential task of the inverter. Due to its simplicity, the perturb-and-observe (P&O) algorithm is perhaps the most commonly used in practice for MPP tracking.

  – It is based on the fact that when the DC voltage is perturbed by a small increment dV, a change in dP takes place due to the nonlinear I-V characteristic of a photovoltaic array.

  – Based on the sign of dP, the voltage is then perturbed up or down and the process is repeated until maximum power is reached. Perturbations are repeated on a periodic basis.
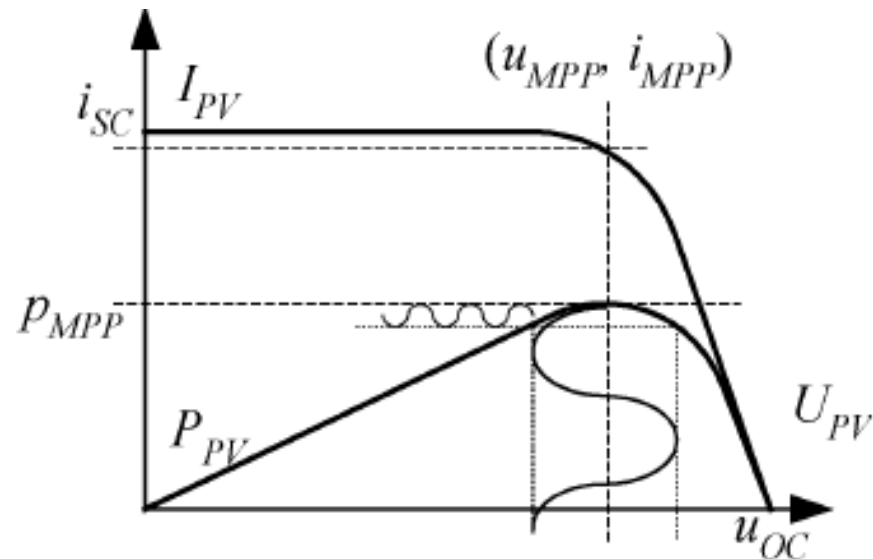
Measured voltage and currents fluctuations due to MPPT based on P&O method
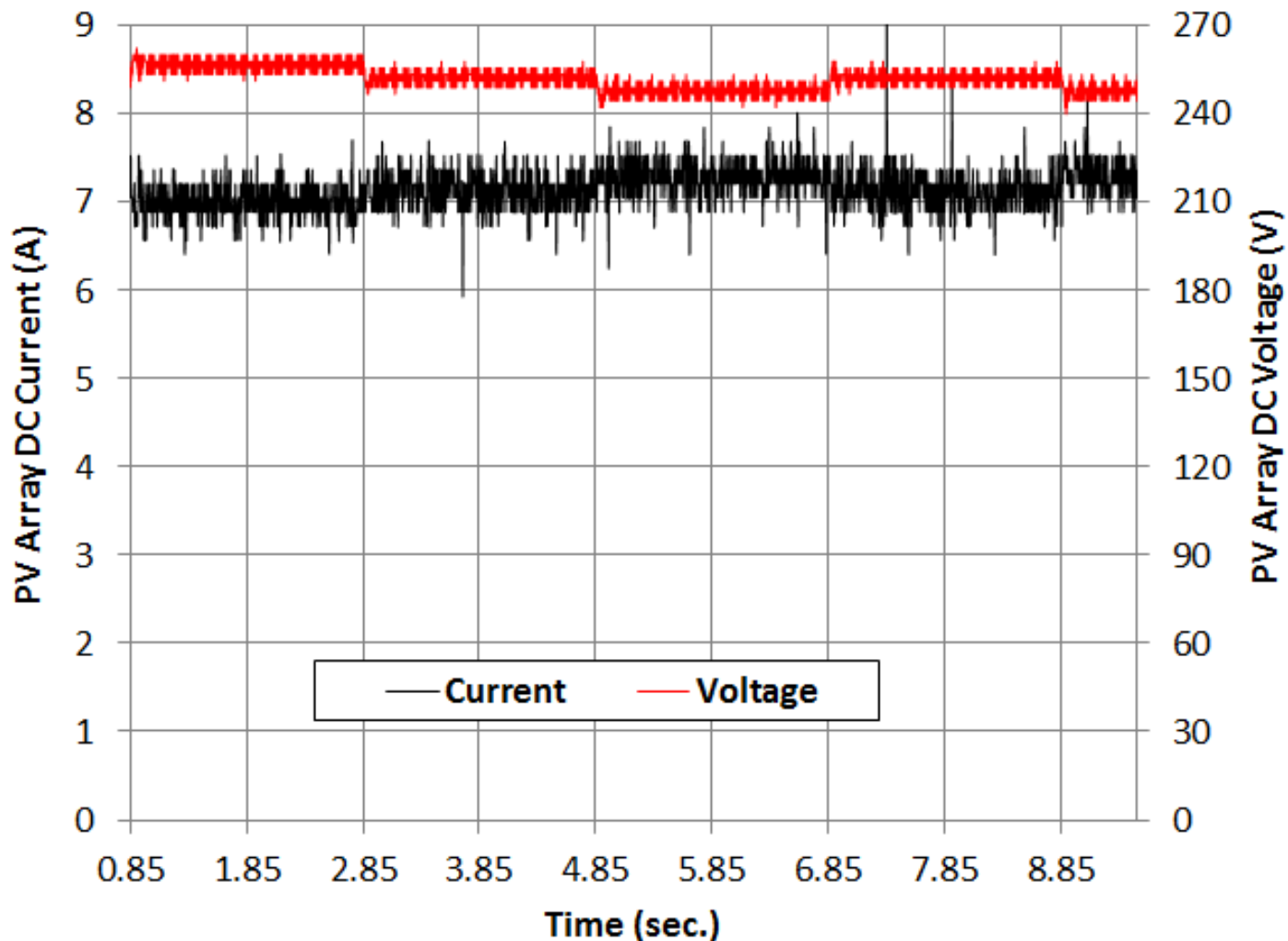
Unity vs non-unity power factor operation

- Current interconnection requirements prohibit inverters from providing reactive power (i.e., must operate at unity power factor), but this trend is changing.

- Modern inverters can supply reactive power (Q) to the system but this capability has quantifiable boundaries:

  – If no power is being produced by the PV array (as in the early evening), an inverter can use its entire rating to supply Q.

  – When the PV array is producing its full rated power, the inverter has no Q capability unless it is intentionally oversized.

- It is important to recognize that moderate oversizing results in significant Q capacity.
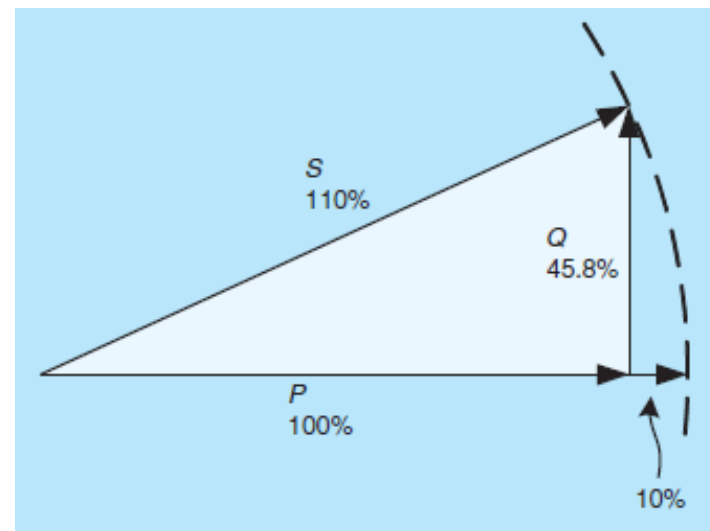
AC Rated Power

- The AC rated power of a grid-connected PV array is defined as

$$P_{ac} = P_{dc,STC} \text{ x (Conversion Efficiency)}$$

  - where $P_{dc,STC}$ is the dc power of the array obtained by simply adding the individual module ratings under standard test conditions.
  - The conversion efficiency accounts for inverter efficiency, dirty collectors, mismatched modules, and differences in ambient conditions. The impact of the above losses can easily de-rate the power output by 25%.
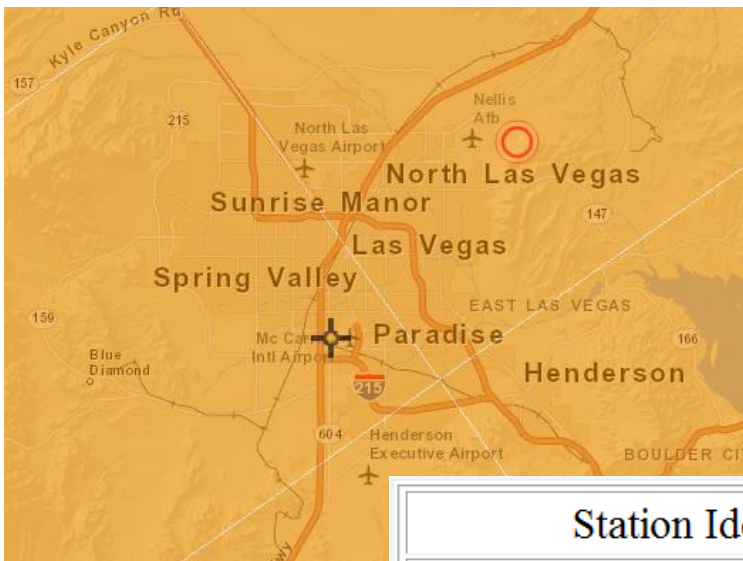
Useful Tool: PV-Watts
http://www.nrel.gov/rredc/pvwatts/grid.html

PV Watts

A Performance Calculator for Grid-Connected PV Systems

PV-Watts performs an hour-by-hour calculation using TMY weather data, with corrections for things such as the PV module temperature's impact on PV efficiency and inverter efficiency as a function of power generation.

Example of 2 kW PV system Performance in North Las Vegas using PVWATTS.

Station Identification	
Cell ID:	0184360
State:	Nevada
Latitude:	36.3 ° N
Longitude:	115.0 ° W
PV System Specifications	
DC Rating:	2.00 kW
DC to AC Derate Factor:	0.800
AC Rating:	1.60 kW
Array Type:	Fixed Tilt
Array Tilt:	36.3 °
Array Azimuth:	180.0 °
Energy Specifications	
Cost of Electricity:	13.0 ¢/kWh

Results

Month	Solar Radiation (kWh/m²/day)	AC Energy (kWh)	Energy Value ($)
1	5.03	239	31.07
2	5.67	237	30.81
3	6.40	292	37.96
4	6.87	302	39.26
5	6.94	301	39.13
6	6.93	282	36.66
7	6.90	284	36.92
8	6.95	289	37.57
9	6.93	284	36.92
10	6.45	286	37.18
11	5.48	245	31.85
12	4.89	232	30.16
Year	6.29	3274	425.62

Variability and Uncertainty of PV Power

- Photovoltaic resources differ from conventional and fossil-fired resources in a fundamental way: their fuel (sunlight) cannot presently be controlled or stored.

- There are two major attributes of variable generation that notably impact the bulk power system planning and operations:

  - **Variability:** The output of variable generation changes according to the availability of sunlight, resulting in fluctuations in the plant output on all time scales.

  - **Uncertainty:** The magnitude and timing of variable generation output is less predictable than for conventional generation.

Variability and Uncertainty of PV Power

- As indicated earlier, power system planners and operators are already familiar with designing a system which can be operated reliably while containing a certain amount of variability and uncertainty, particularly as it relates to system demand.

- However, large scale integration of variable generation can significantly alter familiar system conditions due to unfamiliar and increased supply variability and uncertainty.

without PV

with large scale PV
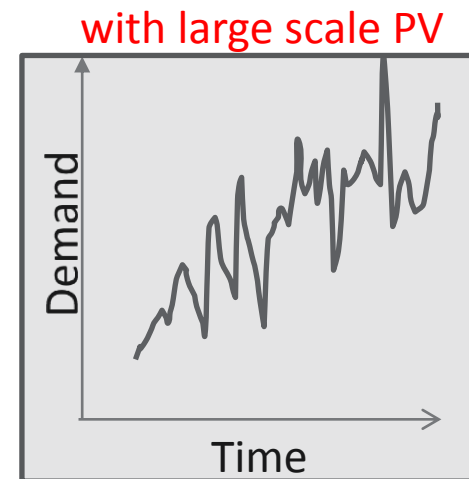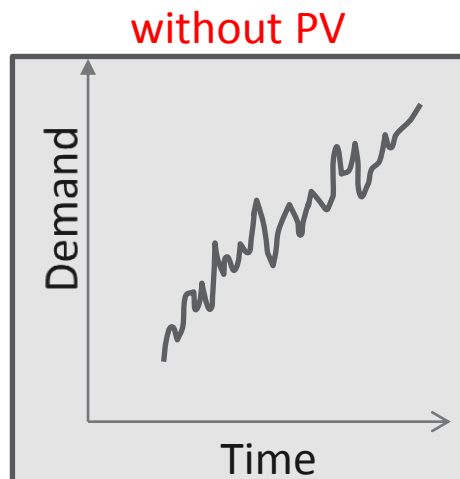
PV Power Variability

Display of power generated by a small PV array on two different days in February.

- Red curve: large power production fluctuations on a cloudy day,
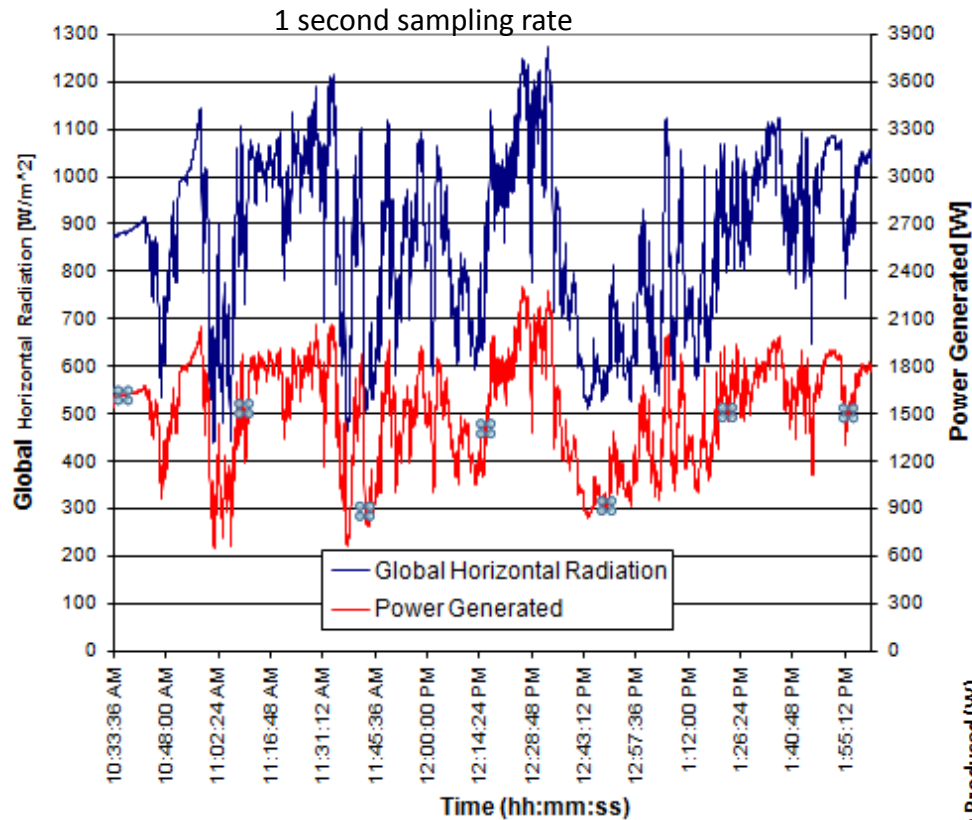- Black curve: smooth power production on a clear day.
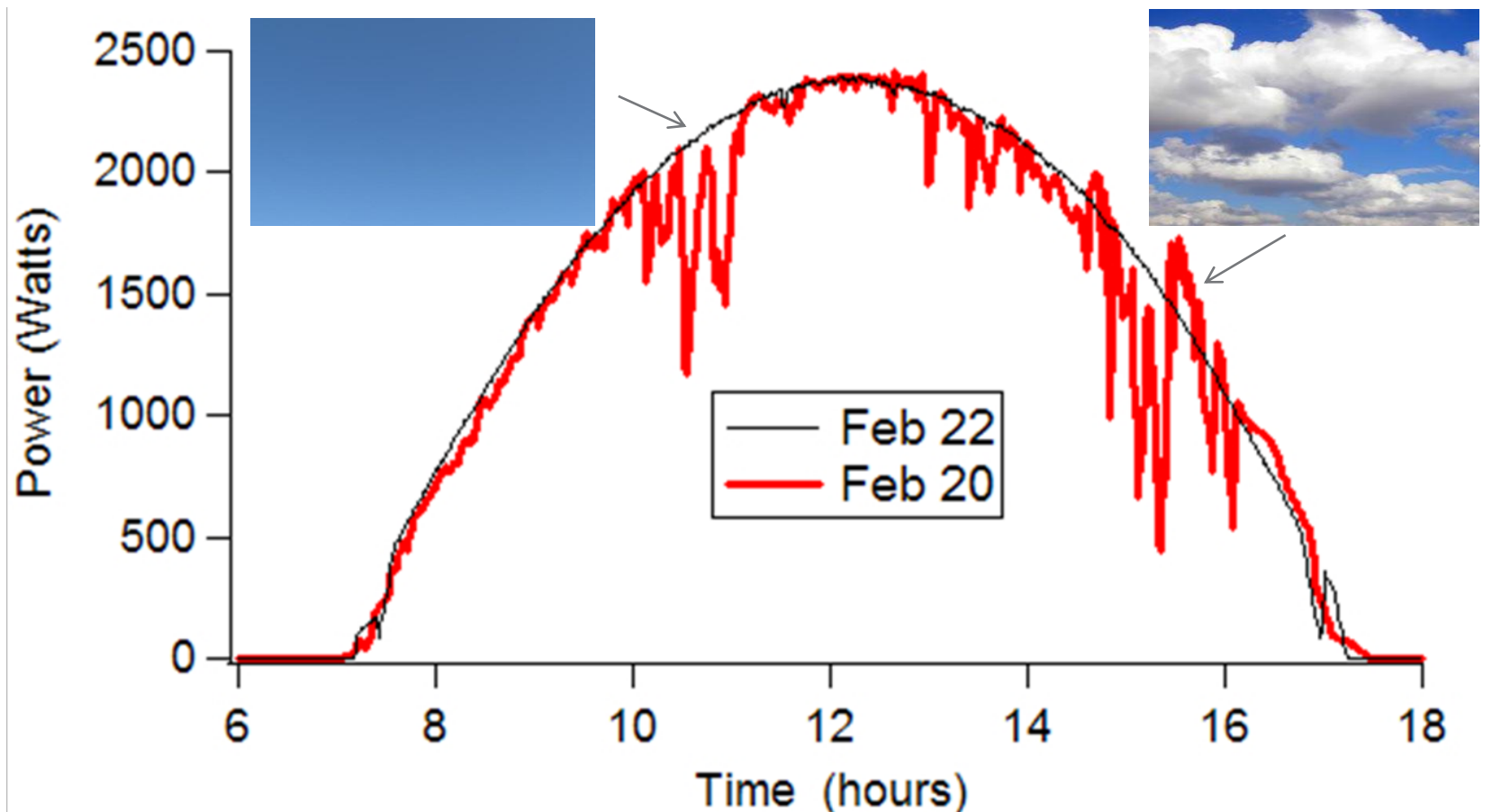
PV Power variability of a local 14 MW plant

Due to lack of inertia, PV power can change by up 50% in 0.5-1.5 minute time frame, and by up to 70% in 2-10 minute time frame, many times per day!
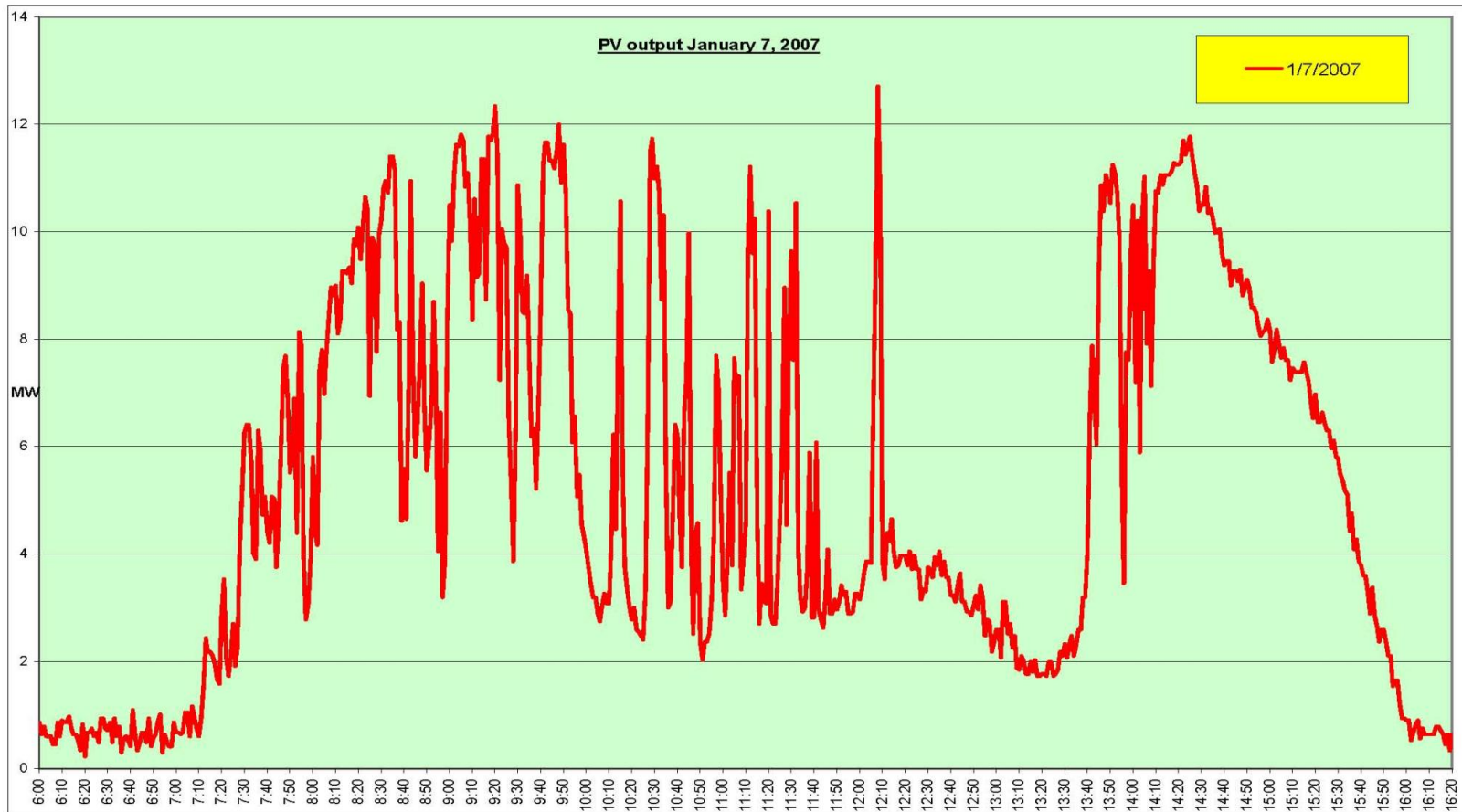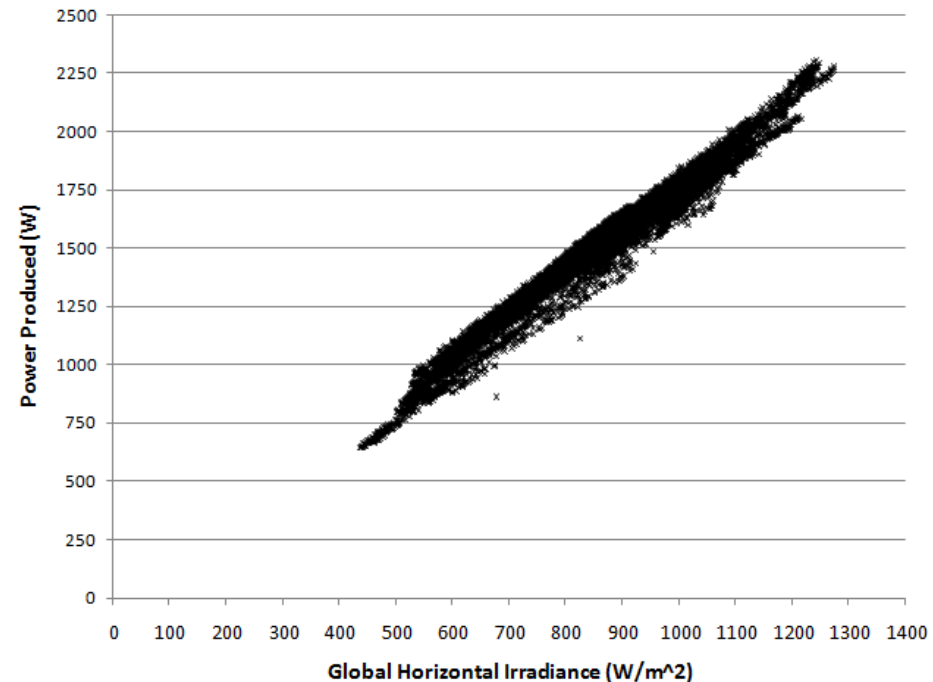
Relation between solar irradiance and power produced by a small PV system on a cloudy day


1 second sampling rate

≈ 4 hours

In a small PV system, global solar irradiance and power production are stronly correlated (Correlation Coefficient ≈ 1)

Relation between solar irradiance and power produced by a large (6 MW) PV system on cloudy day

The power is proportional to the spatial average irradiance of several sensors, rather than the reading of a single sensor.
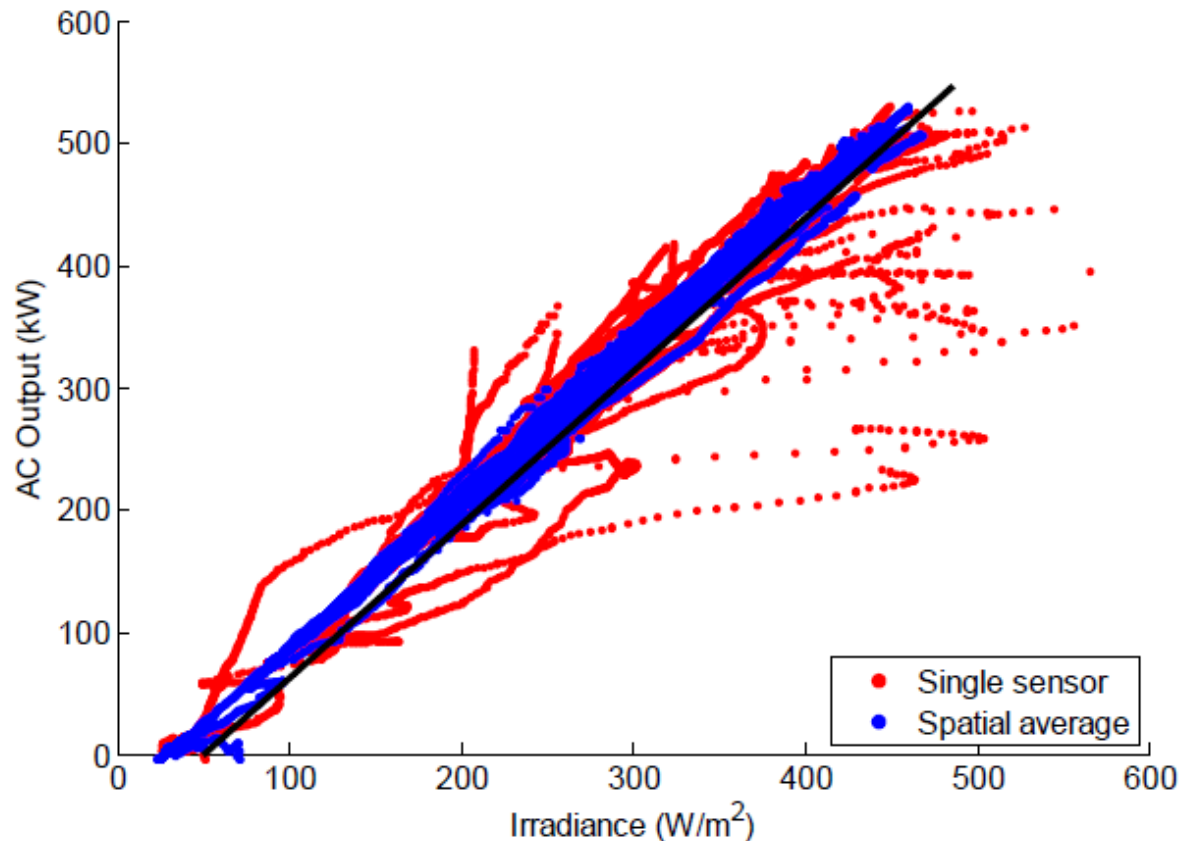
Source: Kuszmaul, S., A. Ellis, J. Stein, L. Johnson, *Lanai High-Density Irradiance Sensor Network for Characterizing Solar Resource Variability of MW-Scale PV System*, 35th IEEE PVSC, Honolulu, HI, 2010

Correlation in power output of different inverters within a large PV plant on cloudy day

- 1-min changes in the output of inverters are nearly perfectly correlated for close inverters.
- Inverters far apart within the same plant show correlation coefficients between simultaneous 1-min changes in output that drop as low as 0.1
- The magnitude of the reduction in the maximum 1-min change in output therefore depends on the size of the plant. Increasing the plant size increases the relative reduction in 1-min changes in plant output.


Source: NREL

Solar generator variability loses correlation as the time frame of interest decreases and the geographical spread increases
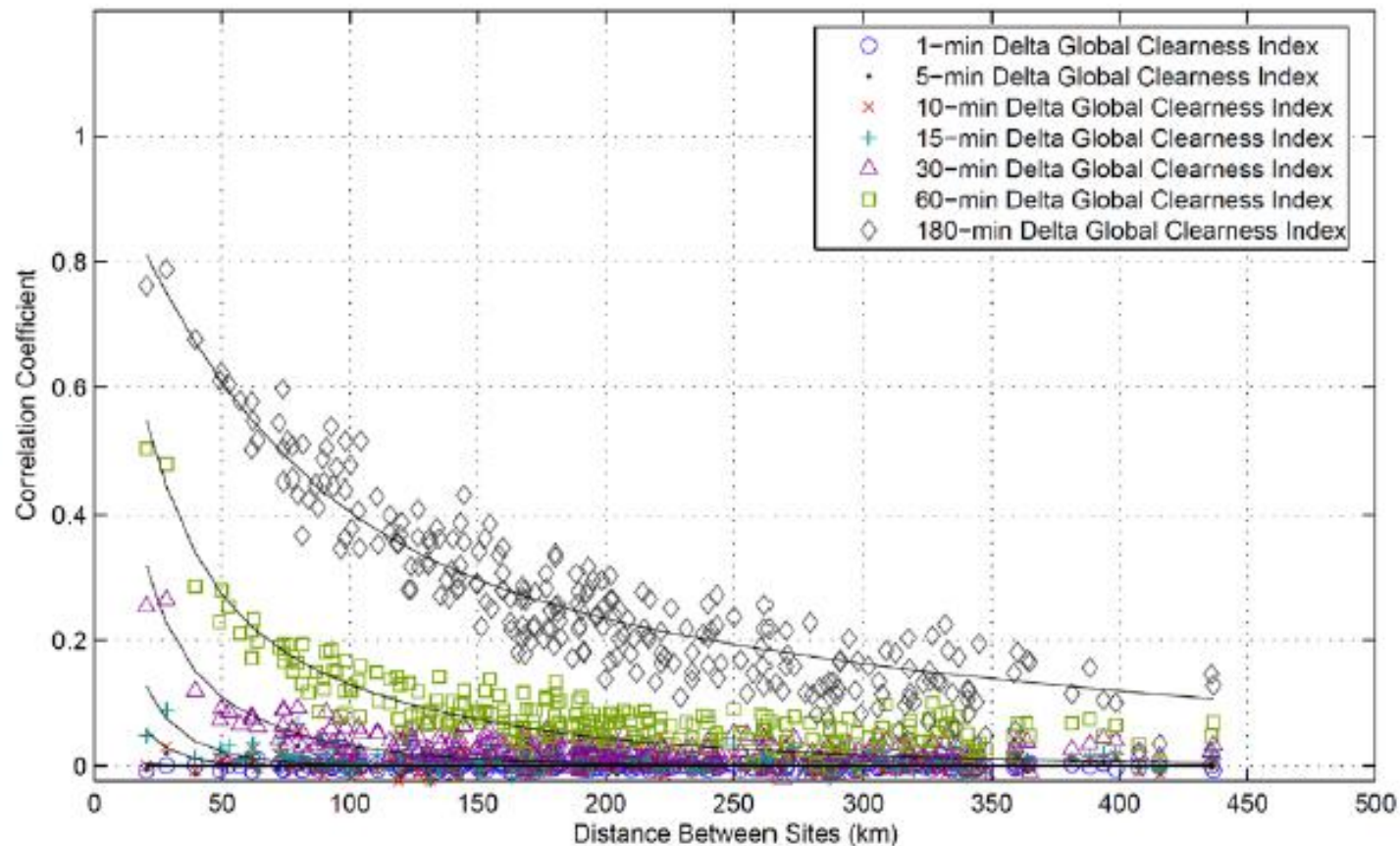

Source: Mills, A. et al, Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System, The Electricity Journal, December 2009.

Comparison of variations in PV and solar thermal power (30 miles apart)

The PV plant shows significantly more variability than a CSP plant (without storage). CSP has inherent short-term storage in the form of thermal inertia of the hot circulating fluid.
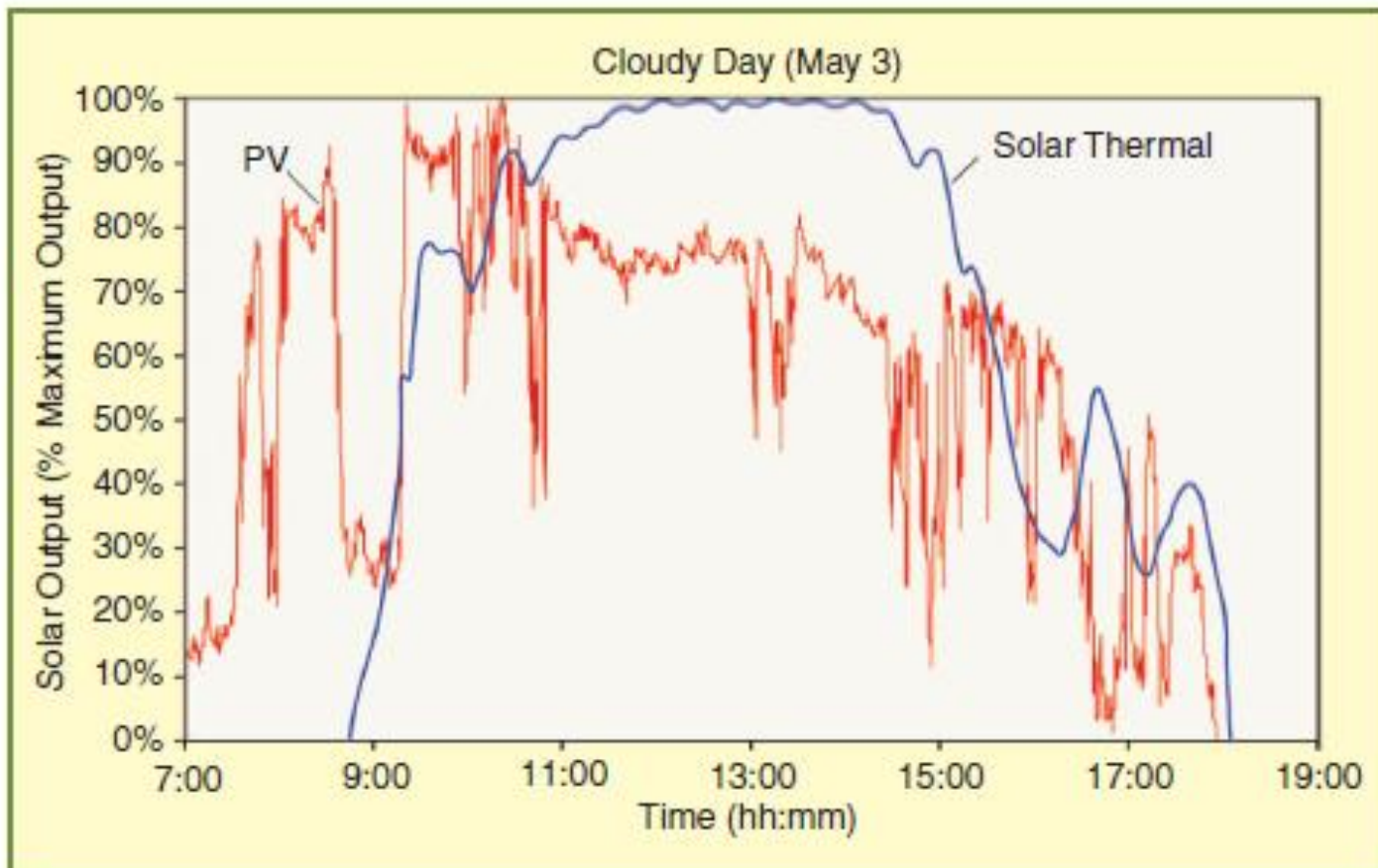
# Solar variability is influenced by cloud type, size, and speed
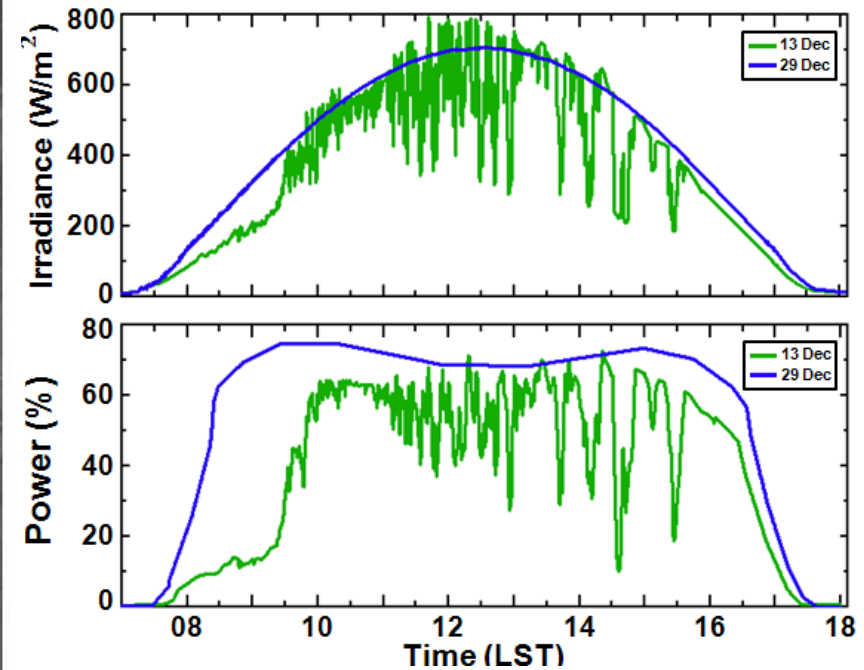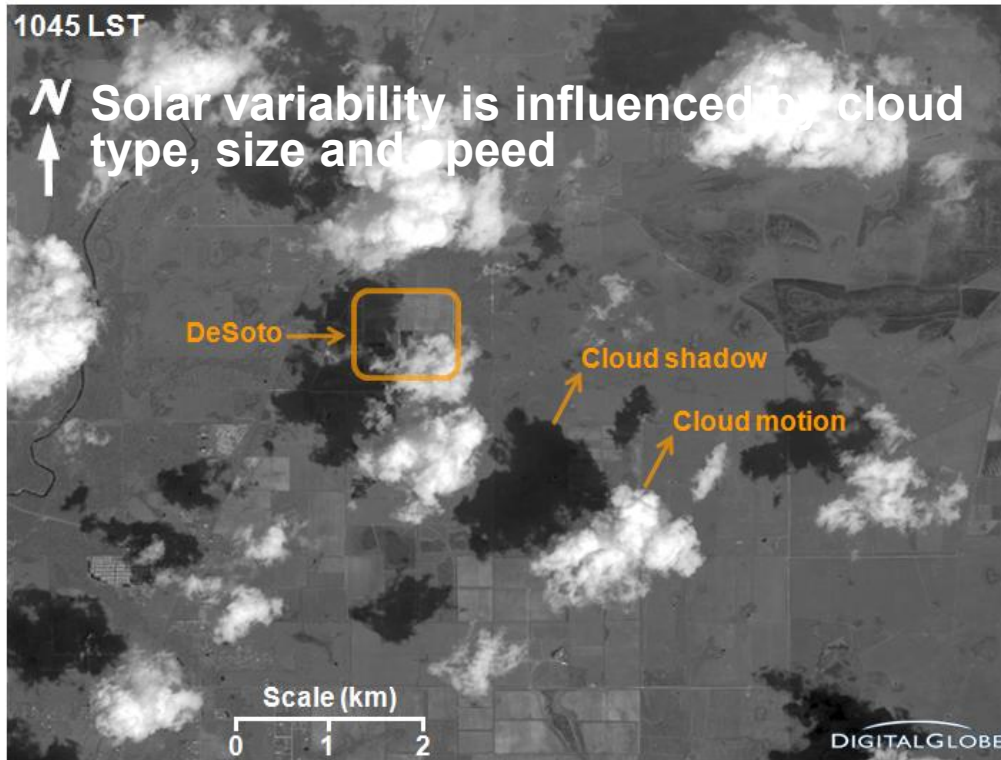
Example of clouds over the DeSoto PV Site (Central Florida)
System Type: Single-Axis Tracking
System Rating: 25 MW

Solar Power Forecasting

- Clouds are largest influence on variability and forecasting
  - Can see coherent patterns of motion for "stable" clouds.
  - Convective events ("unstable" clouds) are more challenging to predict.
  - Newer, higher resolution weather models are showing promise.
- Satellite-based cloud resources are available to guide short term solar forecasts (an advantage over wind forecasting)
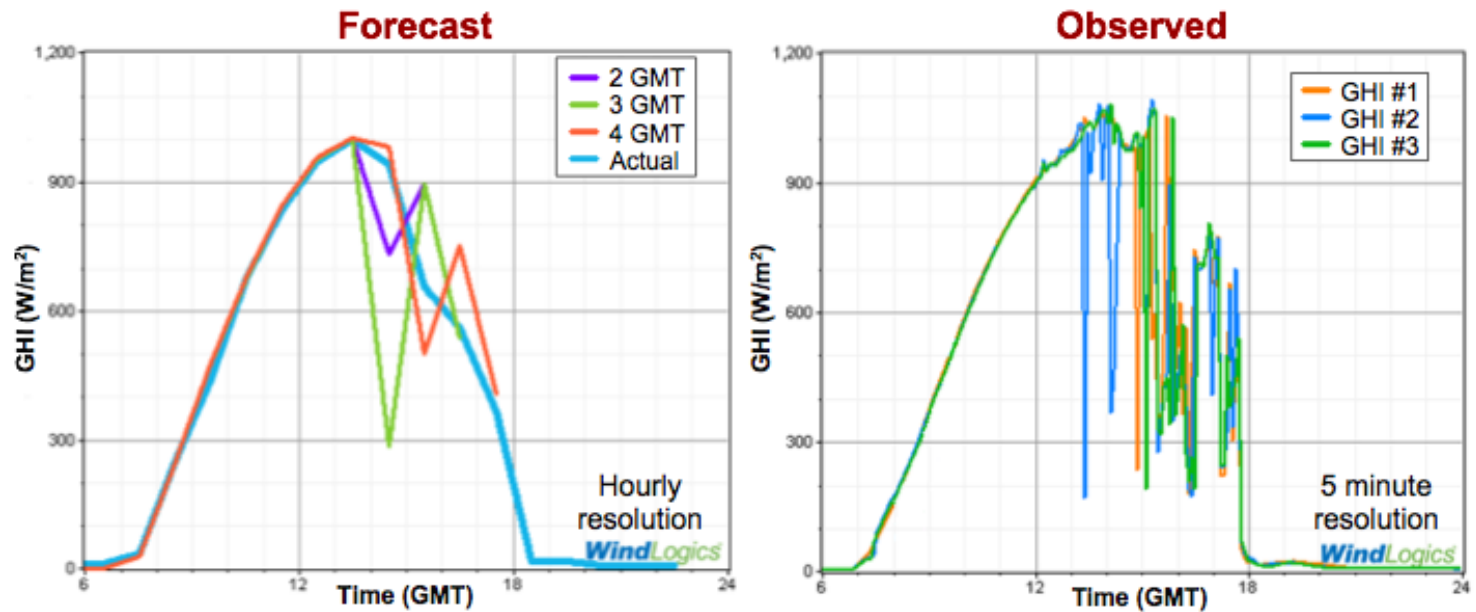
The NOAA HRRR is a 3-km resolution, hourly updated, cloud-resolving atmospheric model

Break!