Characteristics of PV Power Systems

Yahia Baghzouz
UNLV
Las Vegas, NV, USA
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 $\lambda$ (m), and frequency $f$ (Hz):
  \[ f = \frac{c}{\lambda} \]
  where $c$ is the speed of light: $c = 3 \times 10^8$ m/sec.
- Note that photons can be described by either their wavelength, their frequency, or their energy
  \[ E = hf = \frac{hc}{\lambda} \]
  Where $h$ is Planck’s constant ($= 6.626 \times 10^{-34}$ J-s).
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
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 $\beta$.
  - 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.

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

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

"top" of atmosphere
Spectrum shifts towards longer wavelengths.
Sun declination angle $\delta$

- 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 $L$:

\[
\sin \beta = \sin \delta \sin L + \cos \delta \cos L \cos H
\]

\[
\sin \phi = \frac{\cos \delta \sin H}{\cos \beta}
\]
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
Bogota, Columbia

Sun path diagram: [http://solardat.uoregon.edu/](http://solardat.uoregon.edu/)
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

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

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 \( \theta \):** 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:

\[
I_{BH} = I_B \cos(90^\circ - \beta) = I_B \sin \beta
\]
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 $\rho$ 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 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.
TMY3 data sets for 1020 stations
Live Local Data: http://www.nrel.gov/midc/unlv/

August 17, 2012

Current:
- Global Horizontal: -2.0 W/m²
- Direct Normal: -0.2 W/m²
- Diffuse Horizontal: 0.0 W/m²

Daily Total:
- Global Horizontal: 6.754 kWh/m²
- Direct Normal: 6.608 kWh/m²
- Diffuse Horizontal: 2.148 kWh/m²
Band gap energy

• The band-gap $E_g$ for silicon is $1.12 \, \text{eV}$ (where $1 \, \text{eV} = 1.6 \times 10^{-19} \, \text{J}$). 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 $\lambda > 1.11 \, \mu\text{m}$ have energy less than the $1.12 \, \text{eV}$ needed to excite an electron. Hence, their energy is wasted and just heats the cell.
  – photons with $\lambda < 1.11 \, \mu\text{m}$ have more than enough energy to excite an electron. Any extra energy above the $1.12 \, \text{eV}$ needed is also dissipated as waste heat in the cell.
Band gap and cut-off wavelength of common photovoltaic materials: Silicon (Si), gallium arsenide (GaAs), cadmium telluride (CdTe), indium phosphide (InP).
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 25°C,

\[ I = I_{SC} - I_0 \left[ e^{38.9(V + IR_S)} - 1 \right] - \frac{1}{R_P} (V + IR_S) \]
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.
Cells connected in series

- When photovoltaics are wired in series, they all carry the same current, and their voltages add. The overall module voltage \( V_{\text{module}} \) is found by:

\[
V_{\text{module}} = n(V_d - IR_S)
\]

where \( n \) is the number of cells in series.
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 cell temperature is 25° C.

<table>
<thead>
<tr>
<th>Standard Test Conditions (STC)</th>
<th>STC = 1000 W/M² irradiance, 25°C module temperature, AM 1.5 spectrum*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KD230GX-LPB</td>
</tr>
<tr>
<td>$P_{mp}$</td>
<td>230</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>29.8</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>7.72</td>
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<tr>
<td>$V_{oc}$</td>
<td>36.9</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>8.36</td>
</tr>
<tr>
<td>$P_{tolerance}$</td>
<td>+5/-3</td>
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</table>
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.
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/m², air temp. = 20°C, wind speed = 1 m/s, mounting = open back side.
Power rating under NOCT (PVUSA)

- Approximate formula for calculating cell temperature:

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>KD230GX-LPB</th>
<th>KD235GX-LPB</th>
<th>KD240GX-LPB</th>
<th>KD245GX-LPB</th>
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<tbody>
<tr>
<td>Temperature Coefficients</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$P_{\text{max}}$</td>
<td>-0.45</td>
<td>-0.46</td>
<td>-0.46</td>
<td>-0.46</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>-0.51</td>
<td>-0.52</td>
<td>-0.52</td>
<td>-0.52</td>
</tr>
<tr>
<td>$I_{mp}$</td>
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<td>0.0065</td>
<td>0.0064</td>
<td>0.0065</td>
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<tr>
<td>$V_{oc}$</td>
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<td>-0.36</td>
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<td>-0.36</td>
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<tr>
<td>$I_{sc}$</td>
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<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>Operating Temp</td>
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<td>-40 to +90</td>
<td>-40 to +90</td>
<td>-40 to +90</td>
</tr>
<tr>
<td></td>
<td>%/°C</td>
<td>%/°C</td>
<td>%/°C</td>
<td>%/°C</td>
</tr>
</tbody>
</table>
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.
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.
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

Array Power Rating: 0.150x12x8 = 14.4 kW

Note shadow of power pole at the bottom left

Impact of partial shade by utility pole
Components of a residential grid-connected PV system
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 than 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

**Input (DC)**
- Max. recommended PV power (@ module STC)
- Max. DC power (@ cos φ = 1)
- Max. DC voltage
- DC nominal voltage
- MPP voltage range
- Min. DC voltage / start voltage
- Max. input current / per string
- Number of MPP trackers / fused strings per MPP tracker

**Output (AC)**
- AC nominal power
- Max. AC apparent power
- Nominal AC voltage / adjustable
- AC voltage range
- AC grid frequency; range
- Max. output current
- Power factor (cos φ)
- Phase conductors / connection phases
- Harmonics
- Efficiency
- Max. efficiency
Inverter Efficiency

• The efficiency of the inverter depends on the output power
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

\[ P_{ac} = P_{dc,STC} \times (\text{Conversion Efficiency}) \]

- 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

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.

<table>
<thead>
<tr>
<th>Station Identification</th>
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<tbody>
<tr>
<td>Cell ID:</td>
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<tr>
<td>State:</td>
</tr>
<tr>
<td>Latitude: 36.3 ° N</td>
</tr>
<tr>
<td>Longitude: 115.0 ° W</td>
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<table>
<thead>
<tr>
<th>PV System Specifications</th>
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<tr>
<td>DC Rating: 2.00 kW</td>
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<tr>
<td>DC to AC Derate Factor: 0.800</td>
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<tr>
<td>AC Rating: 1.60 kW</td>
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<tr>
<td>Array Type: Fixed Tilt</td>
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<tr>
<td>Array Tilt: 36.3 °</td>
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<tr>
<td>Array Azimuth: 180.0 °</td>
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<table>
<thead>
<tr>
<th>Energy Specifications</th>
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<td>Cost of Electricity: 13.0 ¢/kWh</td>
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<table>
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<tr>
<th>Month</th>
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<th>AC Energy (kWh)</th>
<th>Energy Value ($)</th>
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<td>425.62</td>
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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.
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

In a small PV system, global solar irradiance and power production are strongly correlated (Correlation Coefficient $\approx 1$)

$\approx 4$ hours
The power is proportional to the spatial average irradiance of several sensors, rather than the reading of a single sensor.

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.

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.
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!