Block 6: Field Data and Performance Monitoring

34553: Applied Photovoltaics

Outline

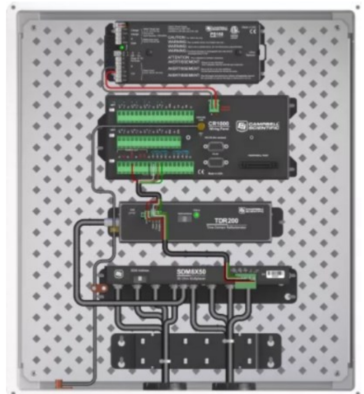
- Intro to PV monitoring
  - Equipment and sensors (IEC 61724-1)
  - Capacity Evaluation (IEC 61724-2)
    - Performance Index (PI)
- Performance Metrics
  - Performance Ratios / Specific Yield
- Degradation Rate (Rd)

The Building Blocks of a PV Monitoring System

- Equipment / *Sensors*
  - AC power / *transducers or inverter*
    - Nice to haves: DC data, voltage (Vmp) and current (Imp)
  - In plane irradiance / *pyranometer or reference cell*
  - Global horizontal irradiance / *pyranometer*
    - Nice to haves: DfHI, DNI
  - Back of module temperature / *RTD, TC etc.*
  - Ambient temperature and wind speed / *aspirated temp. sensor + anemometer*
    - Nice to haves: other meteo data such as rain fall, RH, soiling etc.

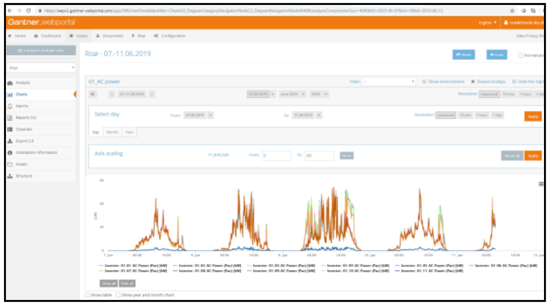
Sensor network

Analog and/or digital signals



Enclosure with data logging and transfer (SCADA)

Ethernet, Wi-Fi, 4G, or Satelite



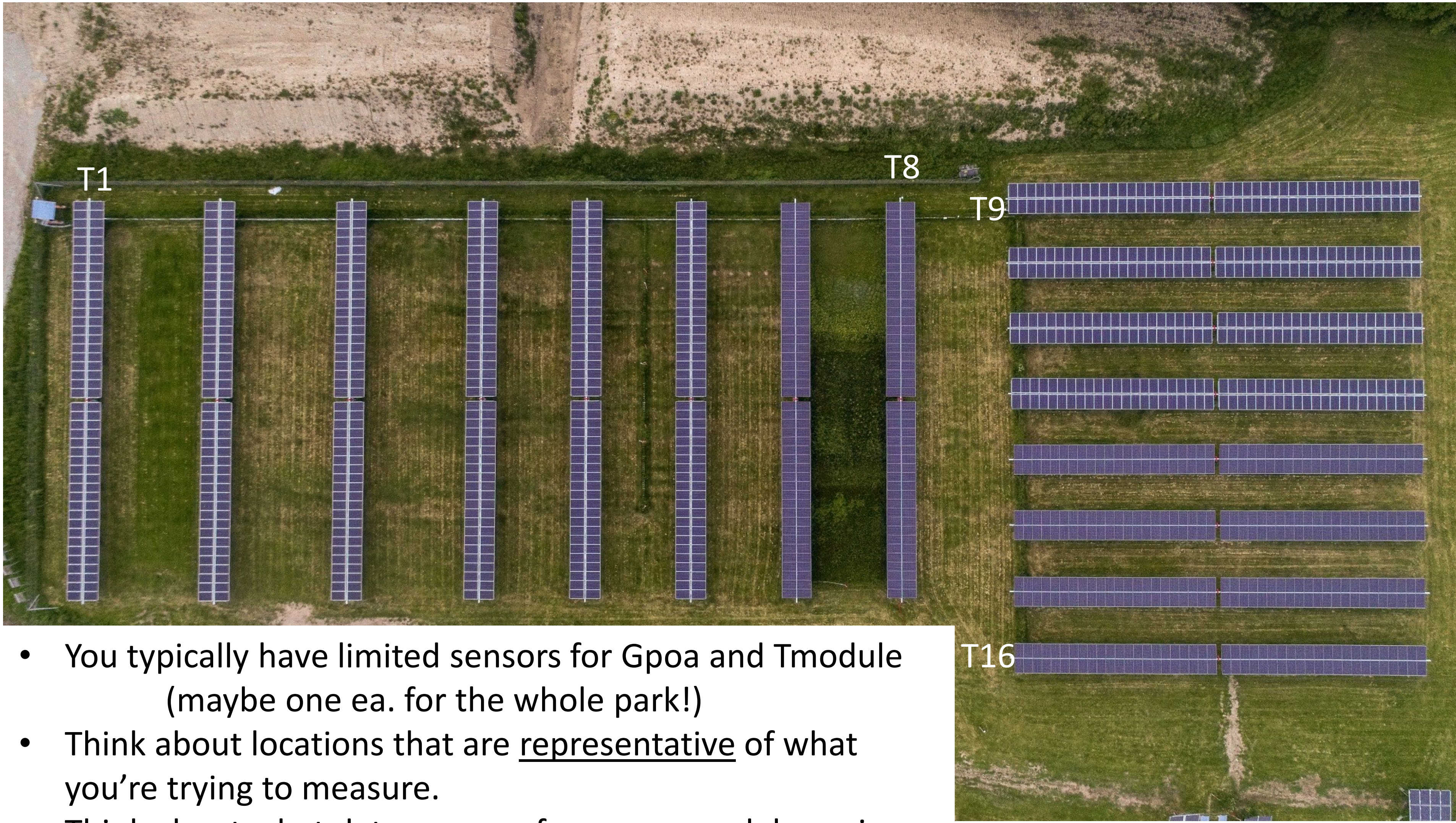
PV system analytics

Classifications of Monitoring Systems (IEC 61724)

- The accuracy and complexity of a monitoring system depends on customer needs and contractual terms.
  - Not only in terms of physical hardware, but calibration and cleaning schedules, and analytics.
- Three classes and guidelines are specified in IEC 61724
  - The more valuable the asset (utility scale), typically the higher the class.

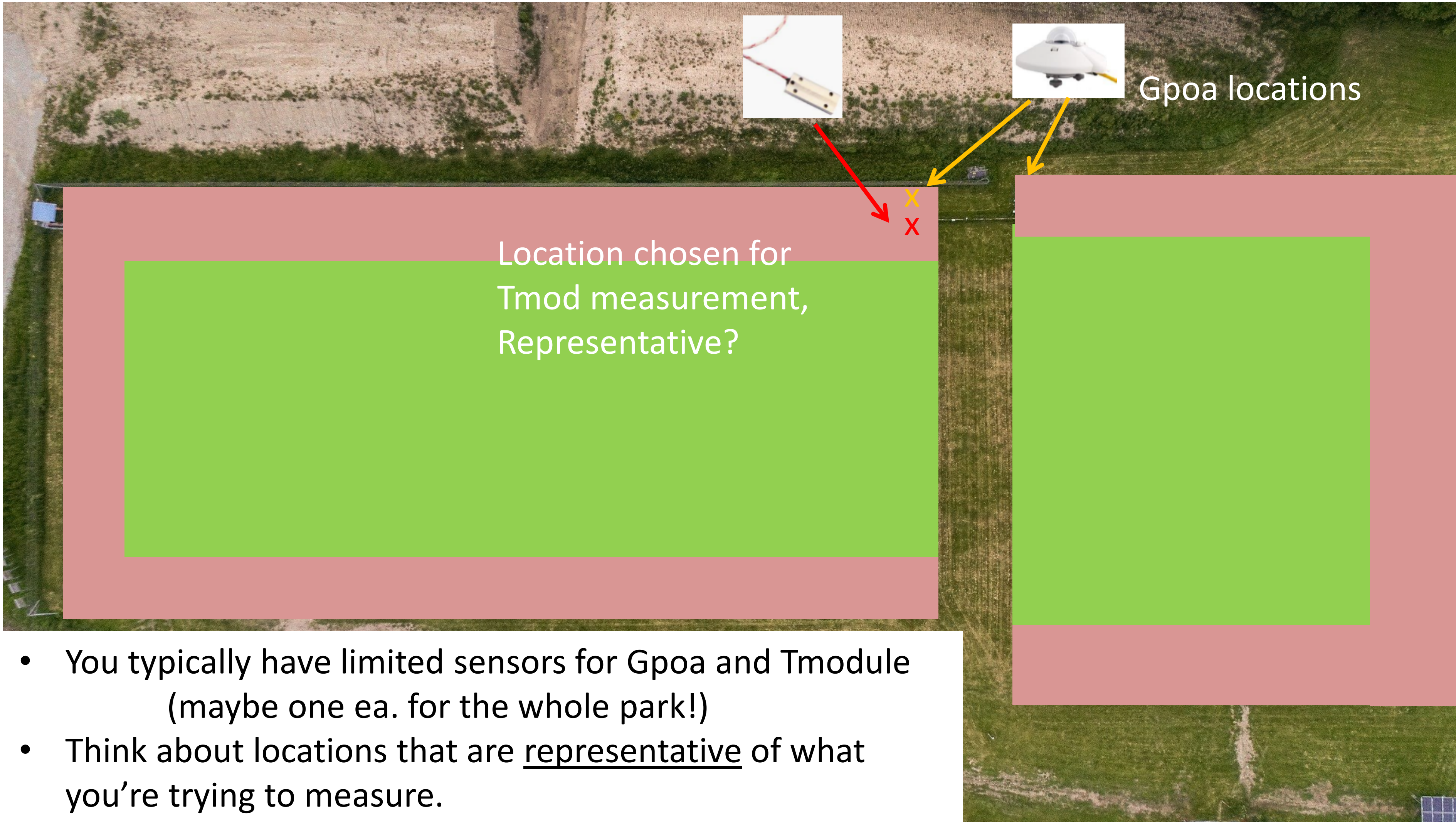
General Requirements	Class A System	Class B System	Class C System
Basic system performance assessment	x	x	x
Documentation of performance guarantee/performance index	x	x	
Fault localization	x	x	
Precise PV system degradation measurement	x		
System losses analysis	x		
Electricity network interaction assessment	x		

Where do the Meteorological Sensors Get Mounted???



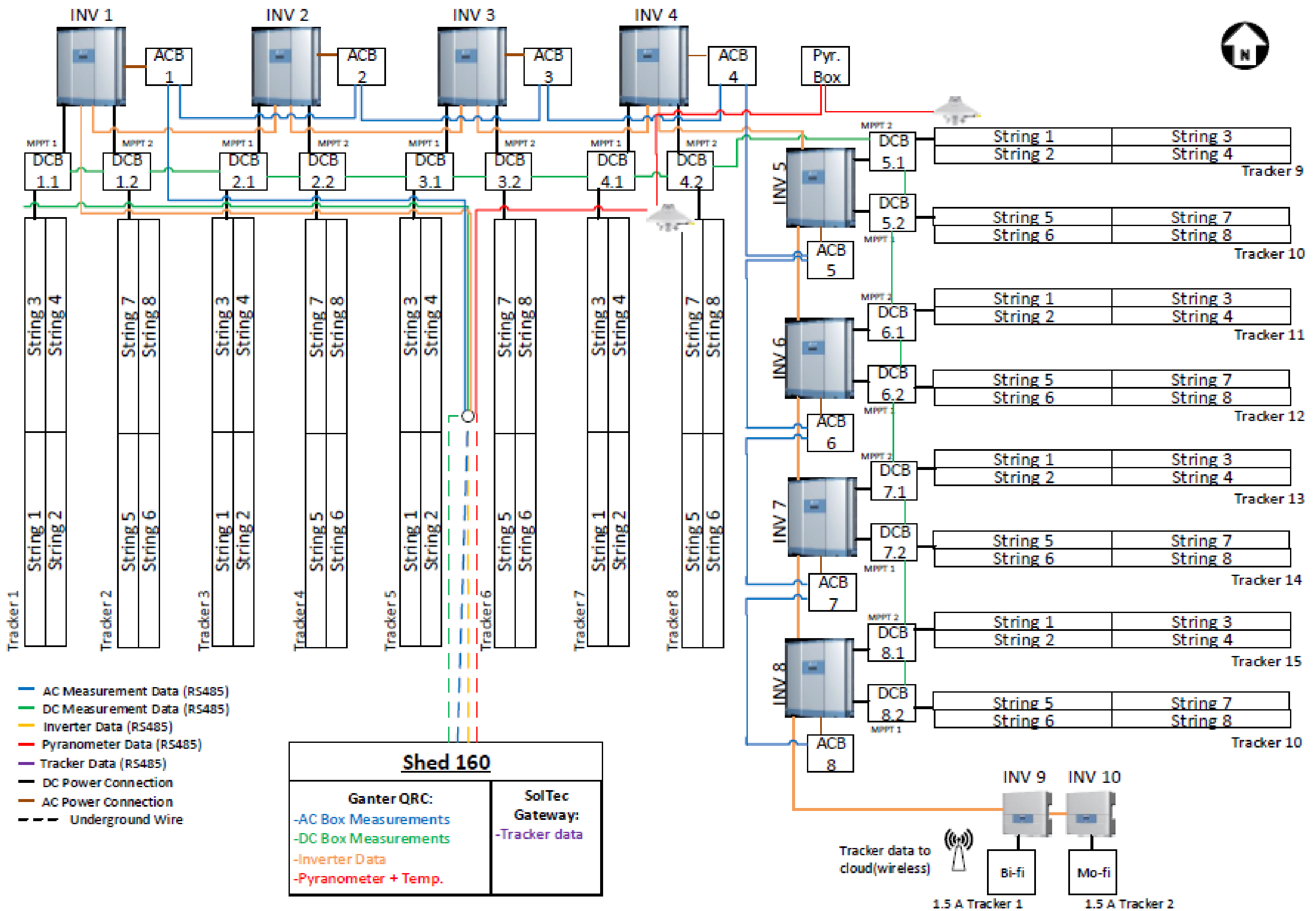
- You typically have limited sensors for Gpoa and Tmodule
  (maybe one ea. for the whole park!)
- Think about locations that are <u>representative</u> of what you're trying to measure.
- Think about what data your performance model requires:
  Eg: Albedo, wind speed (height), RH etc.

Where do the Meteorological Sensors Get Mounted???



- You typically have limited sensors for Gpoa and Tmodule
  (maybe one ea. for the whole park!)
- Think about locations that are <u>representative</u> of what you're trying to measure.
- Think about what data your performance model requires:
  Eg: Albedo, wind speed (height), RH etc.

Placement of Electrical Monitoring Sensors



Pyranometers or Reference Cells?

Pyranometers

- Thermoelectric principle
  - Not spectrally sensitive
- Slower response times
- Can be mounted in PV plane or horizontally
  - Better angular performance

Reference Cells

- Photovoltaic principle
  - Spectrally sensitive
- Fast response times
- Can be mounted <u>only</u> in PV POA
  - High reflection when AOI > 45°

Pyranometer Classification

Reference number	ISO Pyranometer Categories		
ISO 9060:2018 classification	Class C	Class B	Class A
1 Response time (95 %)	< 60 s	< 30 s	< 15 s
2 Zero offsets (a) (b)	± 30 W/m² ± 8 W/m²	± 15 W/m² ± 4 W/m²	± 7 W/m² ± 2 W/m²
3a Non-stability	± 3.0 %	± 1.5 %	± 0.8 %
3b Non-linearity	± 3 %	± 1 %	± 0.5 %
3c Directional response (for beam radiation)	± 30 W/m²	± 20 W/m²	± 10 W/m²
3d Spectral selectivity	± 10 %	± 5 %	± 3 %
3e Temperature response	8 %	4 %	2 %
3f Tilt response (leveling, NA to GHI)	± 5 %	± 2 %	± 0.5 %

- New nomenclature for classification is *Class A, B and C,*
- Less confusing than secondary standard as the highest class.
- Within Class A, B, or C sensors can be "**spectrally flat**" or "**fast response**".

Q to Class: Which is spectrally flat and which is fast response? Pyranometers or reference cells?

Additional Irradiance Measurements

Direct Normal Irradiance

Pyrheliometer on 2-axis tracker

Diffuse Horizontal Irradiance

Pyranometer shaded by shadow ball on 2-axis tracker

- Measurement of direct beam light using **5° FOV** collimation tube.
- They must point directly at the sun.

- DfHI is measured w/ a shadow ball or disc that shades the pyranometer with a **5° FOV.**
- Shadow bands can also be used.
    - Less accurate than disc/ball

Review of Transposition

- If we don't have irradiance data in the plane of array (POA) of interest, we can always estimate it from the irradiance data we have available.
  - At minimum we need GHI. But with more data (e.g. DfHI or DNI), comes better accuracy.

- There are many transposition models (see 34552), but we'll review the basic isotropic model.

$$GHI = DNI * \cos(\theta_z) + DfHI$$

Review of Transposition

$$G_{POA} = \boxed{DrHI * R_b} + \boxed{DfHI * \frac{1+\cos(\beta)}{2}} + \boxed{GHI * \rho_g * \frac{1-\cos(\beta)}{2}}$$

Where:
GHI = Global horizontal irradiance
DfHI = Diffuse horizontal irradiance
DNI = Direct normal irradiance
DrHI = Direct beam irradiance on a horizontal surface
β = Collector tilt angle
ρ_g = Ground albedo
R_b = Correction factor for beam component
θ = Angle of incidence

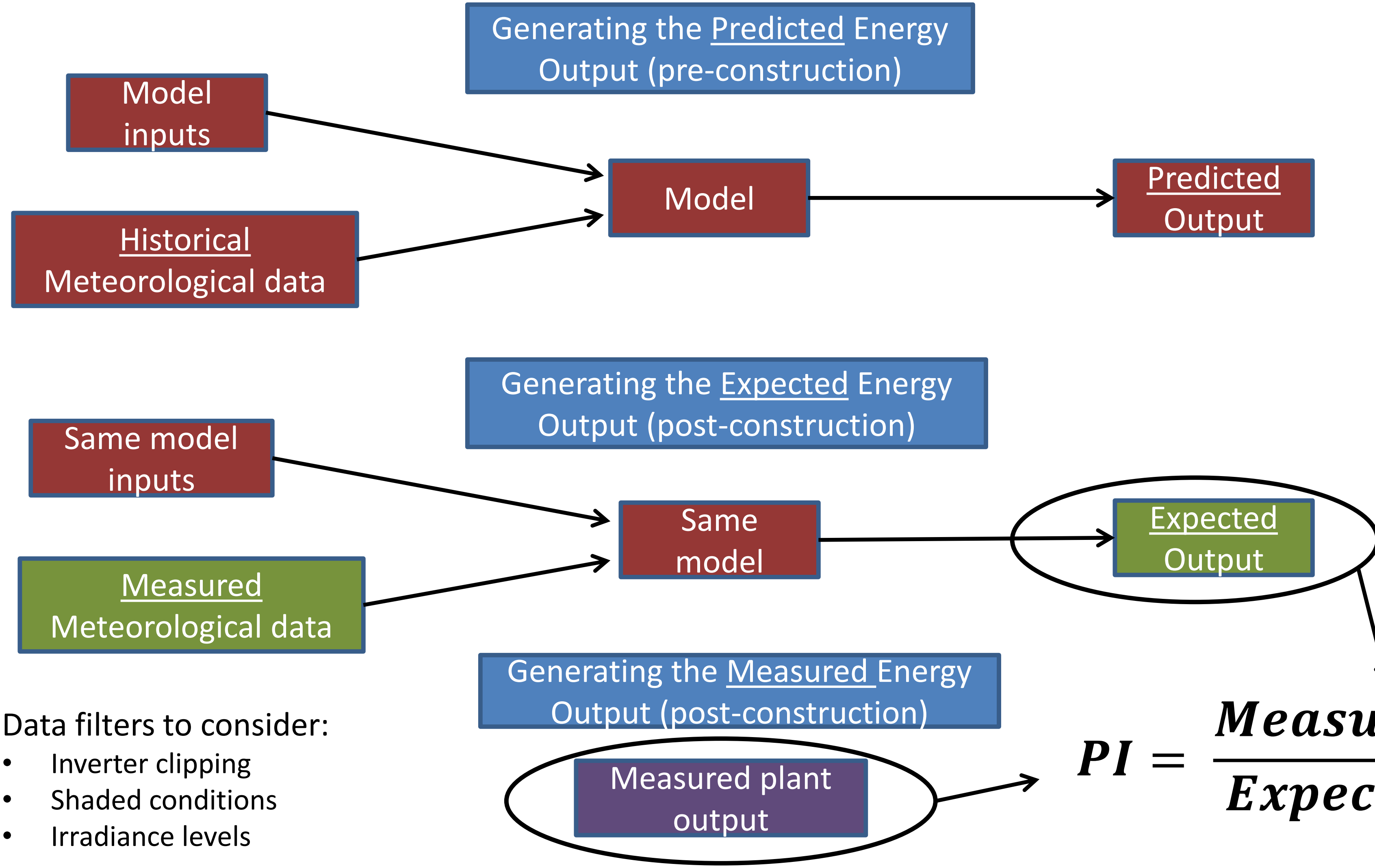
$$R_b = \frac{\cos(\theta)}{\cos(\theta_Z)}$$

The isotropic model is conservative (i.e. tends to underestimate G_{POA})

Outline

- Intro to PV monitoring
  - Equipment and sensors (IEC 61247-1)
  - Capacity Evaluation (IEC 61247-2)
    - Performance Index (PI)
- Performance Metrics
  - Performance Ratios / Specific Yield
- Degradation Rate (Rd)

Checking the Energy Performance Index (PI)



$$PI = \frac{\boldsymbol{Measured}}{\boldsymbol{Expected}}$$

Data filters to consider:

- Inverter clipping
- Shaded conditions
- Irradiance levels

Performance Ratios

- The PR is the ratio of the total AC energy generated by a PV system to the amount of energy it would have generated at STC conditions/efficiency.

$$PR = \frac{AC_{yield}[Wh]/STC_{Mpp}\ [W]}{G_{POA}\ [\frac{Wh}{m^2}]/1000\ [\frac{W}{m^2}]}$$

- Note that the PR is calculated over time (e.g. hours, days, months etc). The equation is often shown in the following form:

$$PR = \frac{Y_{AC}(t)}{E_{POA}(t)}$$

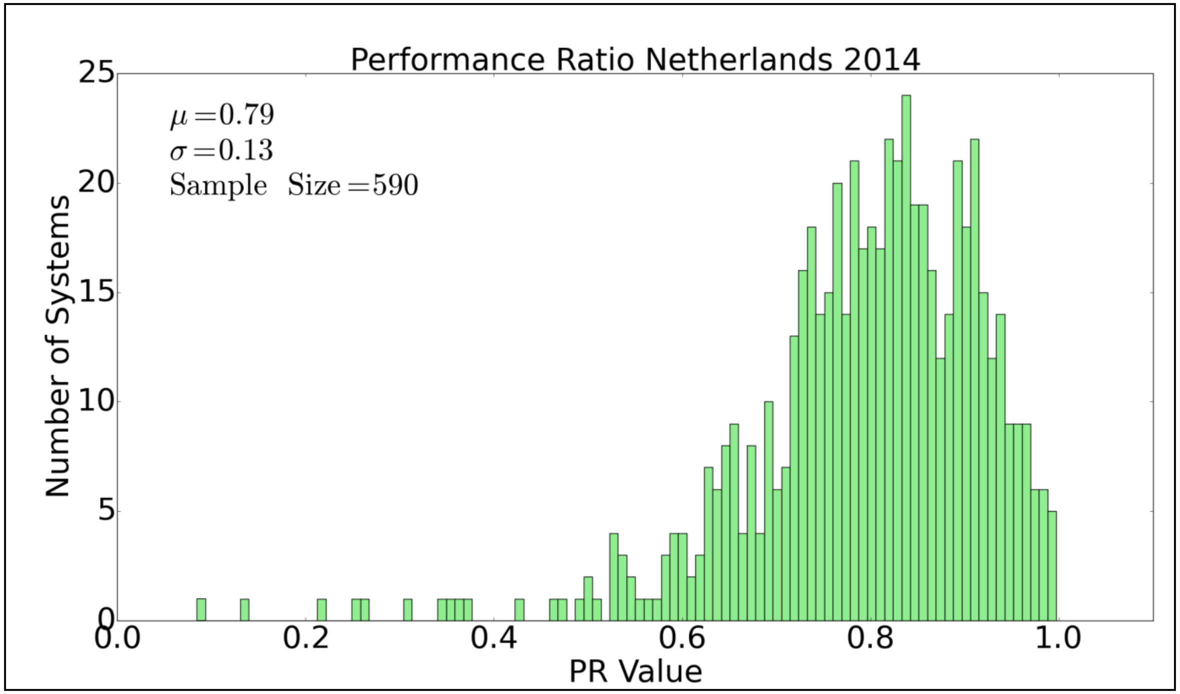
Where:
PR = Performance ratio
$Y_{AC}(t)$ = The AC energy yield over time (kWh/kW_p)
$E_{POA}(t)$ = Cumulative POA irradiance divided by 1000 W/m^2 (STC)

Performance Ratios

- The PR of a PV system characterizes <u>all</u> relevant losses of the system including:
  - Thermal losses
  - Shading losses (from inter-row, near and far objects)
  - DC and AC cabling losses
  - Inverter losses
  - Losses from mismatch (cell and module level)
  - Losses from decreased efficiency under variable light intensity and spectral conditions
  - Reflection losses
  - Soiling and other losses

Case Studies of Performance Ratios

- Avg. system size: 10.7 kWp
  - Avg. PR = 0.79
- “web scrapping” techniques used to acquire Y_{AC} data.
- PV system data correlated to nearest weather station (E_{POA}).
- Severe under performance (PR < 0.5) due to malfunction.
- 0.6 < PR < 0.7 likely due to shade obstruction.
- PR ≈ 1 not realistic. Likely due to inaccurate E_{POA} estimate.



Distribution of PR values for a sample of 590 Dutch PV systems (Source: Moraitis, P. in The 42nd PVSC, 2015)

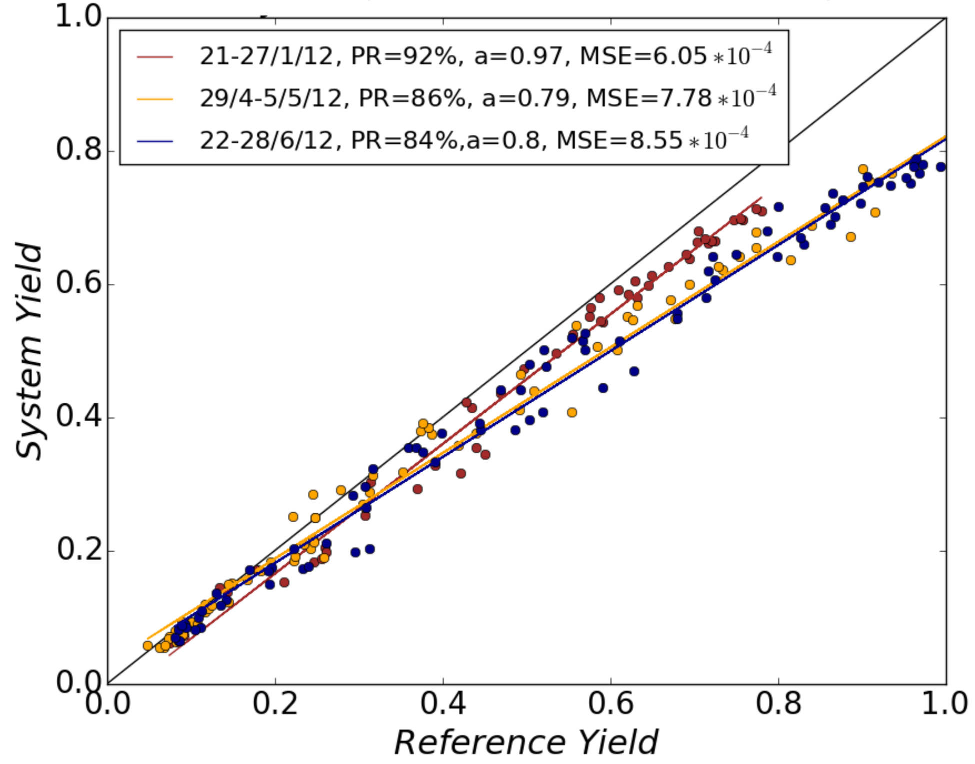
Case Studies of Performance Ratios

Winter PR = 0.92
Spring PR = 0.86
Summer PR = 0.84

$$Sytem\ Yield = AC_{yield}[Wh]/STC_{Mpp}\ [W]$$

$$Reference\ Yield = G_{POA}\ [\frac{Wh}{m^2}] \Big/ 1000\ [\frac{W}{m^2}]$$

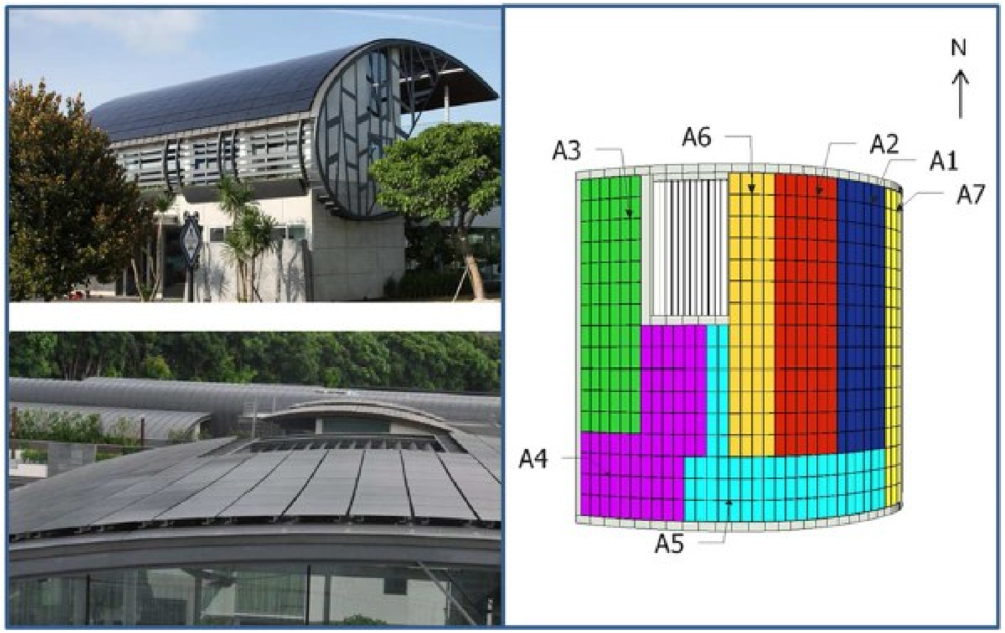
Hourly System PR vs Reference PR for c-Si system in Bolzano Italy

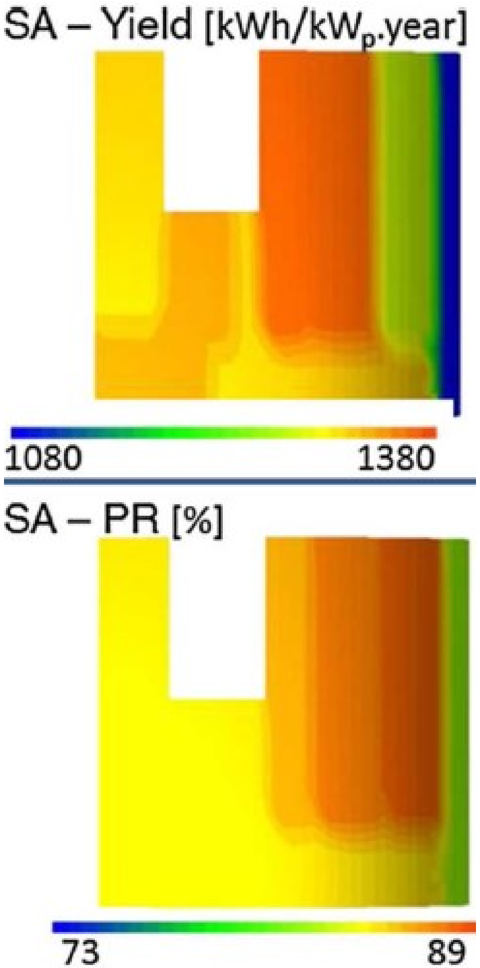


System yield versus reference yield for a 4.14 kWp PV system in Bolzano Italy. The colored data points are for different time periods, the black line is the unity reference yield. Source: (Tsafarakis, O. in 29th EU PVSEC, 2014).

Case Studies of Performance Ratios

- 45 kWp mono-si system in Singapore (1.35°N).
- 7 subsystems w/ β = 2° to 48°
  - Eastern arrays are the steepest.
  - Subsystem A7 is partially shaded.
- AM in Singapore is sunnier than PM.

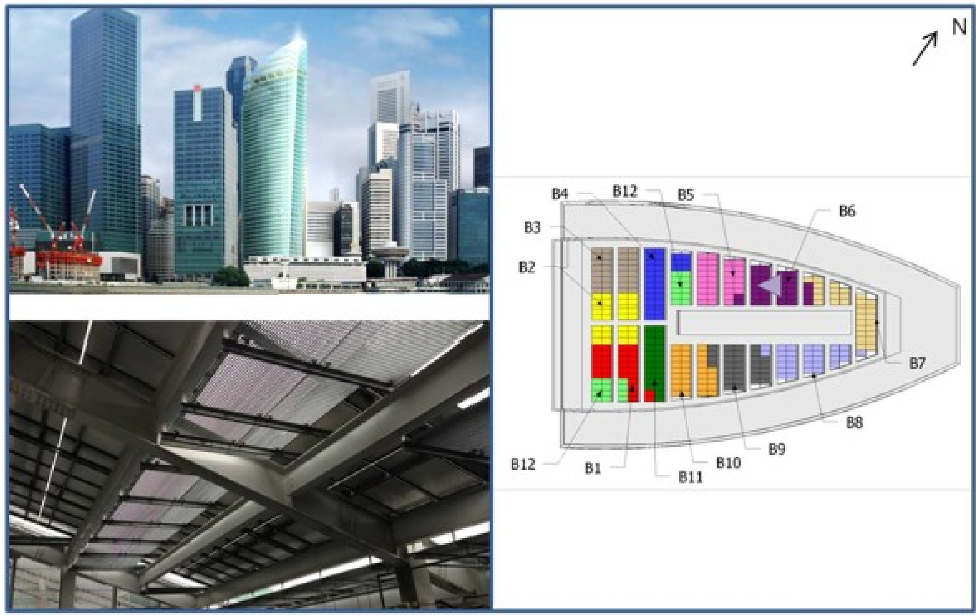


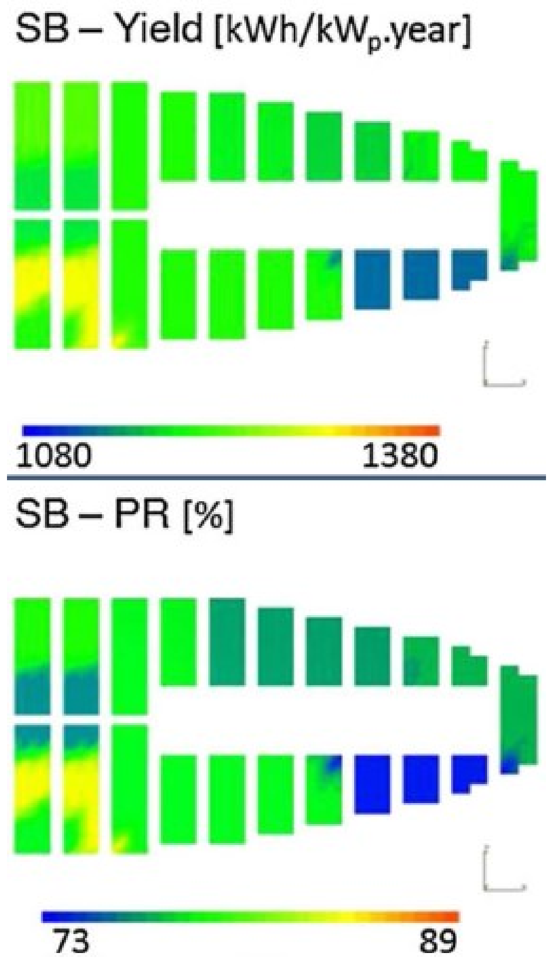


Source: Zomer et al, PiP, 2014

Case Studies of Performance Ratios

- 75 kWp SHJ system in Singapore (1.35°N).
- On top of a high rise building.
- 12 subsystems all with same tilt and azimuth (SW).
  - Lower PR than the 45 kWp system because of the SW azimuth (i.e. cloudy afternoons).





Source: Zomer et al, PiP, 2014

Application of Performance Ratios

- Let's say you have reliable PR data for a specific PV technology in a given area. Then you can calculate the expected energy output simply using:
  1. The expected PR,
  2. The TMY or DRY solar radiation data (in kWh/m^2),
  3. and the installed system's size at STC (in DC W_p).

- **Example in the case of Denmark**:
  - We can assume an average annual performance ratio of 80%.
  - The insolation received on a 35° surface in a TMY is about 1200 kWh/m^2/yr.
  - What will be the energy output of a 3 kWp system?

$$PR = \frac{AC_{yield}/STC_{Mpp}}{G_{POA}\,/1000} \quad \Rightarrow \quad AC_{yield} = PR * \frac{G_{POA}}{1000} * STC_{Mpp}$$

Application of Performance Ratios

- **Example in the case of Denmark**:
  - We can assume an average annual performance ratio of 80%.
  - The insolation received on a 35° surface in a TMY is about 1200 kWh/m^2.
  - What will be the energy output of a 3 kWp system?

$$AC_{yield} = PR * \frac{G_{POA}}{1000} * STC_{Mpp}$$

$$AC_{yield} = 0.8 * \frac{1200}{1000} * 3000 = \mathbf{2880}\ \frac{\boldsymbol{kWh}}{\boldsymbol{yr}}$$

- In this way, the PR can be a convenient metric for “back of the envelope” energy yield calculations that doesn’t require detailed understanding of all system loss mechanisms.

Temperature-Corrected Performance Ratios (PR_{TC})

- The seasonality of PR can be greatly reduced using PR_{TC}

$$PR_{TC} = PR * [1 + \gamma * (T_{mod} - 25)]$$

- If Tmod data is not available, it can be estimated using a suitable heat transfer model such as Faiman 2008.

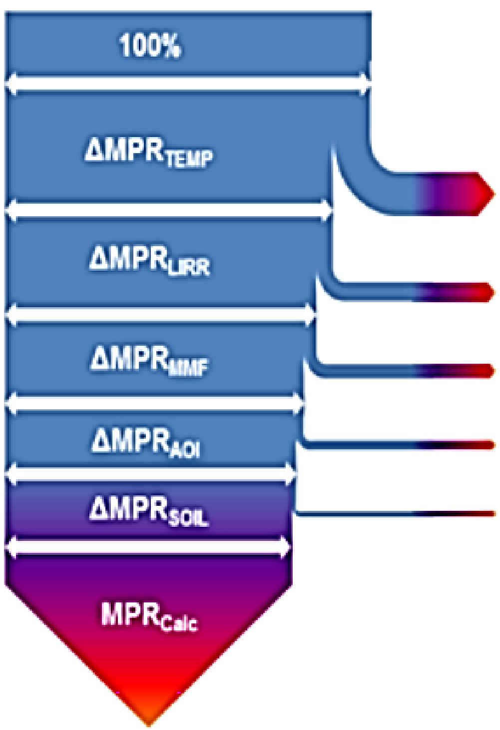
$$T_{mod} = \frac{G_{POA}}{U1 * WS + U0} + T_{amb}$$

Where:
γ = temperature coefficient for power (1/°C)
WS = wind speed (m/s)
Tamb = ambient temperature (°C)
U1 = convective heat transfer coefficient (W·s/m3 ·K) -> **6 W·s/m3 ·K** reasonable for c-Si
U0 = radiative heat transfer coefficient ($W/m^2 \cdot K$) -> **26 W/m2 ·K** reasonable for c-Si

M. Koehl et al. Modeling of the NOCT based on outdoor weathering. Sol. Energy Mater. 2011

Specific Loss Mechanisms and Module Performance Ratios (MPR)

- MPR doesn’t take the inverter losses into account (good for comparing PV technologies).
- By calculating all individual losses (AOI, spectrum etc), then you can derive the overall MPR.



c-Si 1				CdTe 1				CIGS 2			
Cologne	Ancona	Tempe	Chennai	Cologne	Ancona	Tempe	Chennai	Cologne	Ancona	Tempe	Chennai
-2.3%	-3.9%	-8.9%	-9.6%	-1.5%	-3.5%	-6.7%	-6.2%	-2.9%	-4.5%	-8.8%	-9.1%
-1.2%	-0.8%	-0.4%	-0.5%	0.0%	+0.2%	+0.3%	+0.6%	-3.6%	-3.1%	-1.8%	-2.4%
+1.3%	+0.5%	-0.8%	+1.6%	+2.3%	+0.9%	+1.1%	+5.3%	+1.4%	+0.3%	-1.1%	+1.8%
-3.5%	-2.4%	-2.0%	-2.9%	-3.5%	-2.4%	-2.0%	-2.9%	-3.5%	-2.4%	-2.0%	-2.9%
-0.5%	-0.5%	-3.7%	-2.1%	-0.5%	-0.5%	-3.7%	-2.1%	-0.5%	-0.5%	-3.7%	-2.1%
-6.2%	-7.2%	-15.9%	-13.5%	-3.1%	-5.4%	-11.1%	-5.3%	-9.1%	-10.3%	-17.4%	-14.7%
93.9%	**92.8%**	**84.1%**	**86.5%**	**96.9%**	**94.6%**	**88.9%**	**94.7%**	**90.9%**	**89.7%**	**82.6%**	**85.3%**

Source: PV-tech Magazine, May 2017, pp. 56-65

Example of Module Level Loss Mechanism Calculations

- To calculate these loss factors you would need the characterization data from the we talked about in block 3 (optical, spectral and thermal performance).

$$L_{AOI} = \frac{G_{AOI} - G}{G}$$

↓

$$L_{AOI,year} = \frac{H_{AOI,year} - H_{year}}{H_{year}}$$

↓

$$G_{eff} = G_{AOI} * \frac{\int E\,(\lambda) * SR\,(\lambda)\,d\lambda}{\int SR\,(\lambda) * E_{STC}(\lambda) d\lambda}$$

↓

$$L_{Spectral,year} = \frac{G_{eff,year} - H_{AOI,year}}{H_{AOI,year}}$$

↓

Cont. w/ calculations for low light and temperature dependency etc.

Where:
L_{AOI} = global AOI losses (instantaneous)
G = measured in plane irradiance (W/m^2)
G_{AOI} = effective global irradiance adjusted for IAM loss
$L_{AOI,\ year}$ = annual AOI losses
H_{year} = G integrated over 1-year
G_{eff} = G adjusted for spectral shifts deviating from the AM1.5G reference spectrum
$L_{spec,year}$ = annual losses from spectral shifts from AM1.5G

Read more at:

T. Huld et. al, (2016) "Photovoltaic energy rating data sets for Europe", Solar Energy Vol. 133. pp. 349-362

Specific Yield (kWh/kW_p)

- Another commonly used metric to assess PV system performance is the 'Specific Yield', which is in units of AC kWh / DC kWp.

- The specific yield is the numerator in the PR calculation, thus they are closely related.

- For example, using the numbers from before (80% PR and 1200 kWh/m^2/yr).

$$Specific\ Yield \left[\frac{kWh}{kWp}\right] = 0.8 * 1200 \left[\frac{kWh/_{m^2}}{yr}\right]$$

$$Specific\ Yield = \mathbf{960} \left[\frac{\boldsymbol{kWh}}{\boldsymbol{kWp}}\right]$$

- This means that for every 1 kWp of PV, you can expect to generate 960 kWh of AC electricity annually.

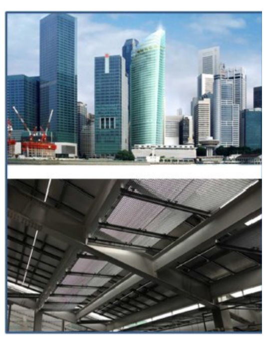
Specific Yield (kWh/kW$_p$)

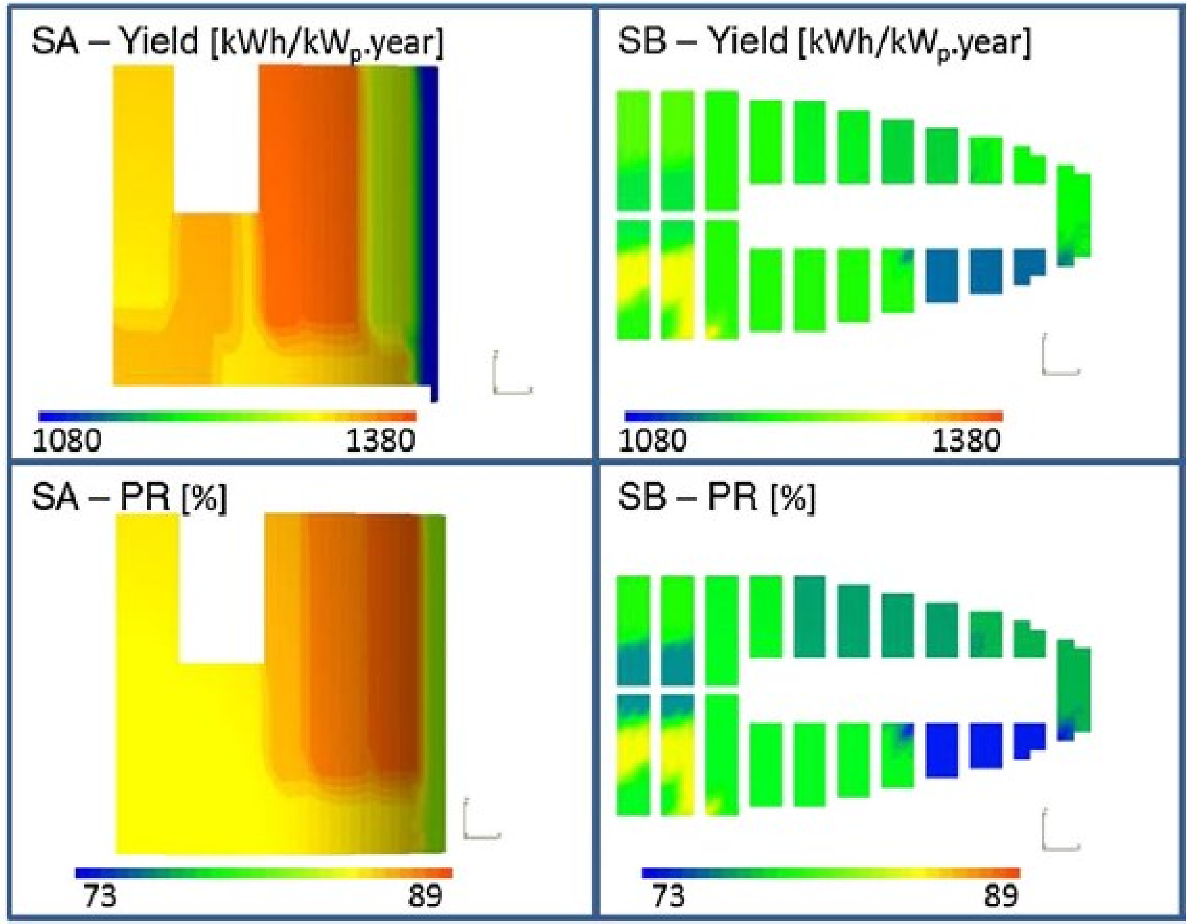
- Specific yield depends on:
  1. Location! (i.e. solar resource).
  2. PV system orientation (e.g. horizontal vs. tilted).
  3. Module type (i.e efficiency under multi-irradiance conditions).
  4. BoS components and loss mechanisms mentioned previously.

- Whether to use PR or specific yield when analyzing the performance of PV systems seems mostly a matter of preference.
  - But if you don't have G_{POA} data, then you can't calculate PR!

Comparing Specific Yield and PR

- Recall our two BIPV systems from Singapore.
- We can see that Specific Yield corresponds to PR for both systems.





Outline

- Intro to PV monitoring
  - Equipment and sensors (IEC 61247-1)
  - Capacity Evaluation (IEC 61247-2)
    - Performance Index (PI)
- Performance Metrics
  - Performance Ratios / Specific Yield
- Degradation Rate (Rd)

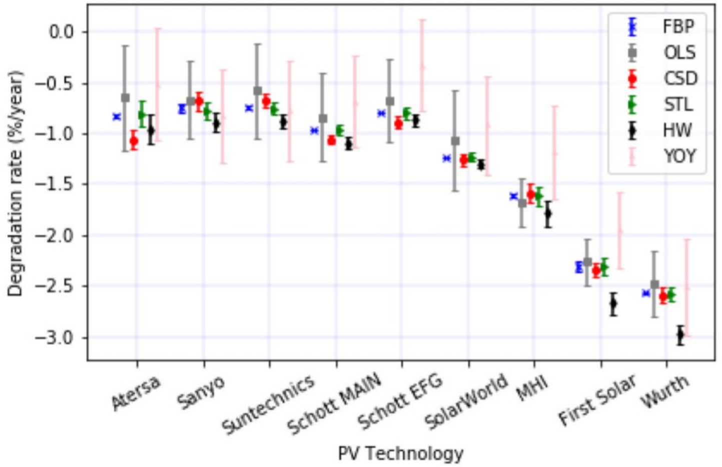
Degradation Rate (Rd)

- Rd describes the decrease of PV power output over time.

- Many methodologies, but no standard calculation exists yet
  - ordinary least squares (OLS), year-on-year (YoY), smoothing (HW) etc.

- Rd can be non-linear
  - e.g. multi-step or exponential

- Rd is dependent on BoM and exposure
  - 0.5-0.6%/year is global avg. for c-Si [1].
  - Hotter climates can cause higher stress.



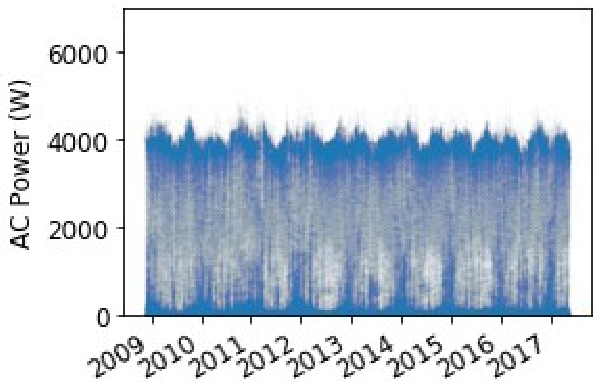
Results of different Rd methods applied to different technologies installed in Cyprus [2]

Example of different Rd trends [1]

1. Jordan, et al. "Compendium of Photovoltaic Degradation Rates", PIPV 2016
2. Theristis, M. et al. "Non-linear photovoltaic degradation rates: modeling and comparison against conventional methods", JPV 2020

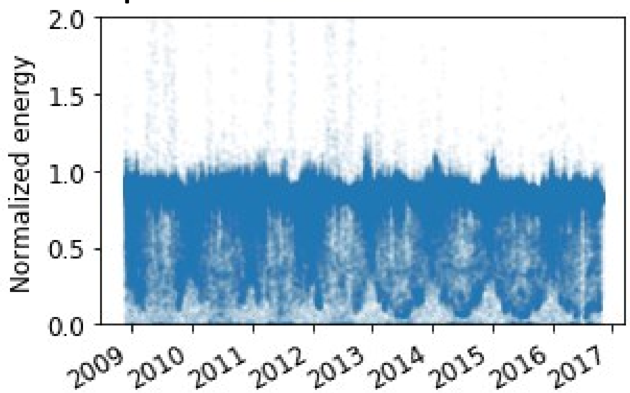
How to Calculate Degradation Rates From Monitoring Data (Rd Tools Method)

Step 0: Import monitoring data



Ex: 9 years of AC data from BP Solar Panels

Step 1: normalize data



https://github.com/nrel/rdtools

Step 1

Data Normalization
- PR, PR + temp correction, *CEC*, SAPM model
- Clearsky model correction

Step 2

Filter raw data
- High DC/AC ratio clipping
- Clear-sky filter
- Outage / data QA screen

Step 3

Aggregation
- Daily, weekly, monthly
- Irradiance weighted

Step 4

Rd & error calculation
- Linear, nonlinear regression, Year-on-Year, Seasonal decomposition

The Rd Tools module for Python can be installed via PyPi in a cmd line type:

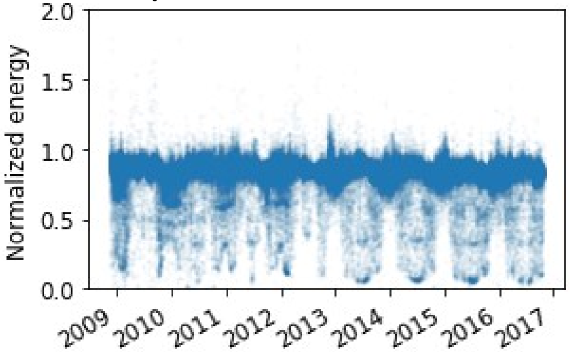
```
pip install rdtools
```

You will also need PVLib installed

```
pip install pvlib
```

How to Calculate Degradation Rates From Monitoring Data (Rd Tools Method)

Step 2: filter data



- Erroneous G and T conditions
- Clipping
- Undue bias etc.

Step 1

Data Normalization
- PR, PR + temp correction, *CEC*, SAPM model
- Clearsky model correction

Step 2

Filter raw data
- High DC/AC ratio clipping
- Clear-sky filter
- Outage / data QA screen

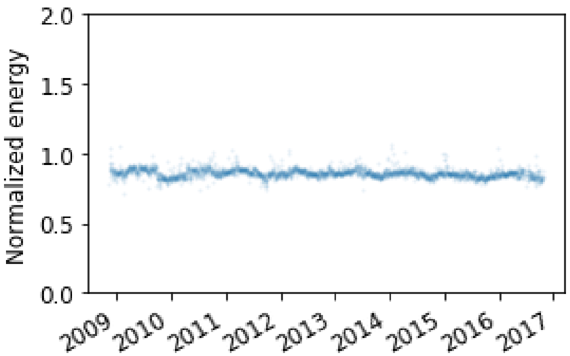
Step 3

Aggregation
- Daily, weekly, monthly
- Irradiance weighted

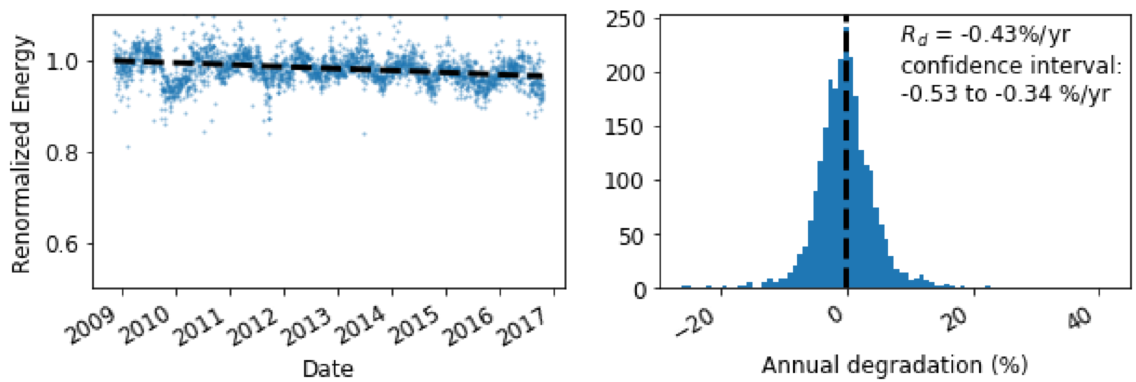
Step 4

Rd & error calculation
- Linear, nonlinear regression, Year-on-Year, Seasonal decomposition

Step 3: Aggregate



Step 4: Rd Calculation



Review of Clear Sky Models

- Estimate the amount of solar radiation reaching the Earth's surface in the absence of cloud cover.

- Clear sky models can help detect errors in measured GHI data.
  i.e. compare the measured GHI data on a clear sky -> does it match the model? Can be used to detect erroneous irradiance measurements.

- There are many (50^+!) clear sky models. Here is a simple one (Haurwitz):

$$GHI = 1098 \times \cos\theta_Z \times \exp\left(\frac{-0.057}{\cos\theta_Z}\right)$$

Where θ_Z = solar zenith angle

B. Haurwitz, "Insolation in Relation to Cloudiness and Cloud Density," Journal of Meteorology, vol. 2, pp. 154-166, 1945.

Degradation Rate Calculation Exercise (Optional)

- Download and analyze historical PV performance data.

- Source: 10^{+} years of performance data from 40^{+} PV systems (Australia)
  - http://dkasolarcentre.com.au/historical-data/download