# A SIMPLIFIED METHOD TO APPROXIMATE BIFACIAL SYSTEM MISMATCH LOSSES

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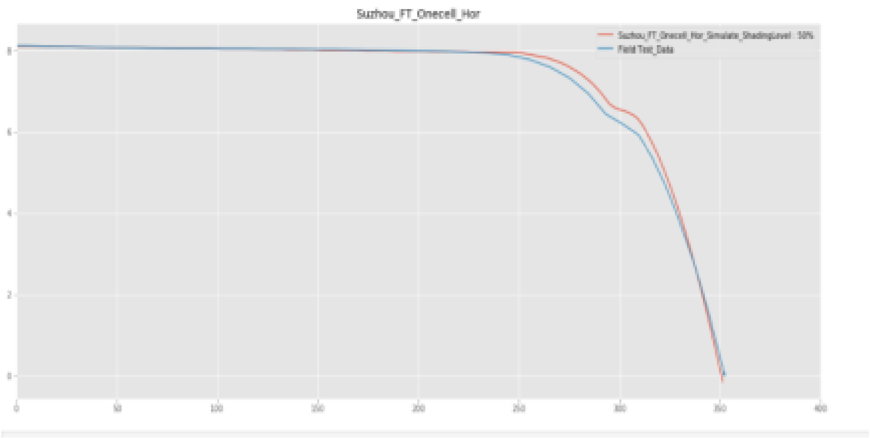
# Methodology introduction – Overview

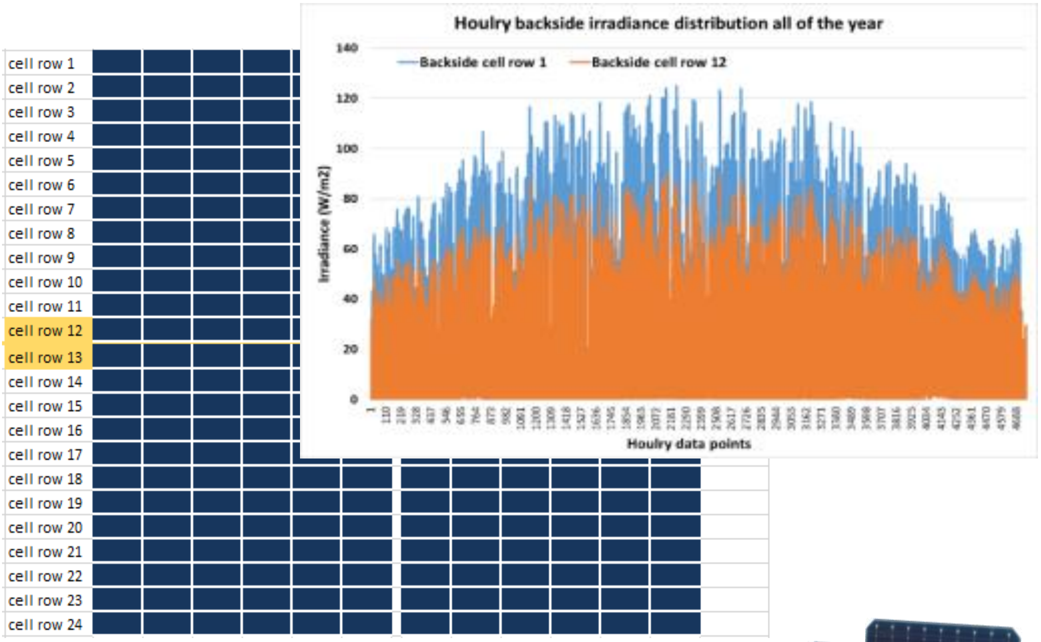
PVmismatch → Array IV curve (t) → Mismatch loss @ time t

NREL bifacialvf → Irradiance profile (t) → Mismatch loss @ time t

Mismatch loss @ time t

Annual Energy loss



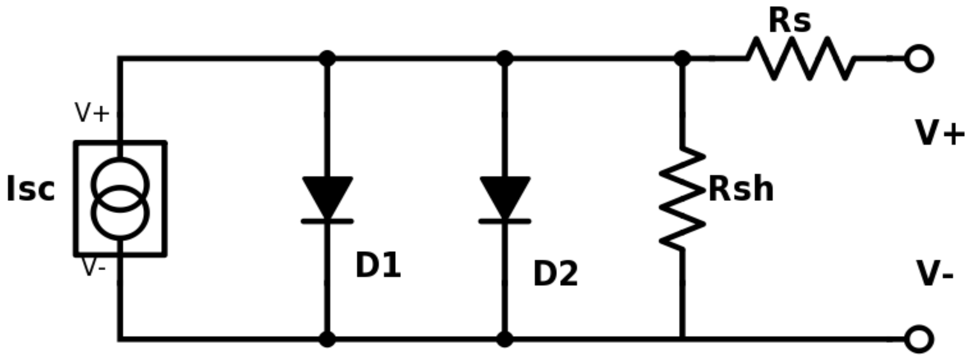

**Methodology limitations:**

- Based on interior arrays, no edge effect taken into account
- Racking system detailed features and posts are not considered

# Methodology introduction – Main tools

## PVMismatch (Sunpower)

- An explicit Python PV system **IV & PV curve trace calculator** which can also calculate mismatch.
- Two-diodes model.




## Bifacialvf (NREL)

- PV **View Factor model** for system performance calculation.
- Allows rear **irradiance spatial non-uniformity** simulation (hourly front and rear irradiance for each cell rows) for both fixed and single-axis tracker systems.

***Open source codes available on GitHub***

# Methodology introduction – Calculation flow

Location selection – TMY weather file

Simulated hourly front and rear irradiance for each cell row (full array)

Synthetic Irradiance = front irradiance + rear irradiance × Bifaciality factor

Cell front I-V STC production data
→ Random sampling

System IV curve for each time stamp
→ Maximum Power Point (MPP)

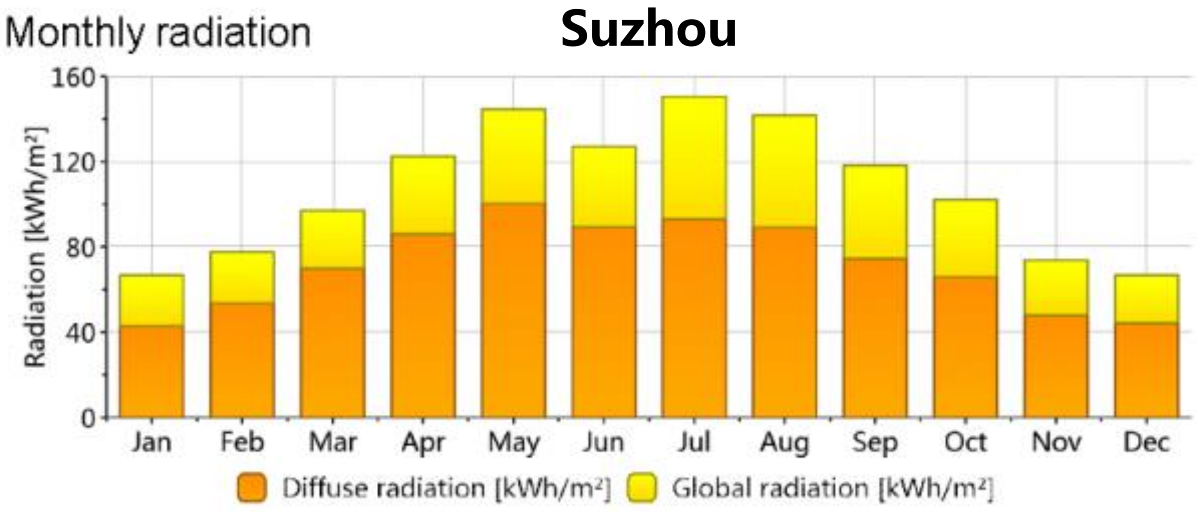
Yearly mismatch loss calculation

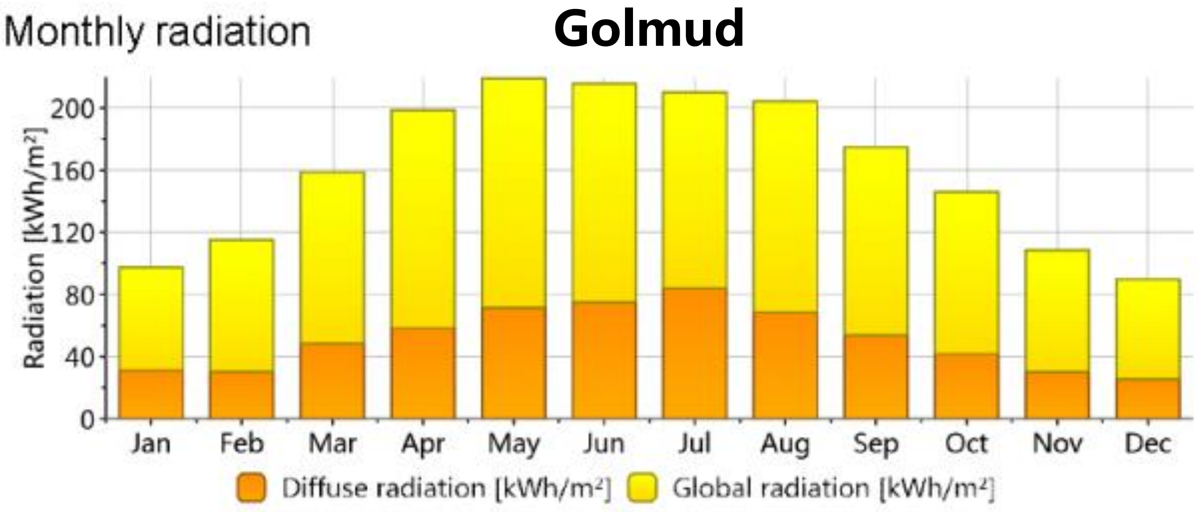
$$\textbf{Yearly mismatch loss} = \left(\sum_{1}^{N} \textit{Array power}\right) / \left(\sum_{1}^{N} (\textit{Cells Power})\right) - 1$$

***N is the number of hourly data points of the whole year, excluding rear irradiance ≤15W/m².***
***To reduce computation time, representative days can be properly selected through the year instead.***

# Study case – Location selection

| Location | Latitude | Longitude | Altitude (m) | Mean global horizontal irradiance GHI (W/m2 ) | Mean diffuse horizontal irradiance DHI (W/m2 ) | DHI/GHI |
|---|---|---|---|---|---|---|
| Suzhou (China) | 31.5 | 120.6 | 30 | 147 | 98 | 67% |
| Golmud (China) | 36.4 | 94.9 | 2809 | 221 | 71 | 32% |



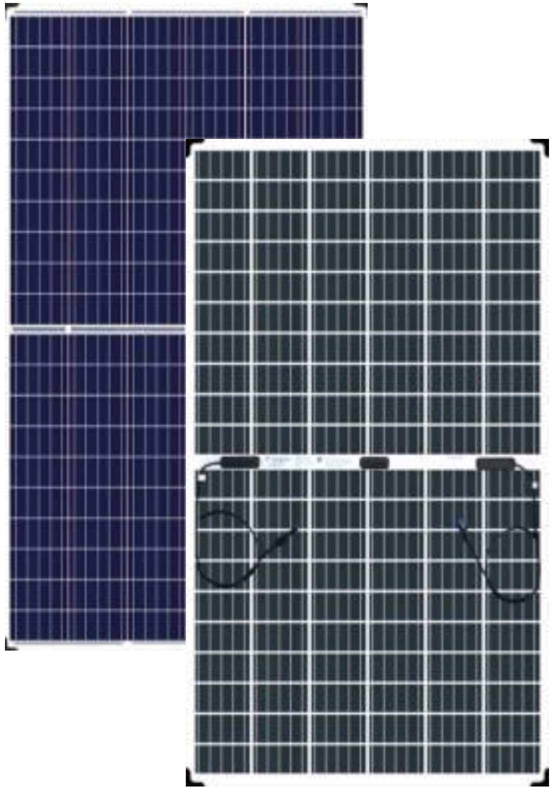



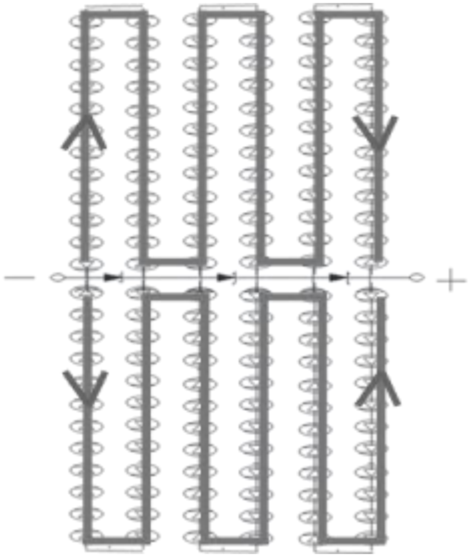

**Two locations, Suzhou and Golmud, with respectively very high and low DHI/GHI ratios are selected.**

# Study case – Cell IV data & module type choice

## Module type:

- Canadian Solar Inc. CS3U-PB-FG (frameless) model.
- 144 poly PERC half-cells bifacial module type



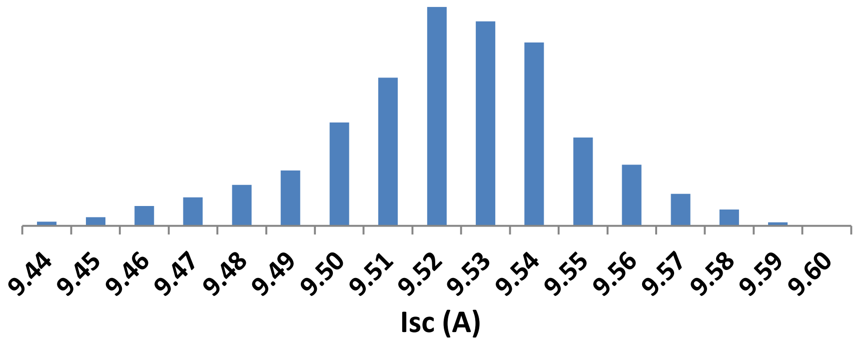


**SPS electrical layout**
**(Series-Parallel-Series)**

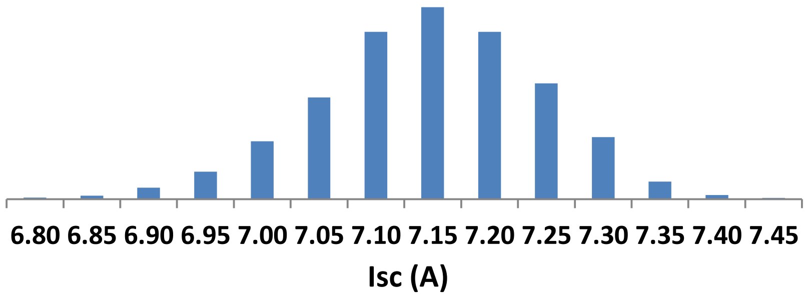
## Cell production IV data:

- Using front & rear half-cell I-V data and typical cells reverse data.

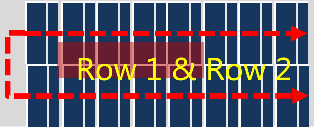
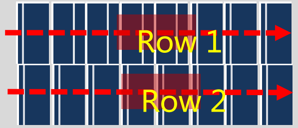
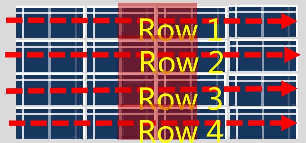
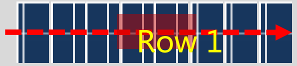
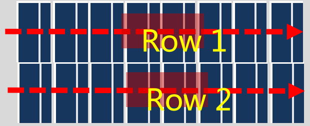
**Front Isc distribution**




**Rear Isc distribution**



# Study case – System and modules connection topology

| Mounting type | Module connection topology | Module orientation | Strings in parallel |
|---|---|---|---|
| Fixed racking |   | Portrait | 1 |
| |   | Portrait | 2 |
| |   | Landscape | 2 |
| |   | Landscape | 4 |
| SAT tracker |   | Portrait | 1 |
| |   | Portrait | 1 |
| |   | Portrait | 2 |

| Application | High DHI/GHI ratio | Low DHI/GHI ratio |
|---|---|---|
| System voltage | 1000V | |
| Modules per string | 20 | 18 |
| Location | Suzhou | Golmud |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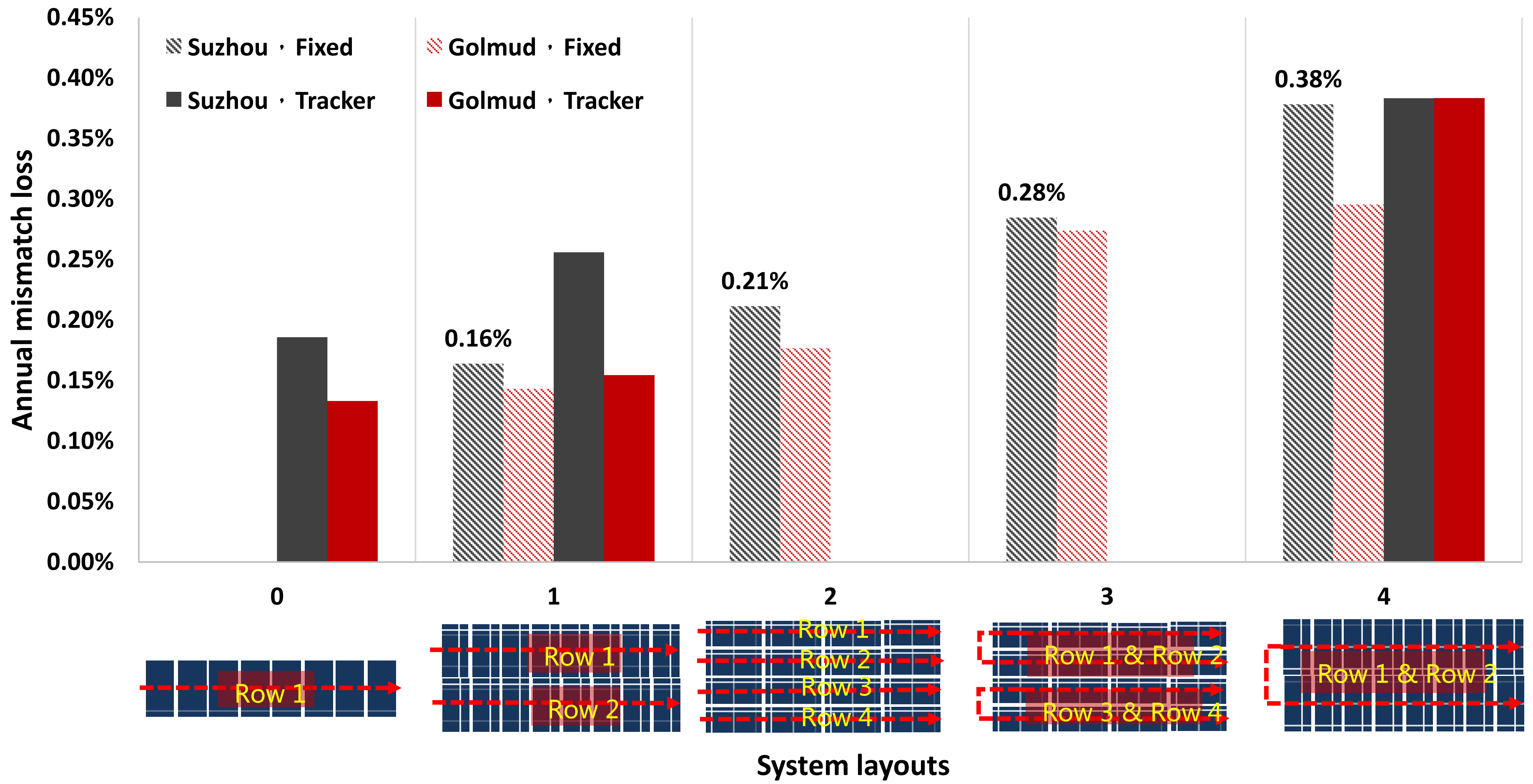
# Mismatch loss for different system layouts and connection topology



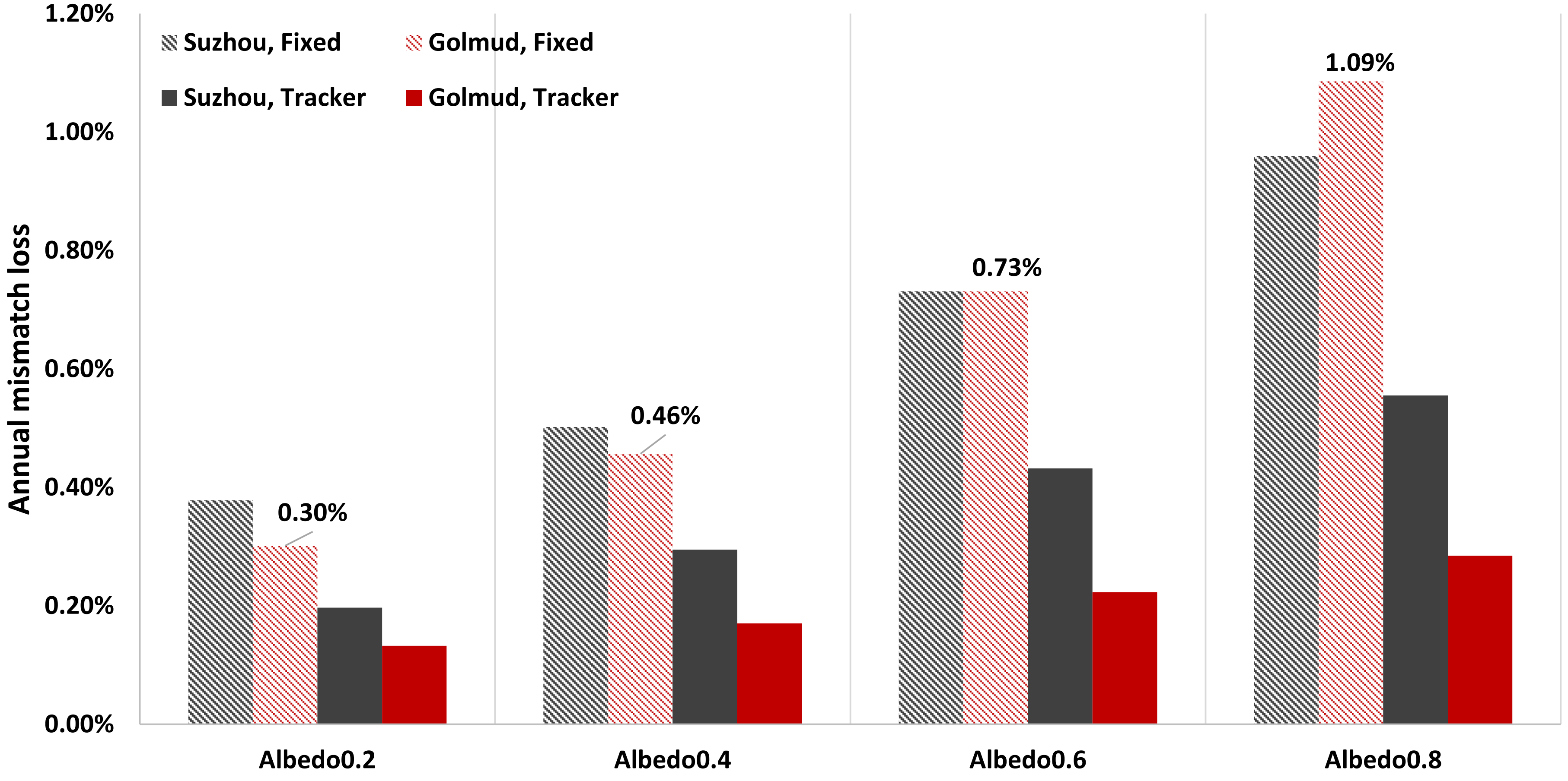

**X2 higher loss for U cable connection**

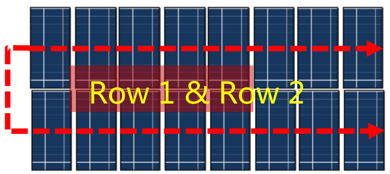
| Fixed racking | | | |
|---|---|---|---|
| Location | GCR | Elevation (m) | Tilt Angle (°) |
| **Suzhou** | 0.62 | 1 | 20 |
| **Golmud** | 0.45 | | 30 |

| Tracker | | | |
|---|---|---|---|
| Tracker type | GCR | Elevation (m) | Tilt Angle (°) |
| **1 portrait** | 0.40 | 1.5 | ±45 |
| **2 portrait** | | 3 | |

- For **0.2 soil albedo**, power mismatch losses within **0.1% to 0.4%** range.
- Similar losses for fixed and tracker arrays, 1P/2P trackers, and different DHI/GHI ratios.

# Mismatch loss sensitivity – Albedo



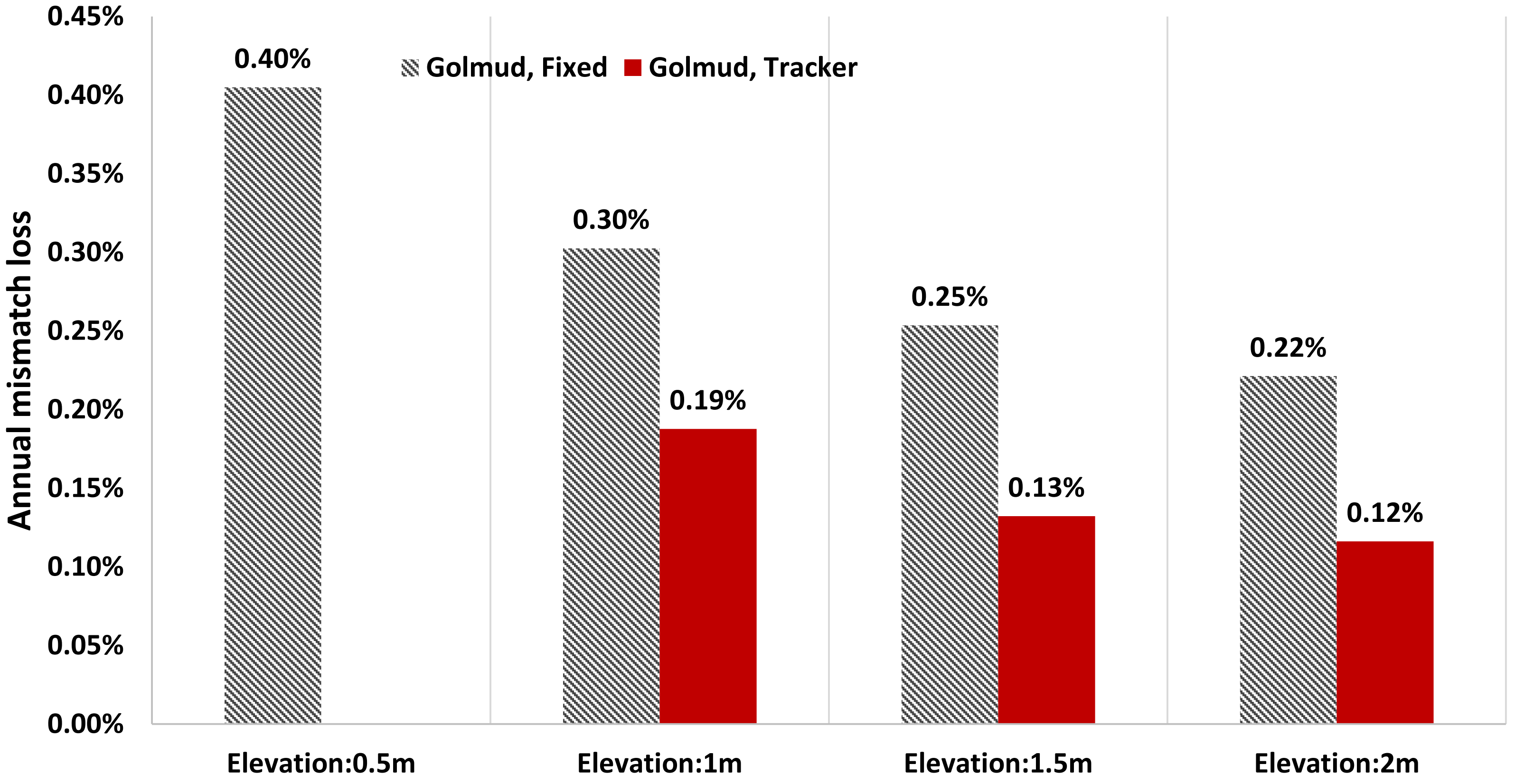



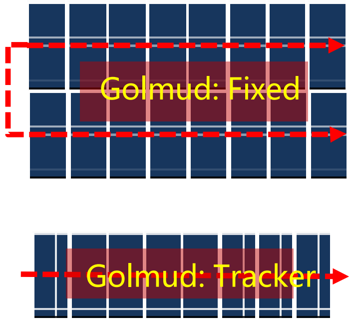

| Fixed | | | |
|---|---|---|---|
| Location | GCR | Elevation (m) | Tilt Angle(°) |
| **Suzhou** | 0.62 | 1 | 20 |
| **Golmud** | 0.45 | | 30 |

| Tracker | | | |
|---|---|---|---|
| Tracker type | GCR | Elevation (m) | Tilt Angle(°) |
| **2 portrait** | 0.40 | 3 | ±45 |

- Mismatch loss **increasing faster as albedo increases**, up to 1.1% for worst case.
- Slightly higher loss for location with low DHI/GHI ratio apparent under high albedo.

# Mismatch loss sensitivity – Racking height




| Fixed | | | |
|---|---|---|---|
| Mounting type | GCR | Albedo | Tilt Angle (°) |
| **2 portrait** | 0.45 | 0.2 | 30 |

| Tracker | | | |
|---|---|---|---|
| Tracker type | GCR | Albedo | Tilt Angle (°) |
| **1 portrait** | 0.40 | 0.2 | ±45 |

- Mismatch loss decreases along with elevation increases, **benefit above 1-1.5m is negligible**, both for tracker and fixed racking.

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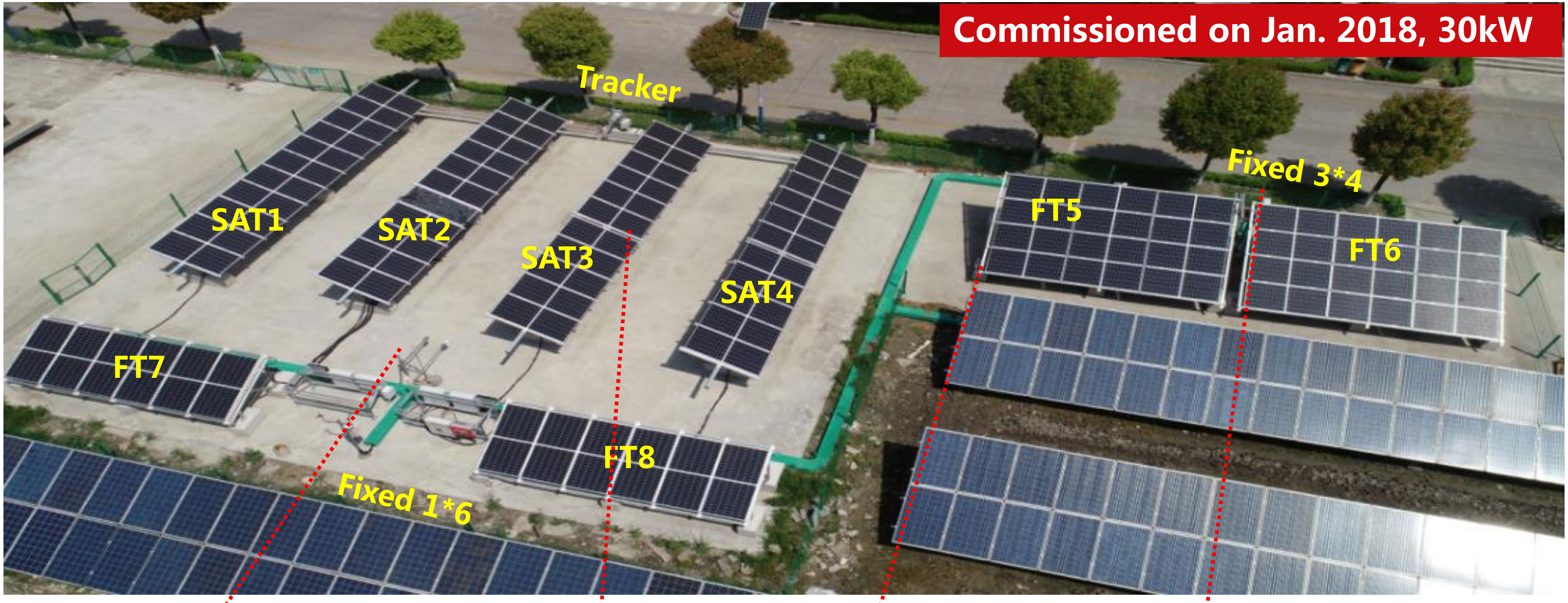
# Changshu field trial test platform – Overview



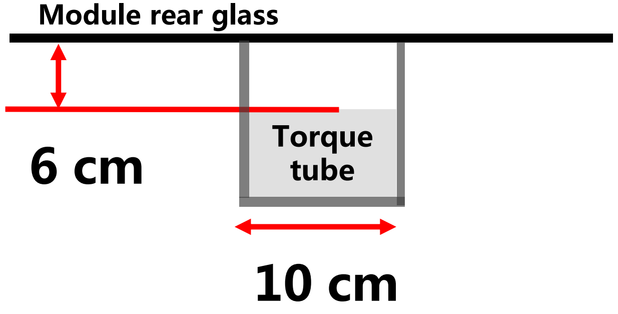

Albedo meters

Rear side silicon sensors

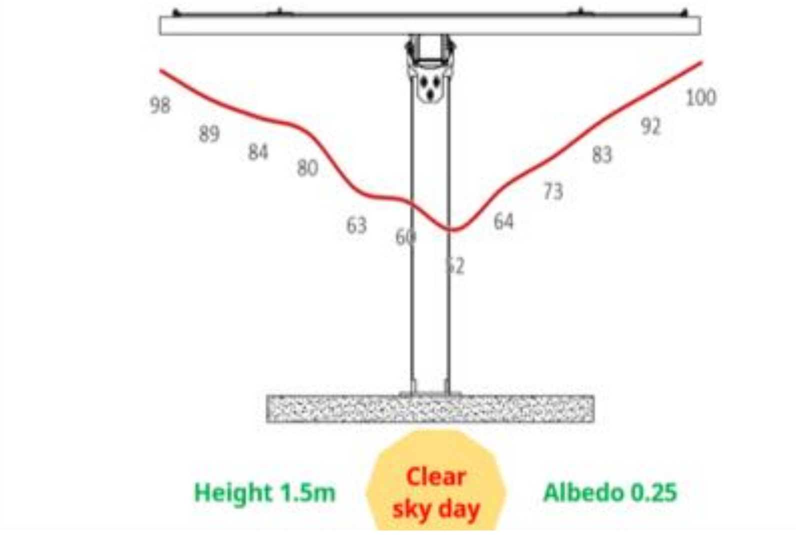
Front side POA sensors

# Rear irradiance non-uniformity measurements

- Continuous measurement of irradiance non-uniformity on tracker system through specially built module.
- Similar trend observed as reported by mainstream SAT tracker suppliers.
- Data used to estimate shading effect of torque tube and apply in the mismatch calculations (constant value).

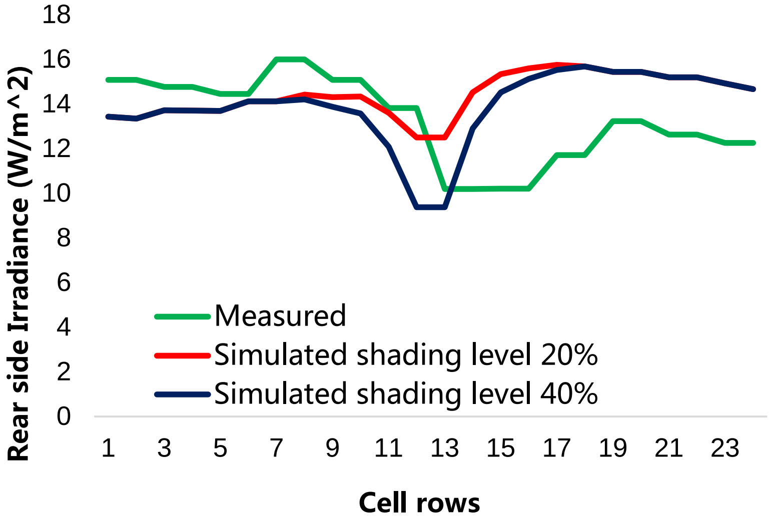



**Measured back side irradiance distribution**
April 9, 12:00PM

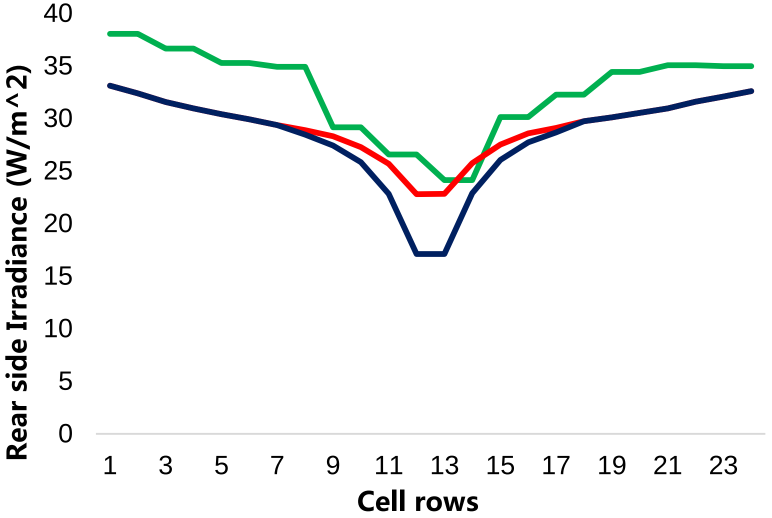


# Rear irradiance non-uniformity – Measured vs simulated

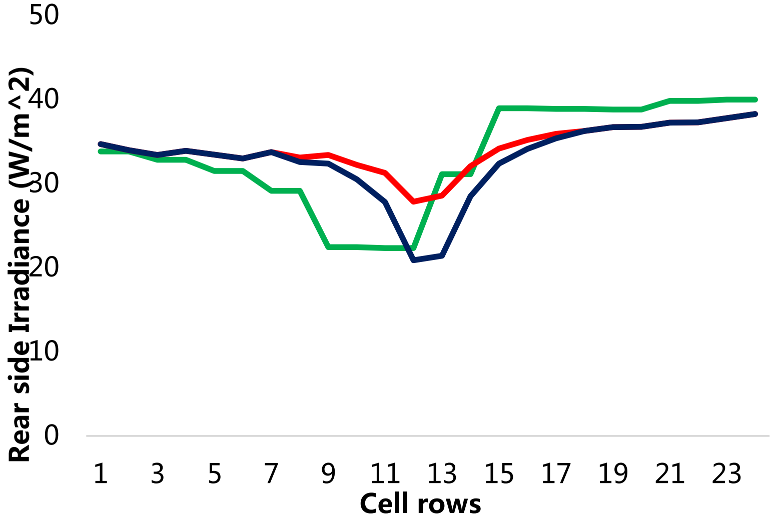
**9:00am**




**12:00pm**

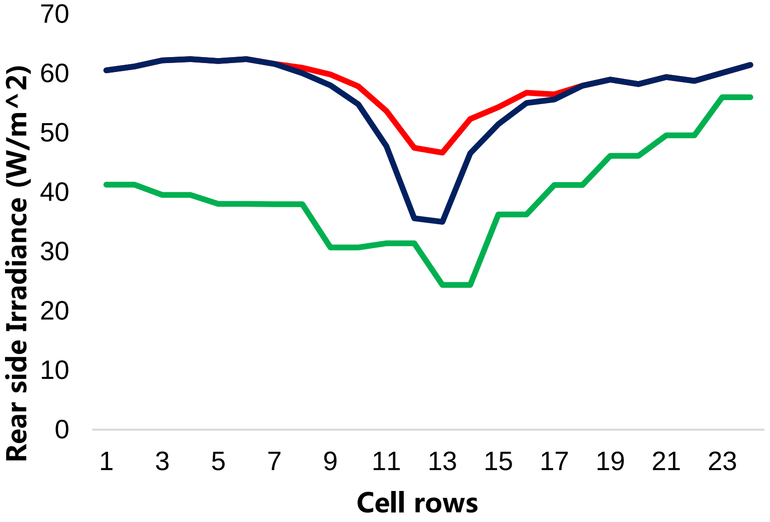



**3:00pm**

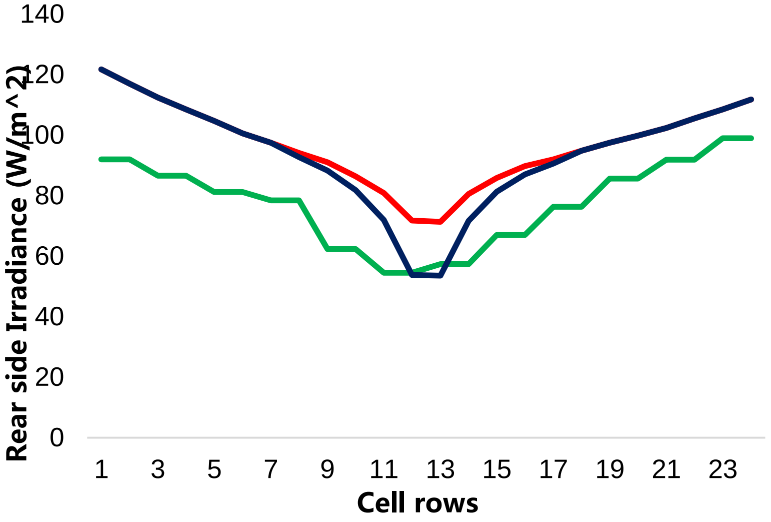



March 5
Cloudy day,
Albedo 0.15

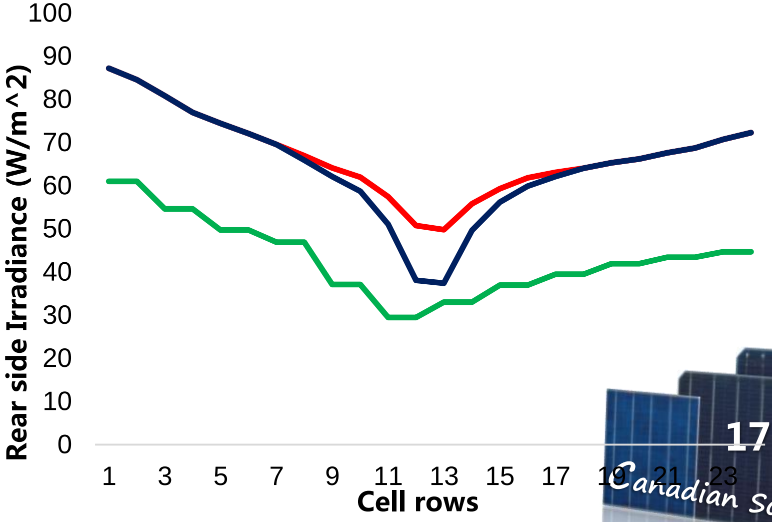
**9:00am**




**12:00am**




**3:00pm**




March 10
Clear day,
Albedo 0.30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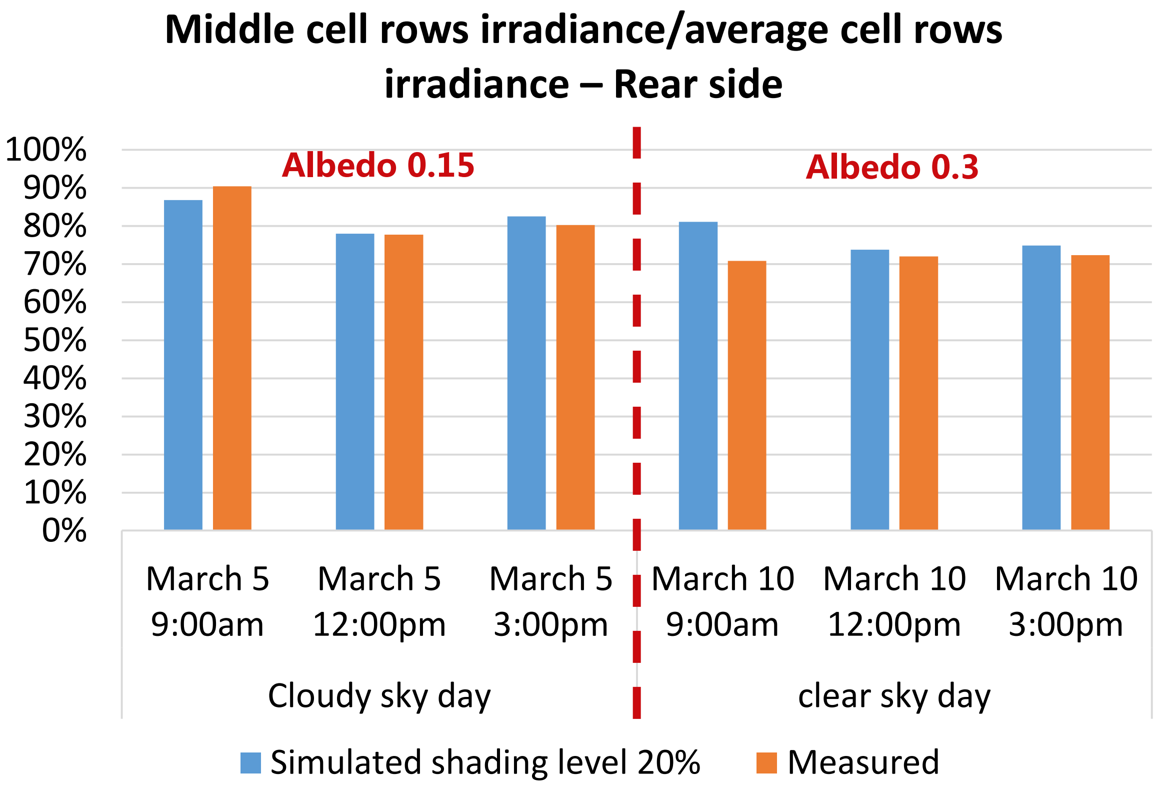
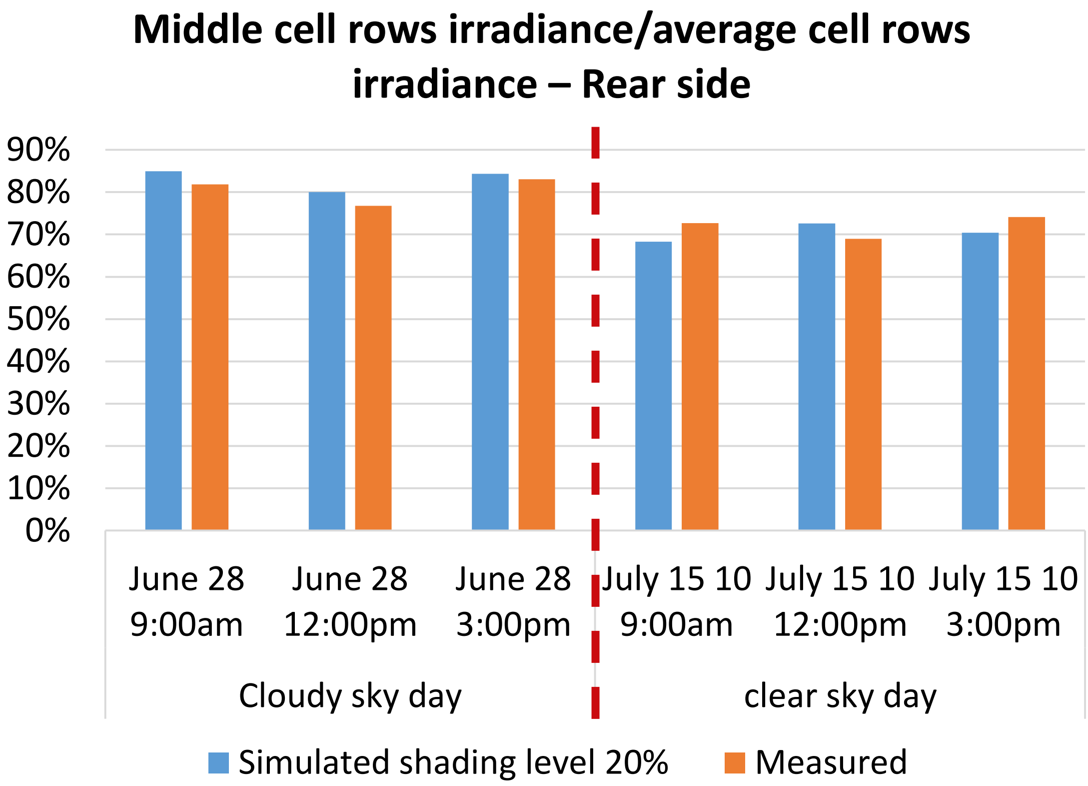
# Rear irradiance non-uniformity – Measured vs simulated

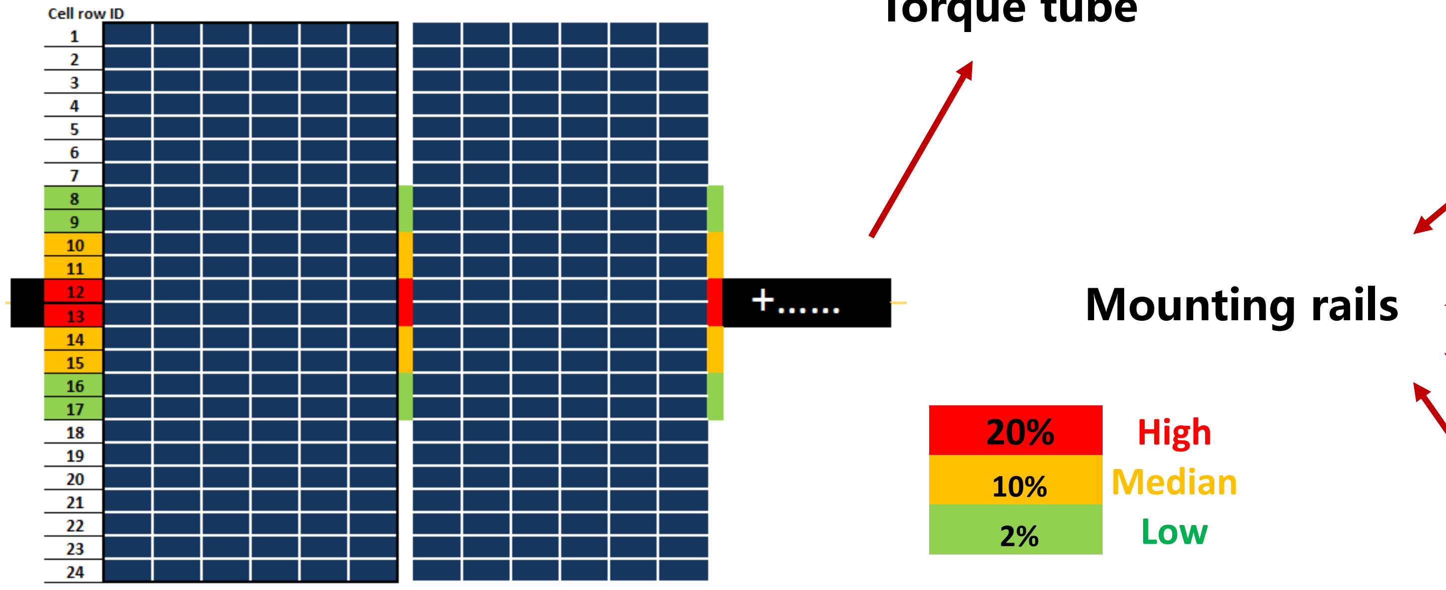


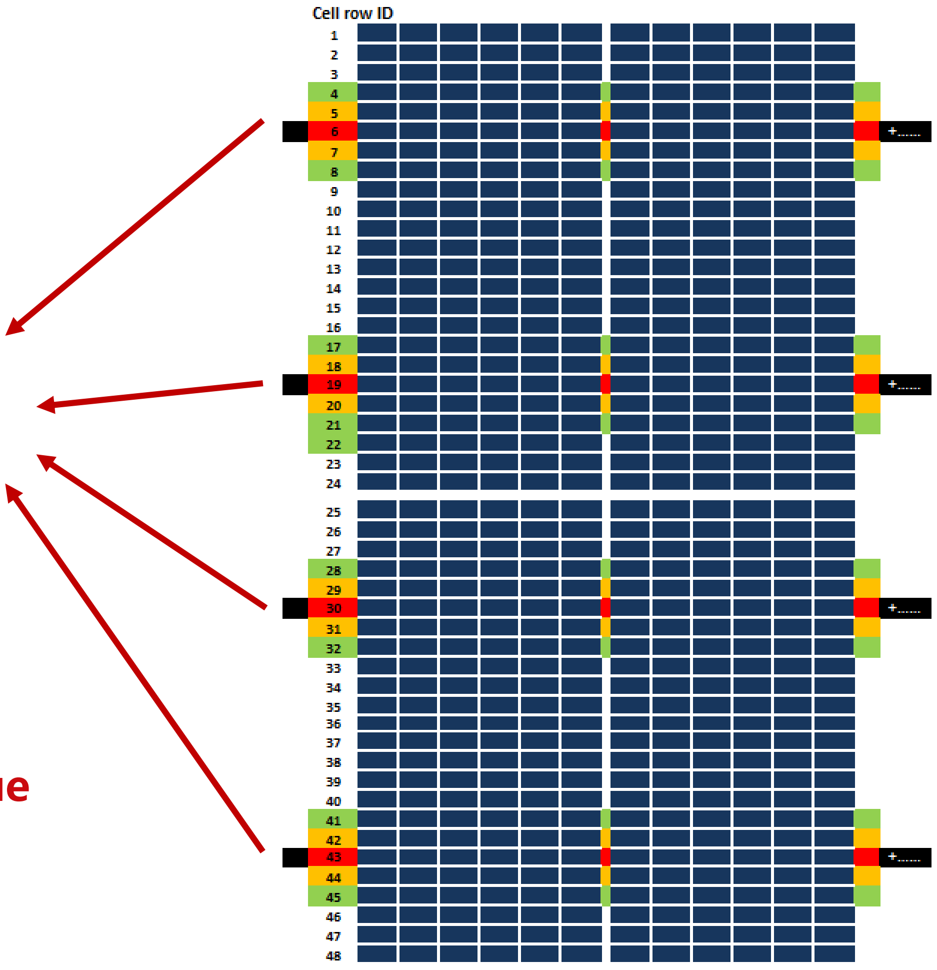

- Same trend with March 5 and 10 can be observed on June 28 and July 15.
- **For 0.15~0.3 albedo, assuming tube shading level 20%, measured and simulated irradiance distributions show matching trends.**
- Similar assumption valid for 0.2 albedo, to be verified for higher albedo.

# Cell rows shading definition

## Tracker system – 1P

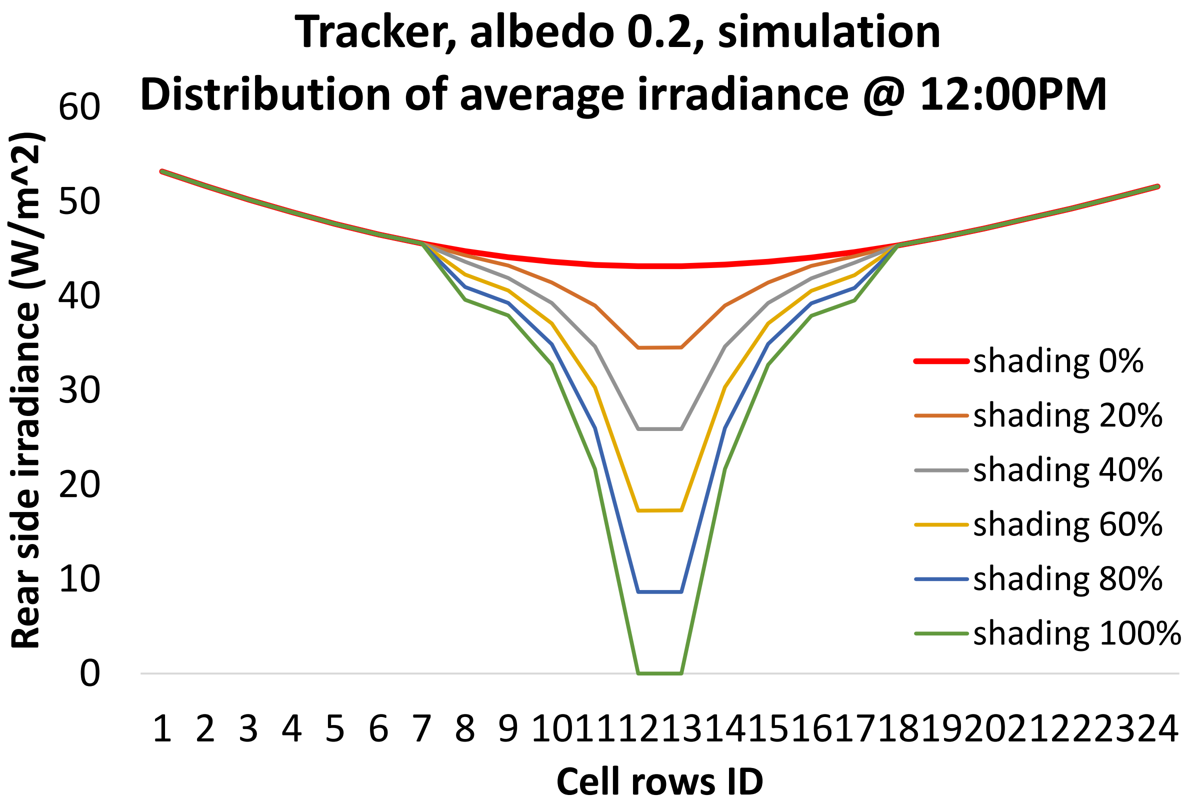


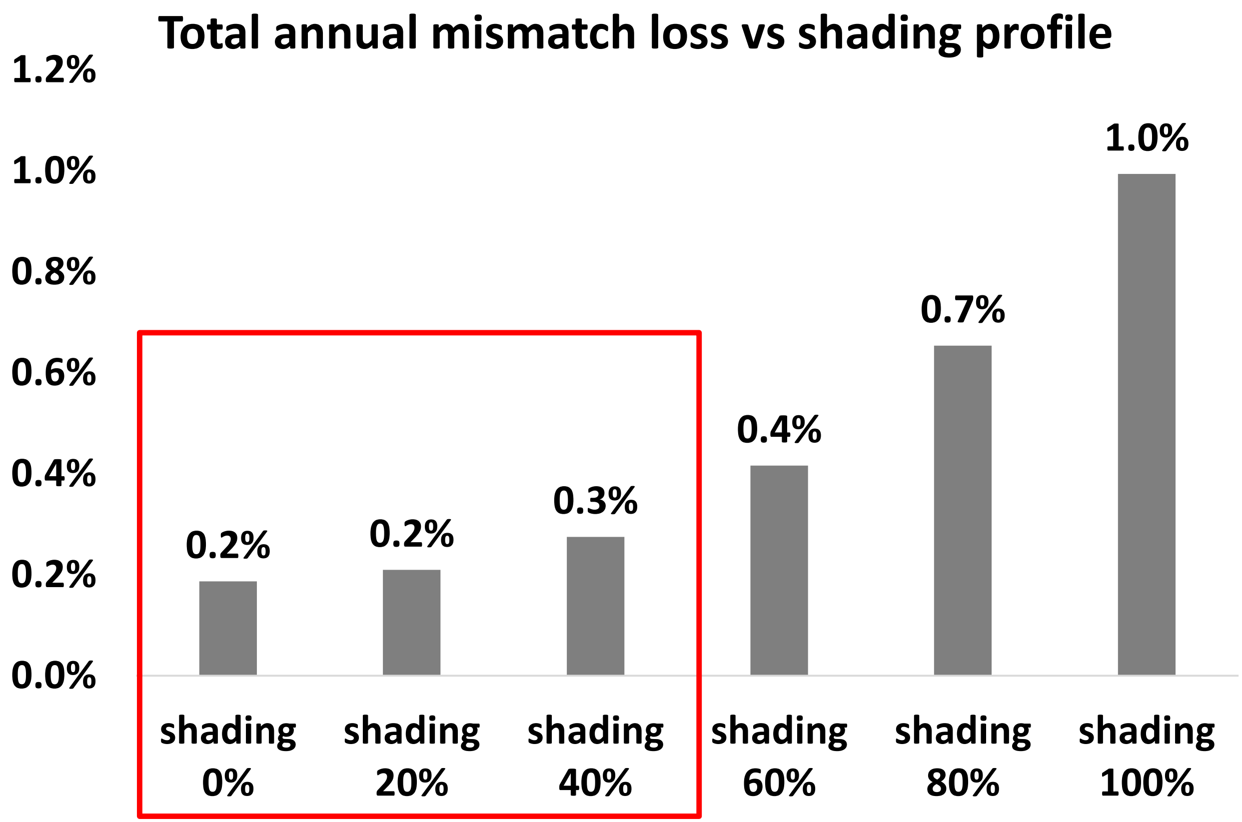

## Fixed racking – 2P




- Shading percentage due to racking structure fixed to **constant value** for the annual mismatch calculations.
- Shading profile applied to 10 half-cell rows, estimated from field measurements (**20% shading** on middle two rows).
- Same shading profile applied for fixed racking system (*to be verified, on-going measurements*).

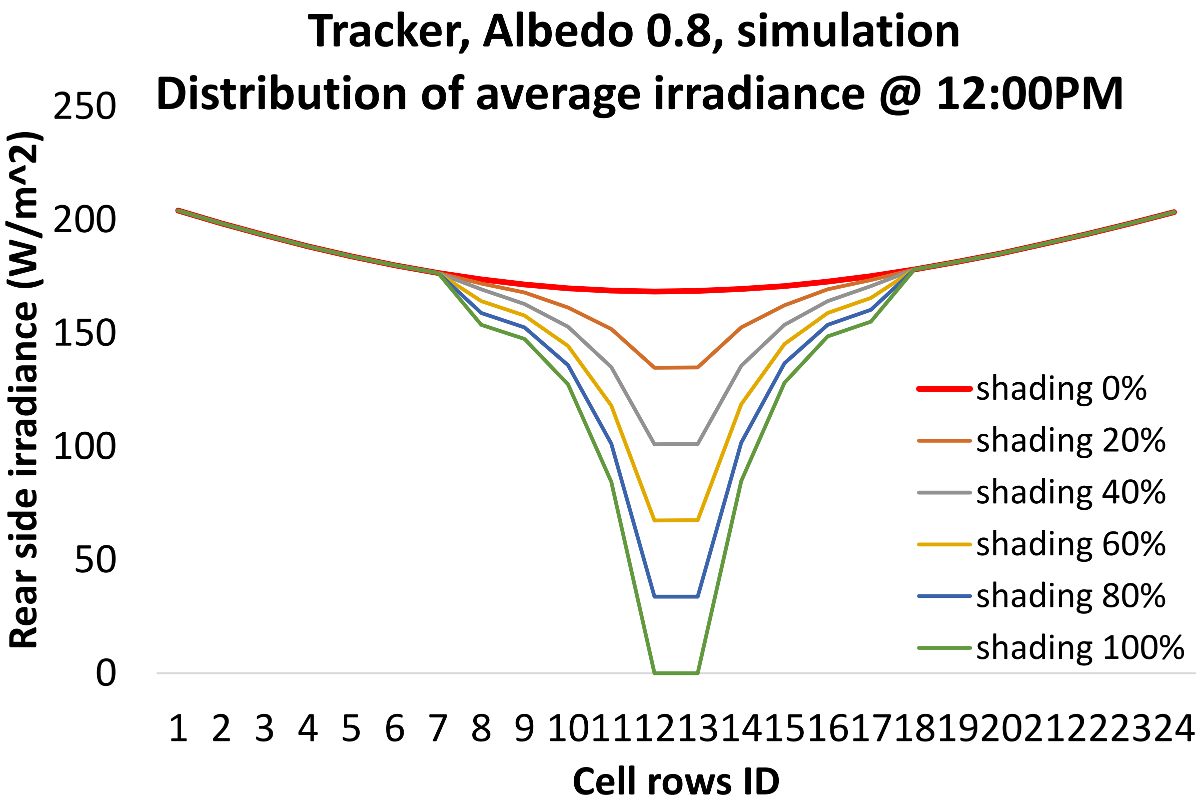
# Mismatch loss results – Tracker case (Suzhou, albedo 0.2)

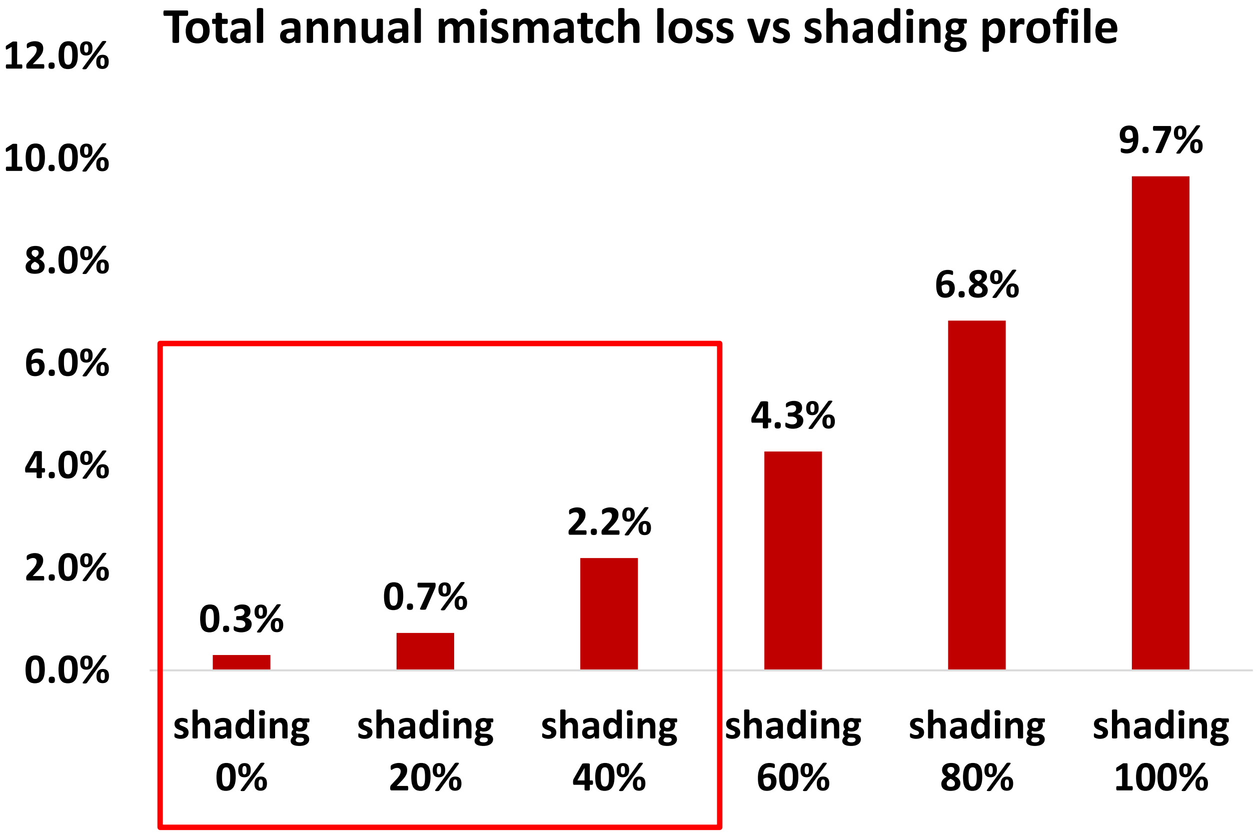



- Considering **worst case shading level 40%**, total mismatch loss is bound to 0.3%, **additional mismatch loss contribution** due to shading of torque tube is **only 0.1%.**

# Mismatch loss results – Tracker case (Suzhou, albedo 0.8)




- Considering worst case shading level 40%, **additional mismatch loss contribution** due to shading of torque tube significantly increases, **up to 1.9%**.
- Must optimize torque tube to module height for high albedo scenario.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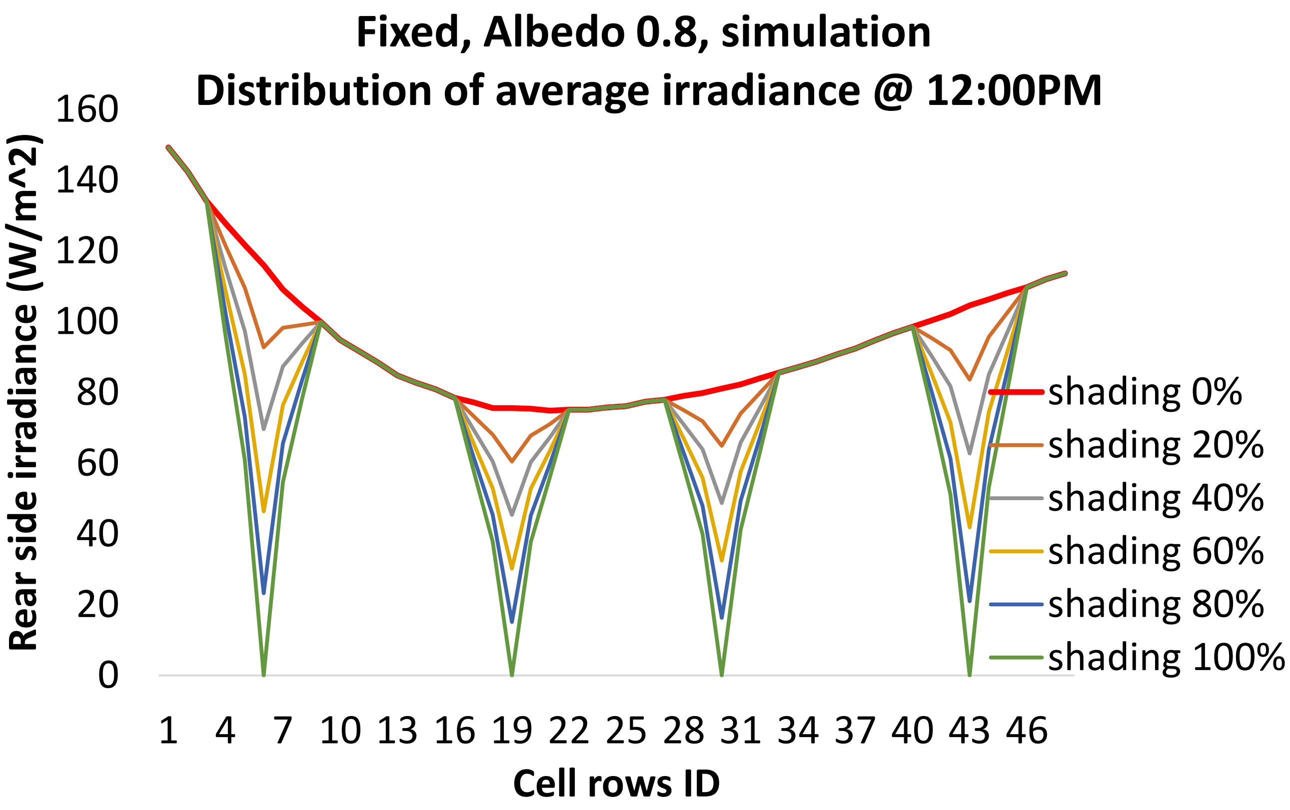
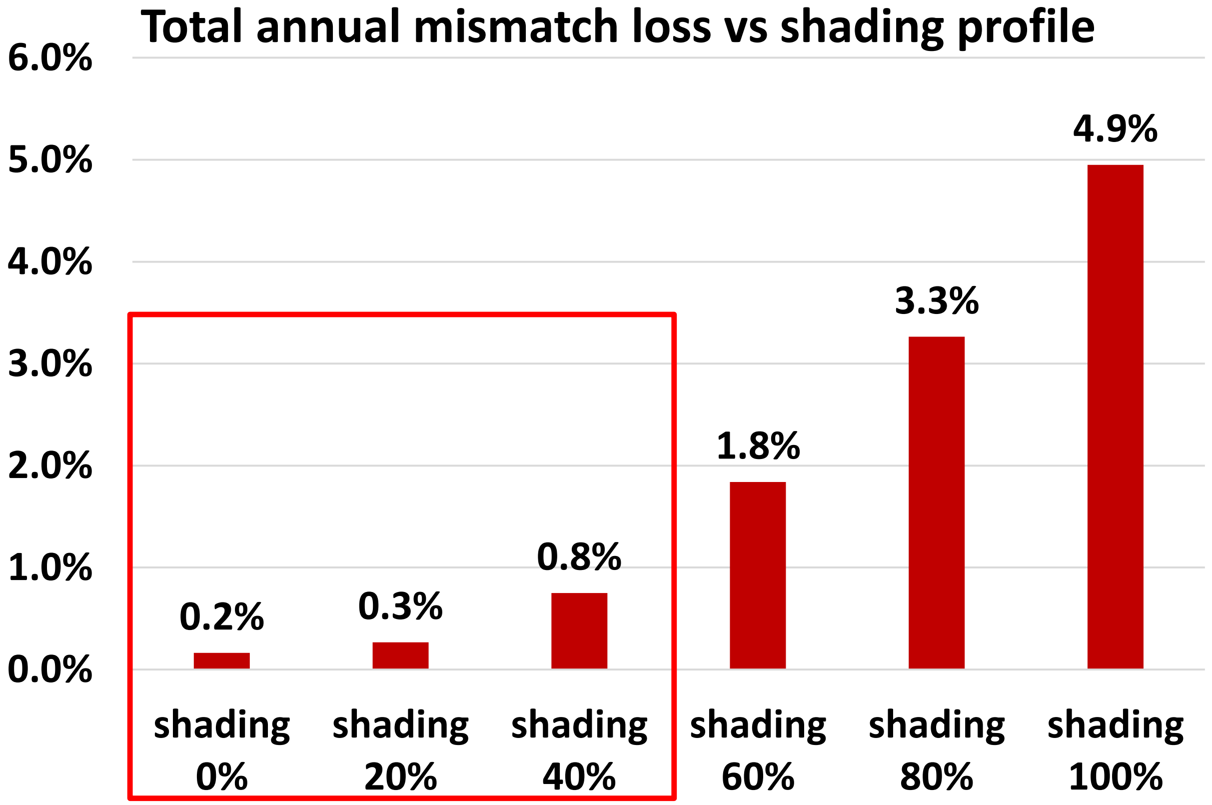
# Mismatch loss results – Fixed racking case (Suzhou, albedo 0.8)




- Considering worst case shading level 40%, **additional mismatch loss contribution** due to shading of mounting rails shading effect contribution is **0.6%**.

*Note: irradiance non-uniformity data for fixed racking is being collected, calculations use same assumptions as for the tracker case.*

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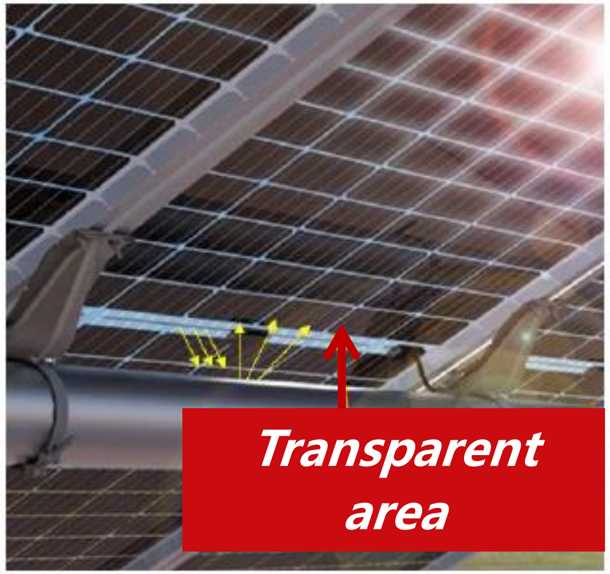
# Conclusions

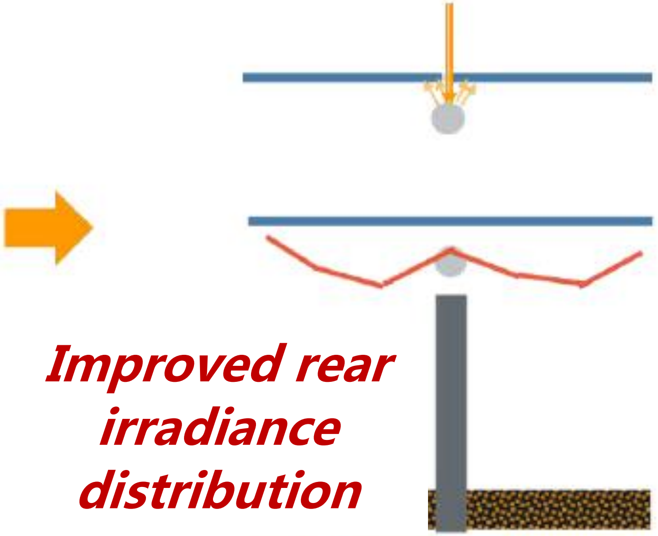
| Mounting structure effect included | Albedo | Mounting structure | Conditions | Total mismatch loss | Remark |
|---|---|---|---|---|---|
| No | 20% | Fixed & Tracker | Height 0.5-2m | 0.1%~0.4% | Considering all kinds of module connection topology |
| | 80% | Fixed | / | 1.1% | Mismatch loss increases significantly with albedo |
| | | Tracker | | 0.6% | |
| Yes | 20% | Tracker | Shading level 40% High DHI/GHI ratio site | **0.3%** | **Torque tube contributes 0.1%** |
| | 80% | | | **2.2%** | **Torque tube contributes 1.6%** |
| | 80% | Fixed | | **0.8%** | **Mounting rails contribute 0.6%.** |

- Simple approach using open-source tools to estimate bifacial system mismatch losses, applicable for any common Photovoltaic system designs.
- Tracker racking structure has large contribution to mismatch loss for high albedo cases, also certain hot spot risk associated, **6 cm minimum gap** recommended between rear glass and torque tube.

# Next steps

- Extend field testing and rear irradiance non-uniformity to higher albedo cases (reflective film with 0.7 albedo).
- Further validate the mismatch loss simplified calculations combining ray tracing and PVMismatch tool, including array edge effects.
- Optimize module design with transparent gap located at the module center position, allowing light transmission and reflection on SAT torque tube (higher average rear irradiance, flatter profile).



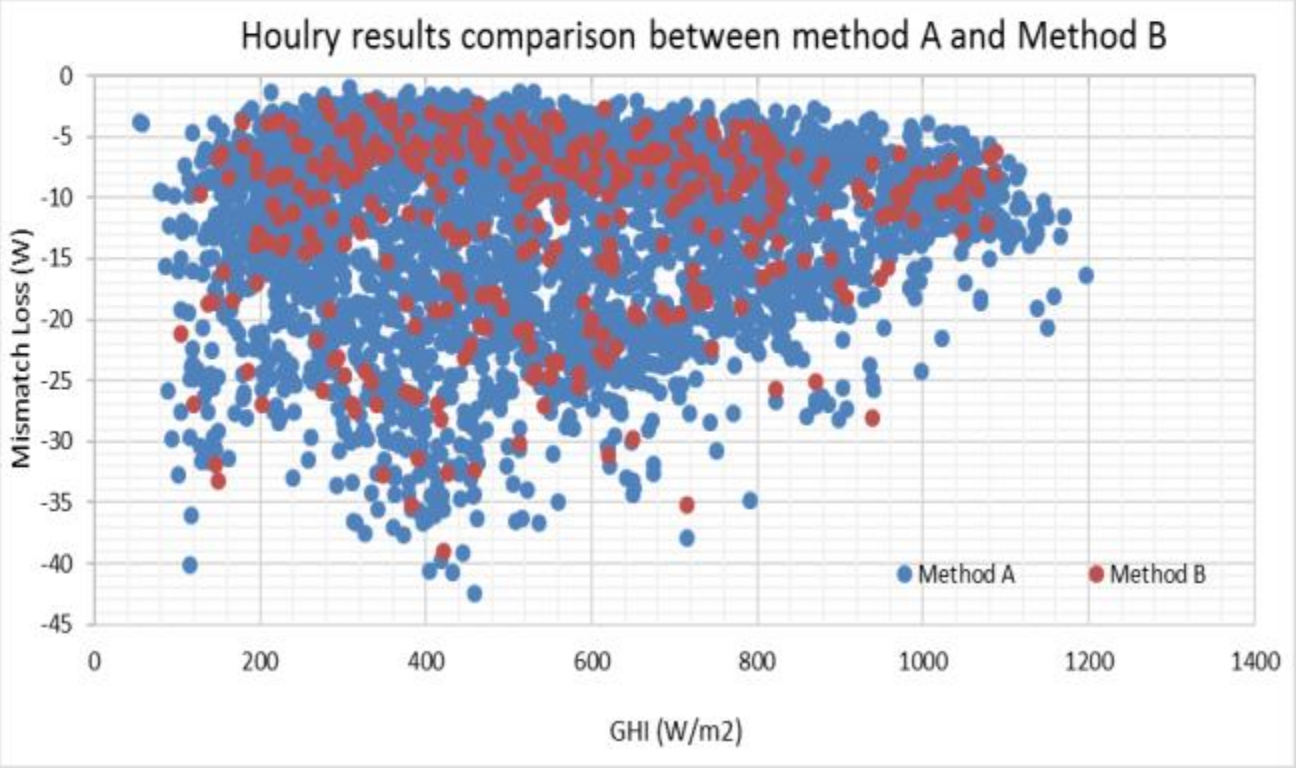




Thank you for
your attention
2018/8

# Back up slides

# Methodology introduction – Data process method selection

| Scenarios | System layouts | Locations | Mounting type | Albedo | Mismatch loss -B | Mismatch loss -A |
|---|---|---|---|---|---|---|
| 1 | Row 1<br>Row 2 | Golmud | Fixed | 0.2 | -0.14% | -0.14% |
| 2 | Row 1<br>Row 2 | Golmud | Fixed | 0.8 | -1.09% | -1.11% |
| 3 | Row 1 & Row 2 | Golmud | Fixed | 0.2 | -0.30% | -0.30% |
| 4 | Row 1 & Row 2 | Golmud | Tracker | 0.2 | -0.11% | -0.12% |
| 5 | Row 1 | Golmud | Tracker | 0.8 | -0.28% | -0.29% |
| 6 | Row 1<br>Row 2 | SuZhou | Fixed | 0.2 | -0.16% | -0.18% |
| 7 | Row 1 & Row 2 | SuZhou | Fixed | 0.2 | -0.38% | -0.37% |
| 8 | Row 1 & Row 2 | SuZhou | Tracker | 0.2 | -0.18% | -0.18% |




$$\text{Yearly mismatch loss B} = \left(\sum_{1}^{N_B} Modules\ power\right) / \left(\sum_{1}^{N_B} (Cells\ Power\right) - 1$$

**Method B is a time-saving way to provide accurate results**

*$N_B$ is the number of hourly data points of 10th, 20th and 28th in each month, excluding rear irradiance ≤15W.*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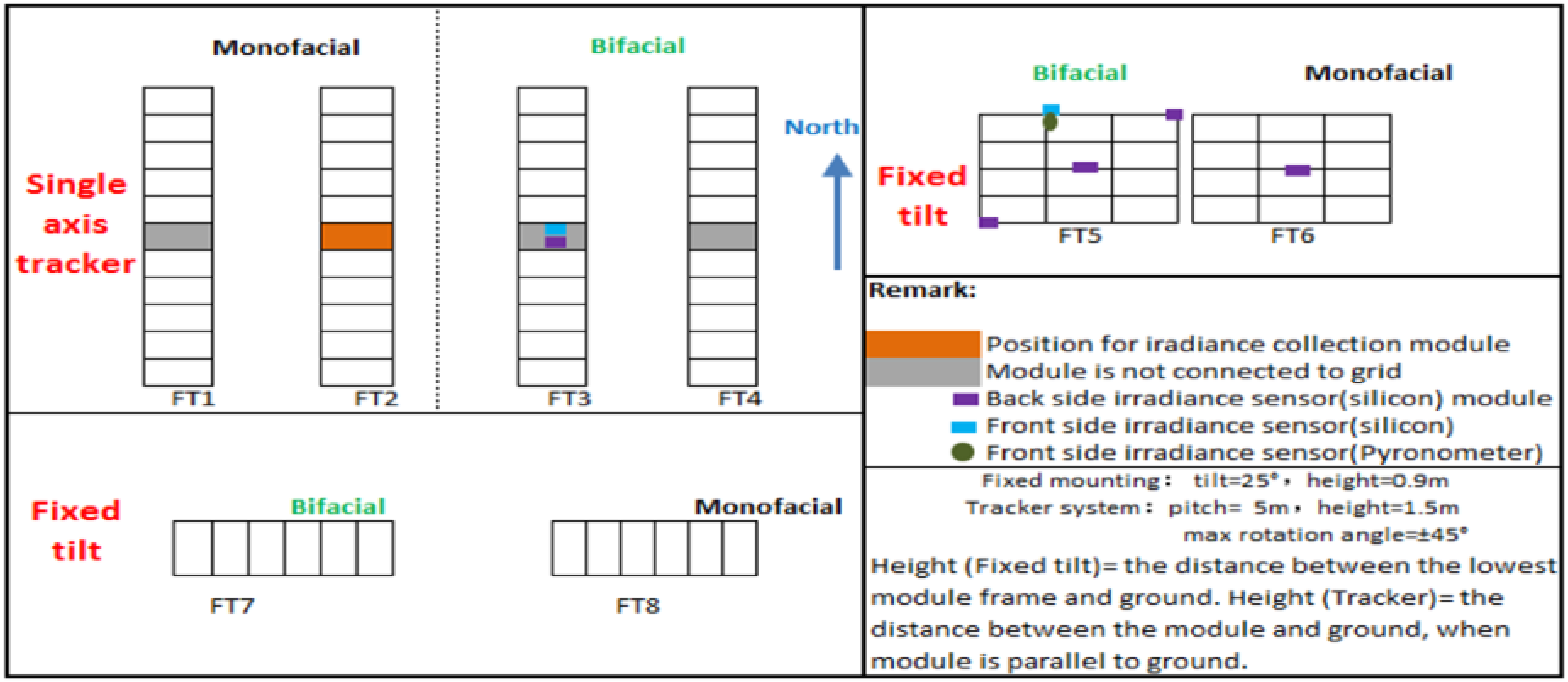
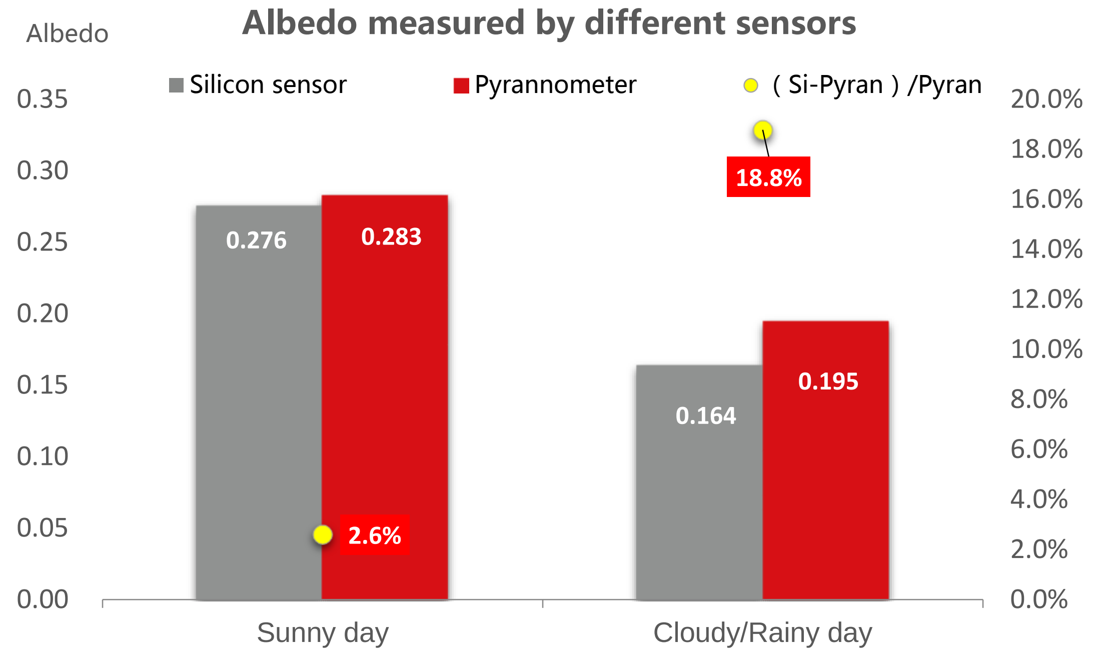
# Changshu field trial test platform – Introduction

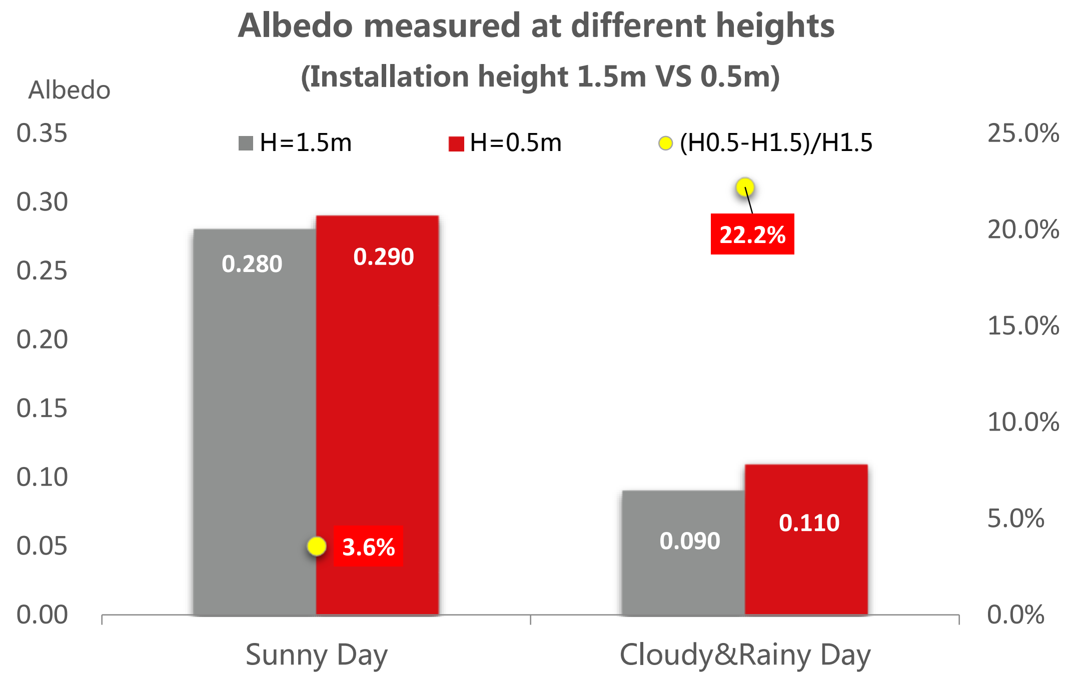
| Item | Mounting type | Module type | Module quantity | DC capacity (Kw) | Inverter | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Name | Nominal power | MPPT number | Max input current |
| SAT1 | Single axis tracker | CS3U-MS-FG | 10 | 3.71 | GROWATT 1000TL3-S | 10kW | 2 | 13A |
| SAT2 | | | 10 | 3.70 | | | | |
| SAT3 | | CS3U-MB-FG | 10 | 3.67 | | 10kW | 2 | 13A |
| SAT4 | | | 10 | 3.69 | | | | |
| FT5 | Fixed tilt | CS3U-MB-FG | 12 | 4.41 | GROWATT 1000TL3-S | 10kW | 2 | 13A |
| FT6 | | CS3U-MS-FG | 12 | 4.45 | | | | |
| FT7 | | CS3U-MB-FG | 6 | 2.20 | GOODWE GW5000-DT | 5kW | 2 | 11A |
| FT8 | | CS3U-MS-FG | 6 | 2.22 | | | | |




***DC/AC ratio***
***<0.75 (SAT)***
***<0.9 (fixed)***

# Changshu field trial test platform – Ground Albedo measurements

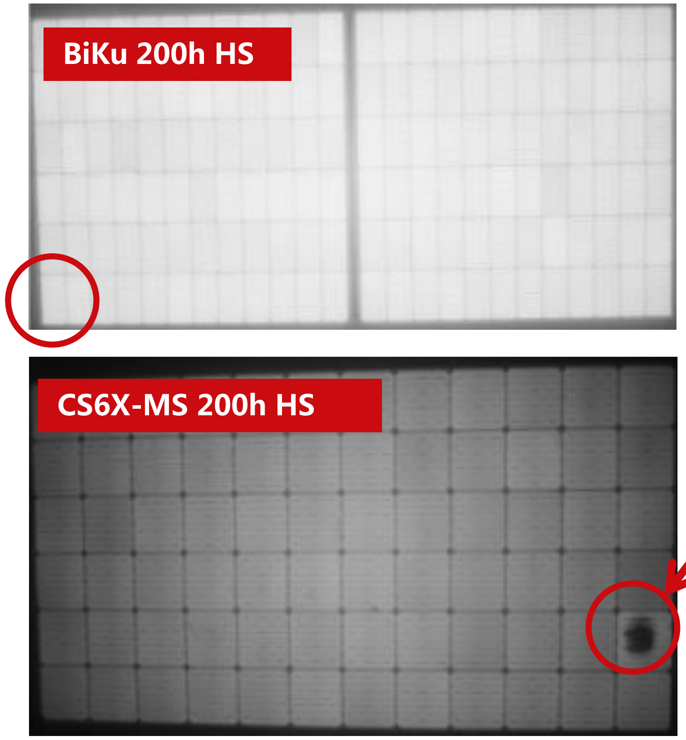


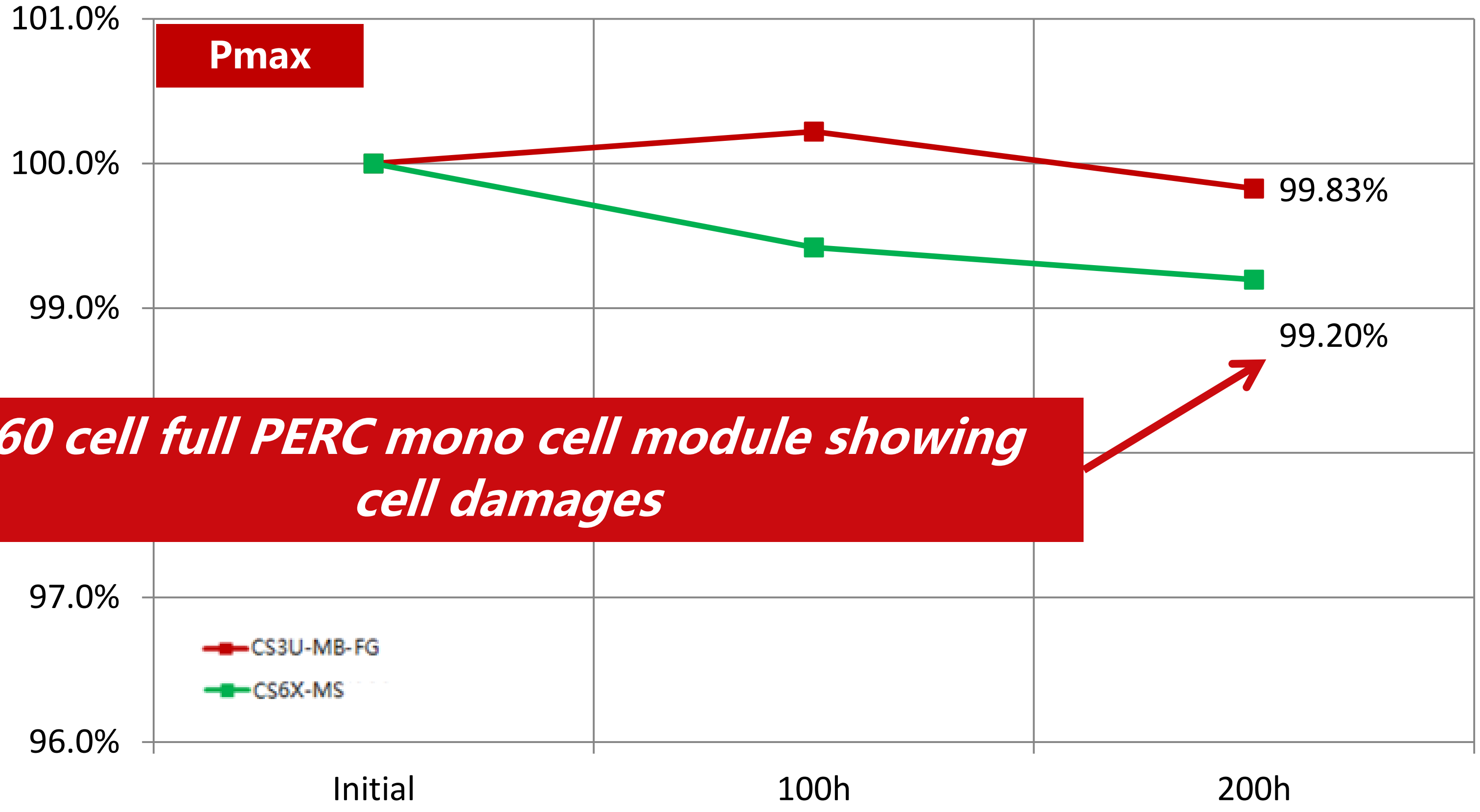

- On sunny days, measured albedo relative differences for pyranometer and silicon cell sensors below 3%.
- On cloudy & rainy days, measured relative differences increasing significantly (unexplained, on-going verification).

*ASTM E1918-16 "Standard Test method for measuring solar reflectance of horizontal and low-sloped surfaces in the field" recommended albedometer height is 0.5m*

# BiKu Module reliability test data – Hot spot 200h




Hot Spot test cell



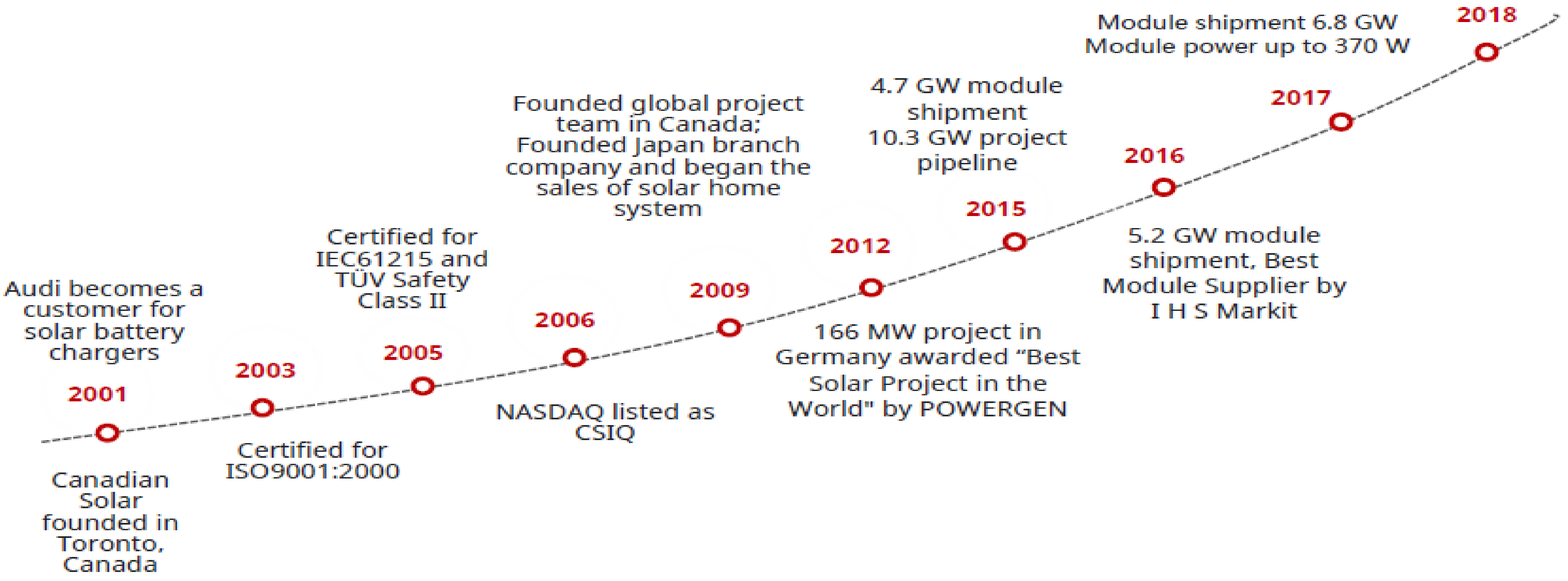

***60 cell full PERC mono cell module showing cell damages***

- CSI half-cell technology BiKu Module with excellent hot spot performance and endurance. **Power degradation <0.2%** observed after severe ASTM 200h hot spot test (1000W/$m^2$ front + 150W/$m^2$ rear), no fingerprint interruption or other EL defects observed.

# CSI Milestones

- No.1 silicon module solar plant developer by GTM 2017
- No. 1 Module Supplier for Quality and Performance/Price Ratio in IHS Module Customer Insight Survey
- BNEF Tier 1 solar company
- One of the leading companies in the 2017 PV Triathlon of PHOTON Consulting, based on financial health, profitability and sustainable strategy

Module capacity above 9 GW
Bifacial module up to 488W & eff. 24.5%，shipment guidance above 500 MW
Poly HiKu up to 405W， eff. 18.3%
Mono HiDM up to 330W，eff. 19.9%



# CSI Bifacial module at a glance


- BiKu CS3U
  Front side power up to: Mono 375 W Poly 365 W
  Front side eff. up to: Mono18.8% Poly18.3%

- BiKu CS3K
  Front side power up to: Mono 315 W Poly 305 W
  Front side eff. up to: Mono18.8% Poly18.2%

- Up to 30% more energy yield due to back side power generation

- Low NMOT: ( 42 ± 3 °C )
- Low temperature coefficient (Pmax): -0.37 % / °C
- Better shading tolerance