CASE STUDY OF POWER MISMATCH OF A BIFACIAL PV CANOPY USING RAY-TRACING MODEL WITH IMPROVED SAMPLING METHOD

EUROPEAN PVPMC WORKSHOP 2023

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OUTLINE

1. Introduction and motivation

2. Improved irradiance sampling method

- How to do the irradiance sampling accurately and efficiently?

Default — Sampling with Shift — One-go scan — Concurrent One-go Scan

3. Discussion on intrinsic mismatch loss

- Irradiance variation
- Module variation

4. Conclusion

Introduction

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Previous results presented in EUPVSEC 2023 (5BO.5.4) and WCPEC-8 (4DO.5.6)

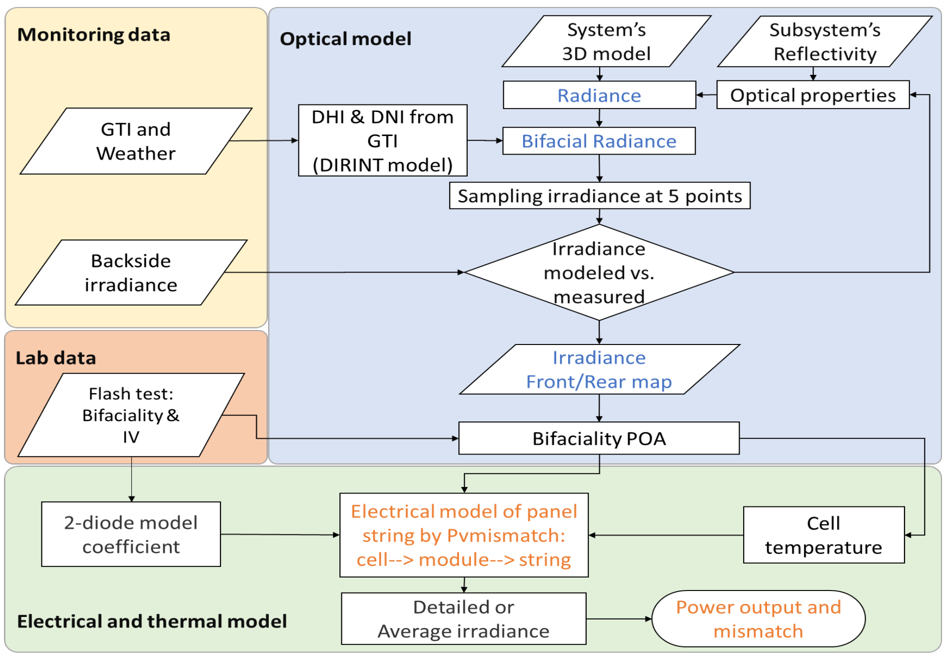
Monitored data

validation

System Modeling

Better understanding:

- Bifacial gain
- Degradation
- Snow loss
- Mismatch loss
- ……



How to simulate (back) irradiance accurately and efficiently?

Improved irradiance sampling method

- × Hardly eliminated
- × Stronger in bifacial system
- × Hardly measured
- ✓ Simulated with raytracing

Method

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Sampling on cell-level module: To get at least one point of irradiance on each cell within the module

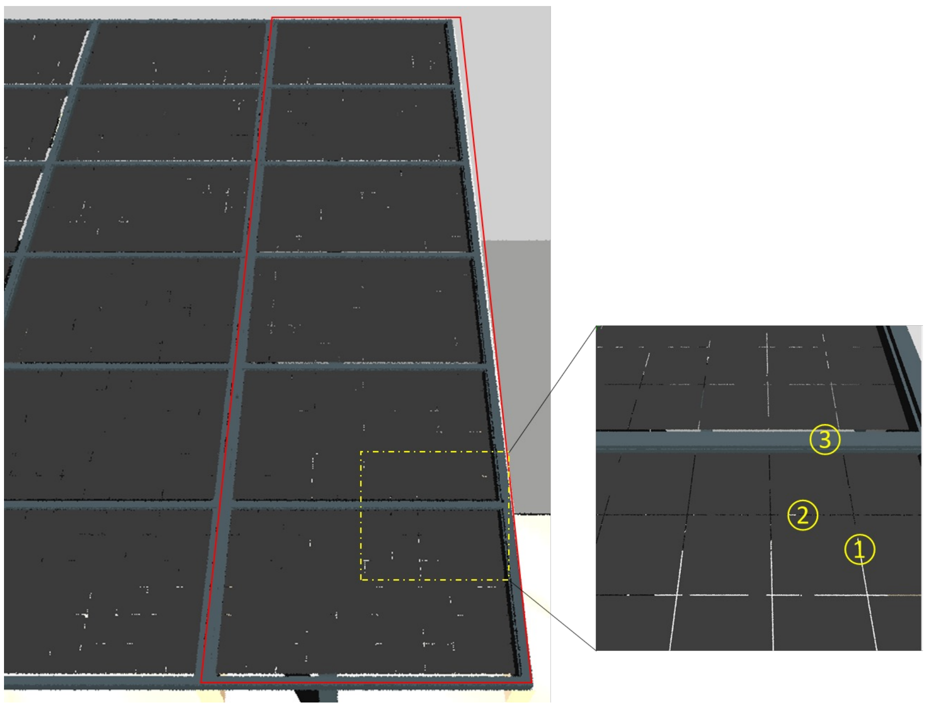
Default:

bifacial_radiance.AnalysisObj.moduleAnalysis

```
AnalysisObj.moduleAnalysis(scene, modWanted=None, rowWanted=None, sensorsy=9, sensorsx=1,
frontsurfaceoffset=0.001, backsurfaceoffset=0.001, modscanfront=None, modscanback=None,
relative=False, debug=False)
```
[source]

With default function in bifacial_radiance toolkit :

- Select one column of PV modules by *modWanted, rowWanted*
- Define number of the points by *sensorsy* * *sensorsx* (evenly distributed)
- Run the sampling in this column
- Repeat for the next column of modules



Challenges:

1. The sensor points may fall into gaps between cells or onto the frame between modules
   - Post-cleaning necessary
   - Missing points for some cells
2. If sampling for the whole array, needs to be done column by column
   - Could be more efficient

For 6*3 modules, 5 timestamps:
~25mins + post cleaning

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More accurate: sample the points with calculated coordinate shift

Sampling with Shift

bifacial_radiance.AnalysisObj.moduleAnalysis

```
AnalysisObj.moduleAnalysis(scene, modWanted=None, rowWanted=None, sensorsy=9, sensorsx=1, frontsurfaceoffset=0.001, backsurfaceoffset=0.001, modscanfront=None, modscanback=None, relative=False, debug=False)
```
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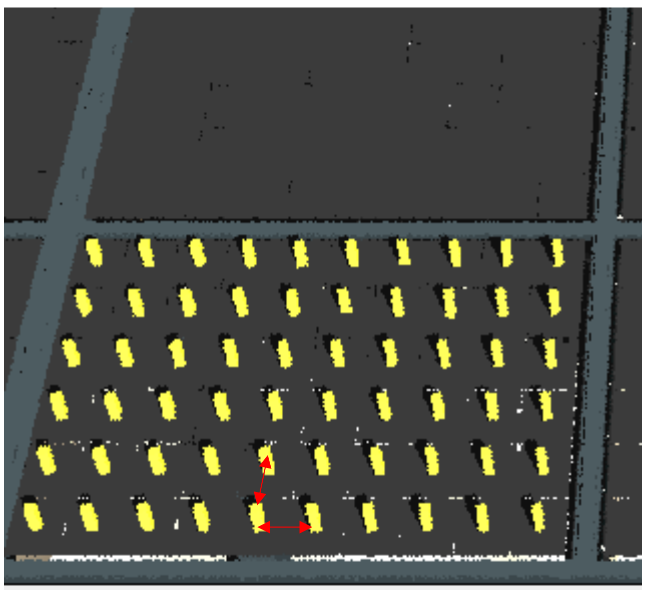
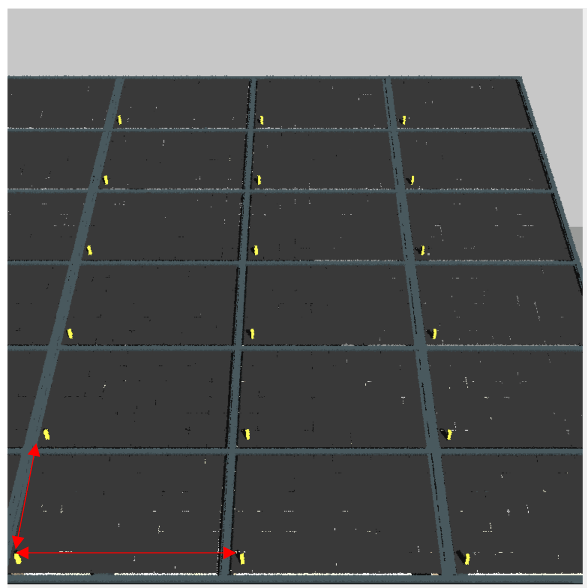
- Calculate the coordinate shifts between cells and modules along x- and y- axis
- First sampling within one module
- Then jump to the next, repeat previous step
- Run over all the cells

First scan within the module



Then move to other modules



- All the cells can be accurately sampled without any post treatment.
- Still with built-in function with *modscanfront* and *modscanback* arguments
- But scan is only possible module by module

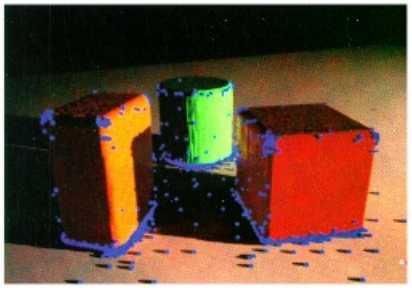
Accurate but too Slow!

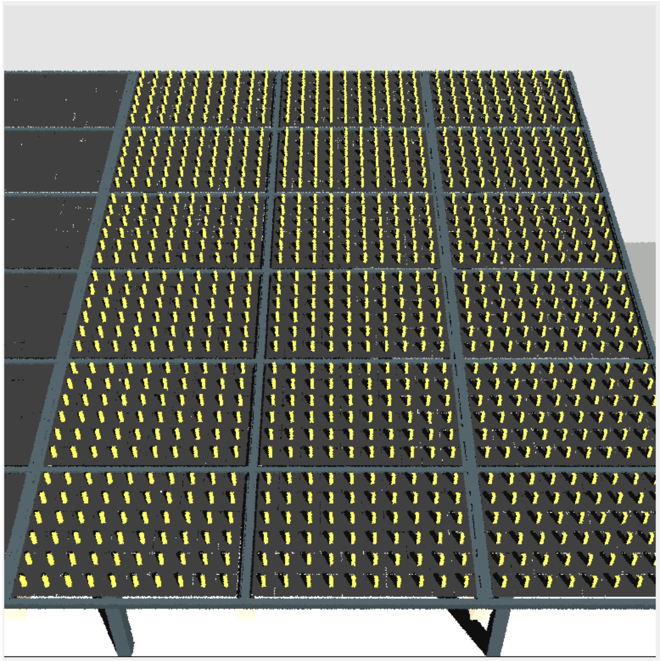
For 6*3 module, 5 timestamps: ~65mins

Method

Faster: Create the coordinate map for all the sensor points and simulate at once

- **Irradiance caching algorithm* in Radiance:**
  - Indirect irradiance varies slowly over the scene
  - The algorithm calculates indirect irradiance sparsely across a scene and caches them
  - The irradiance at the new sampling point can be interpolated from cached values using irradiance gradients instead of initiating new ray tracing





One-go scan

- Jump out of the built-in function
- New Function to generate the coordinates for all the sensor points
- Call *radiance* directly and run the simulation with **ALL** the coordinates at once
- The Indirect irradiance cached for interpolation just needs to be calculated once rather than for every module loop
- Effectively speed up the simulation. The more points, the more time saved.

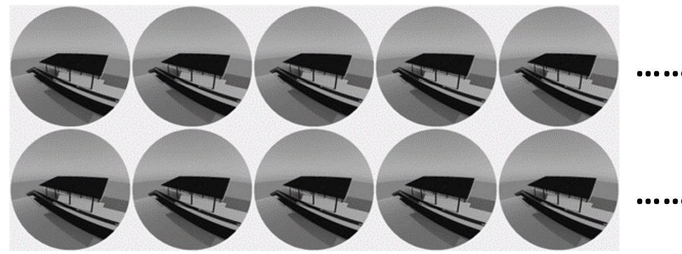
For 6*3 module, 5 timestamps: ~15mins

*Ward GJ, et al. A ray tracing solution for diffuse interreflection. In: Proceedings of the 15th Annual Conference on Computer Graphics and Interactive Techniques: 1988:85-92

Method

Faster: Run simulations for different timestamps concurrently

Concurrent One-go Scan



Select the proper concurrency method in Python:

- **file-based IO-Bound Tasks** → *threading module*
  - reading oct files, coordinates, calling Radiance for each timestamp, writing results into files…
- **Shorter-lived tasks** → *thread pool*
  - a pool of reusable thread workers for different timestamps
- *ThreadPoolExecutor* class

- Create oct files for all the timestamps concurrently
- Run the 'one-go scan' with all the oct files concurrently
  - Several simulations in progress at the same time
  - Take the max capability of the computer, how much gain depends on computer

For 6*3 module, 5 timestamps: 3mins

Method

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Comparison of computing time#

Method	18 modules *1 timestamp [mins]	18 modules *5 timestamp [mins]	48 modules *1 timestamp [mins]	48 modules *5 timestamps [mins]	48 modules*4561 timestamps (one year in Turku) [hr]
Default	5	25	13	64	965
Sampling with Shift	13	65	33	165	2508
One-go scan	2.8	15	5.1	25.5	237
Concurrent One-go Scan	2.75	3	5	5.5	57.8

The simulation speed can be enhanced by around **20 times** without sacrificing any accuracy and without any extra computing resources

#with Laptop computer: Intel Core i7 2.7GHz, 32GB RAM

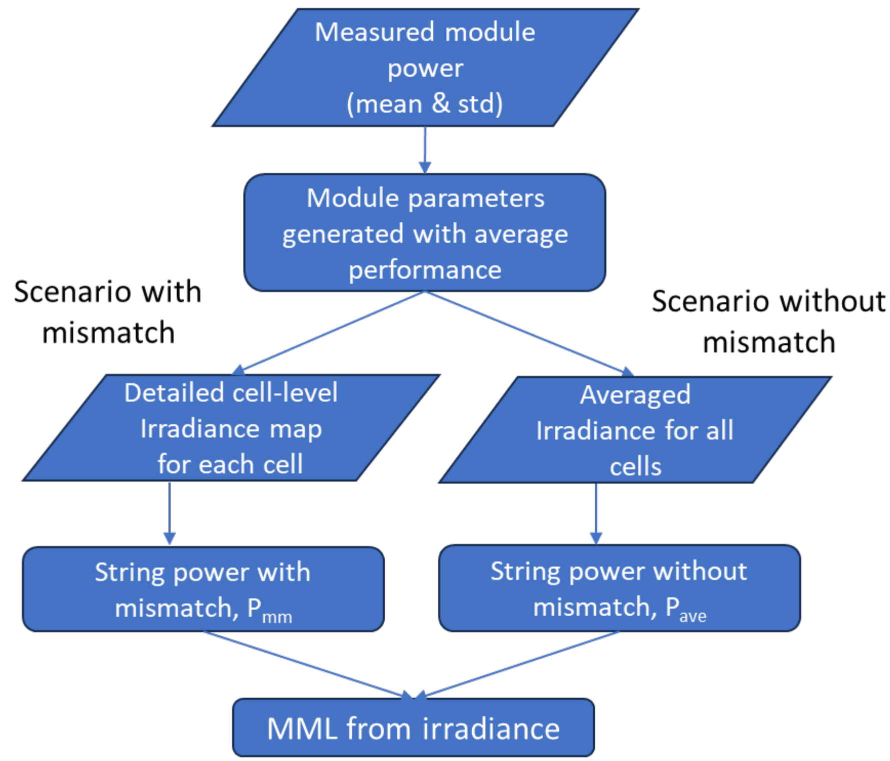
Mismatch loss

Mismatch loss reduces energy yield, comes from both optical and electrical variations:

- Optical
  - Intrinsic: **back irradiance** (sun position, edge effect, supporting structures, ground albedo…)
  - Extrinsic: clouds, soiling, shading from surrounding buildings, trees and other modules…
- Electrical
  - Intrinsic: **module performance variation**
  - Extrinsic: failure or degradation of specific cell or module

Discussion of intrinsic source in this study

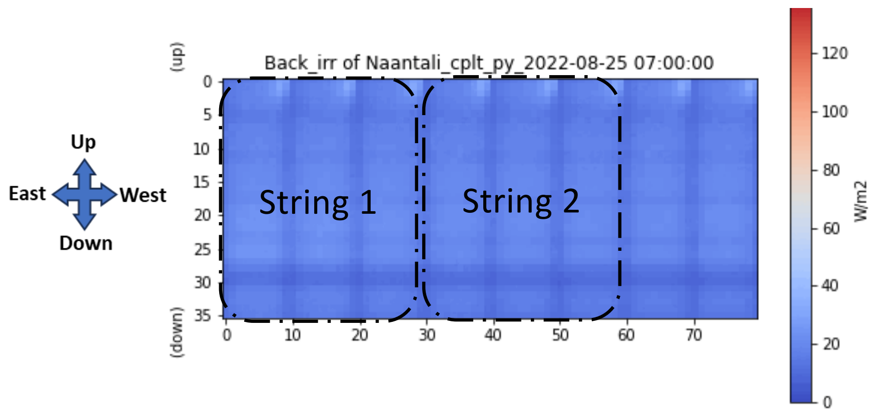
Mismatch loss from irradiance variations



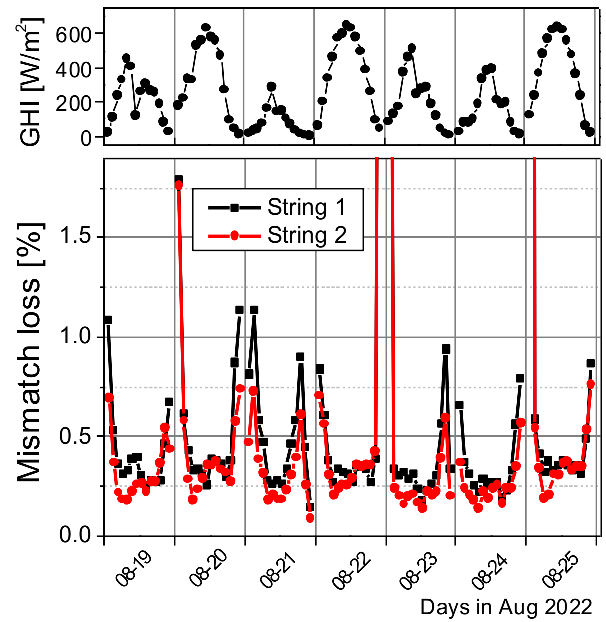
$$MML = (P_{ave} - P_{mm})/P_{ave} * 100\%$$

Mismatch loss from irradiance variation

Back irradiance with the perspective from backside on 25 Aug 2022



Mismatch loss for two monitored strings in real

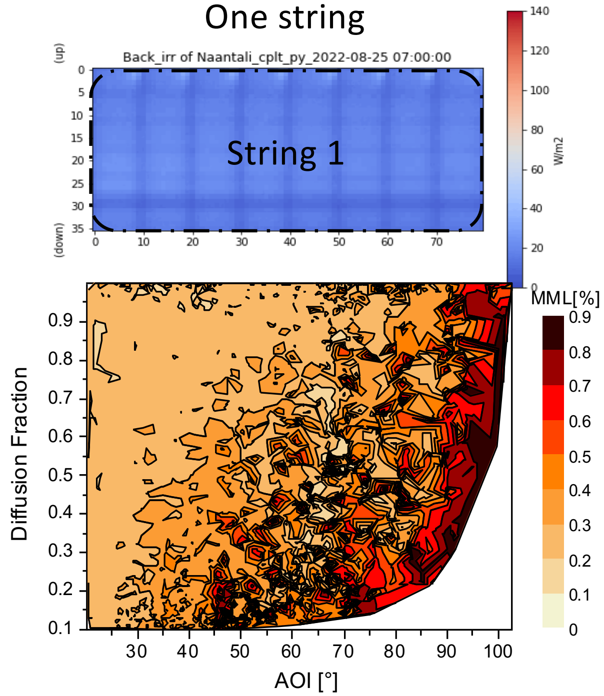


- Primarily dependent on time → **sun position**
- Also seems to depend on solar irradiance → **diffusion fraction in GHI**
- Higher MML for string1→ **connection configuration**
  - Especially in the morning on sunny days

Further Virtual experiments

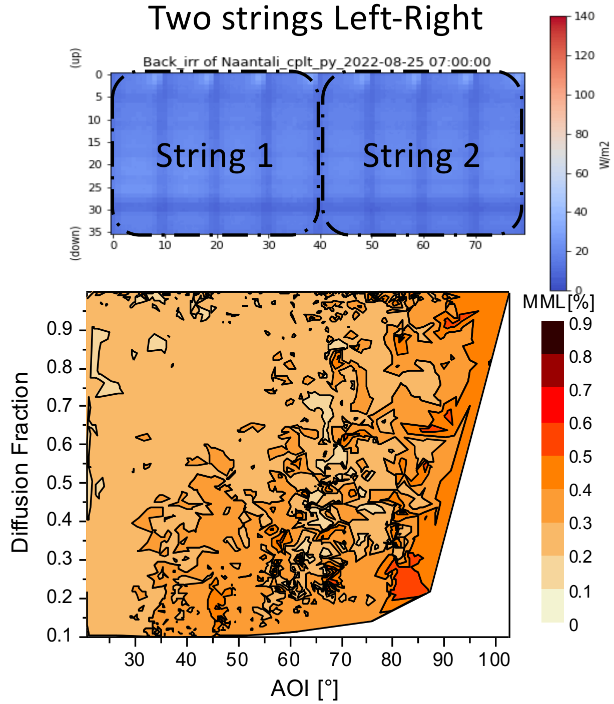
- Different **connection configurations** for the whole canopy
- Modules are connected in series within the string, strings are connected in parallel between strings

One string



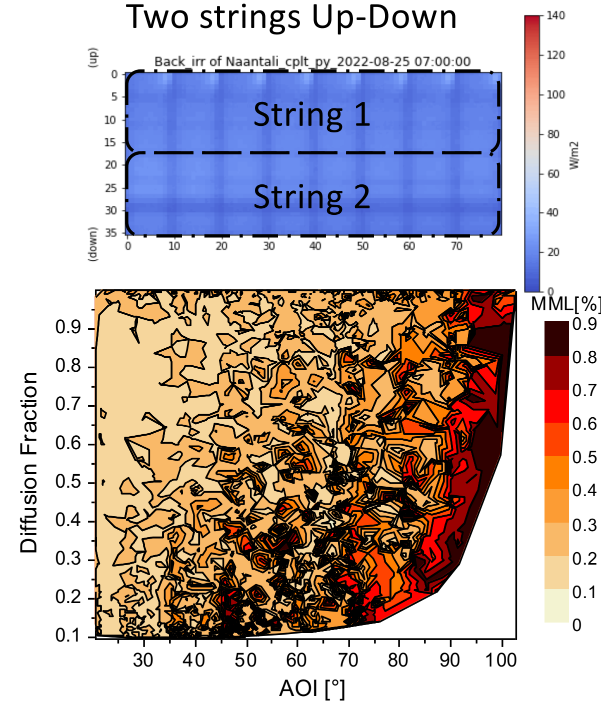
One-year MML: 0.459%

Two strings Left-Right



One-year MML: 0.385%

Two strings Up-Down



One-year MML: 0.379%

- 2-string LR shows lower MML than others with high AOI; 2-string UD shows lower MML with low AOI
- 1-string always show high MML, is worse than others to reduce the MML
- The higher the percentage of low-AOI irradiance is, the more advantage U-D configuration can provide.

Mismatch loss from module variation

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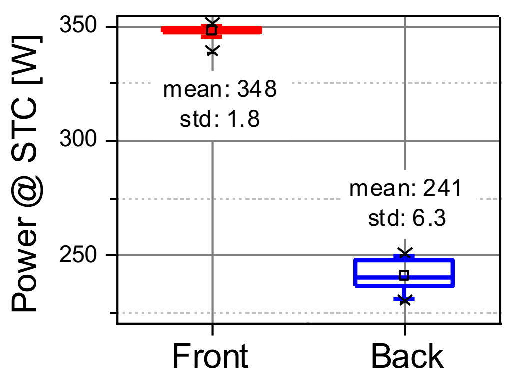
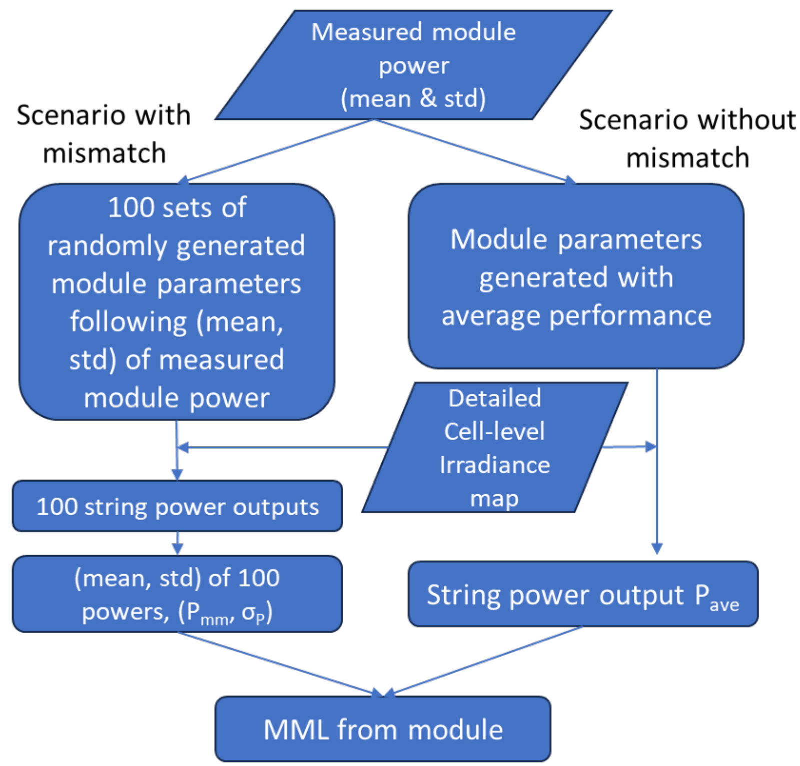
- Non-uniform electrical performance of modules in the array
- Bifacial modules introduce more uncertainties
- Hard to measure, calculate and control (installation sequency usually randomly determined by the worker)
- **Virtual experiments** with measured module statistical properties and detailed simulated irradiance map

Statistics from 50 modules measured from our lab



- Relative std: front 0.51%, back 2.6%
- Higher uncertainty from backside



Mismatch loss from module variation

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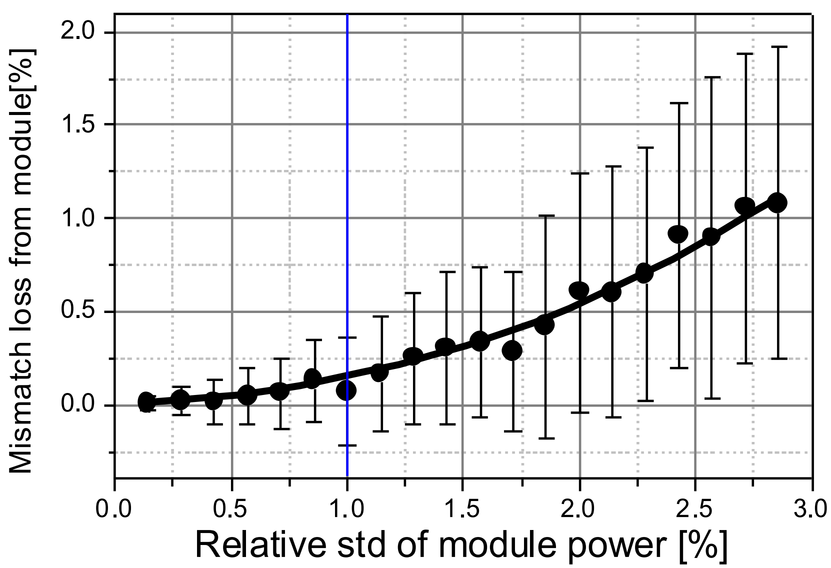
Dependence on power variation

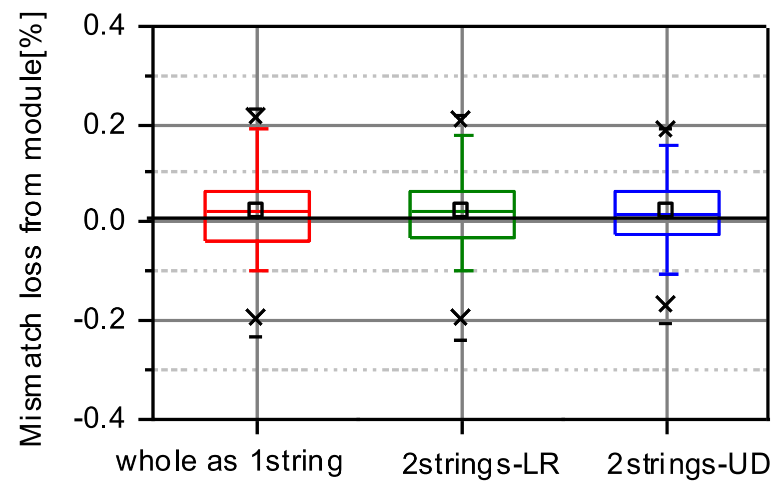
- MML calculated with same mean value but different *std* of modules
- Mean MML and uncertainty increase with increasing module *std*



- Assuming tolerance of 3% and normal distribution, the corresponding std is 1% (99.7% included)
- MML from module of 0.15% expected, with uncertainty of 0.28%

Dependence on connection configuration

- Considering the whole canopy
- 3 types of connection configurations as previously discussed: one string, 2stringLR, and 2stringUD



- 2strings UD configuration shows the lowest mean MML and uncertainty

Conclusion

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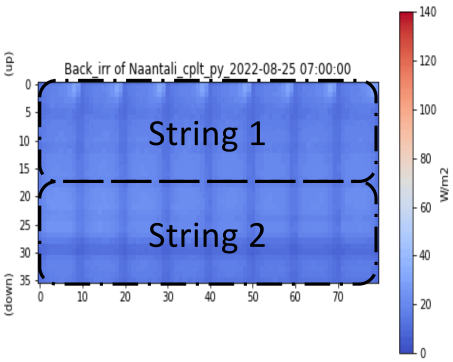
✓ **An improved irradiance sampling method proposed**

- As a complement to the Bifacial_radiance toolkit for accurate sampling on each cell
- Speed up the simulation by about 20 times without sacrificing any accuracy and without any extra computing resources

✓ **Better understanding of intrinsic mismatch loss in the canopy system**

- Caused by irradiance variation:
  - Angle of incidence is the main influencing factor;
- Caused by module variation:
  - Mean MML of around 0.15% is expected when using modules with power tolerance of 3% ;
- For this kind of standalone canopy, **2-string connection with Up-Down configuration** is recommended to minimize the mismatch loss



Extension

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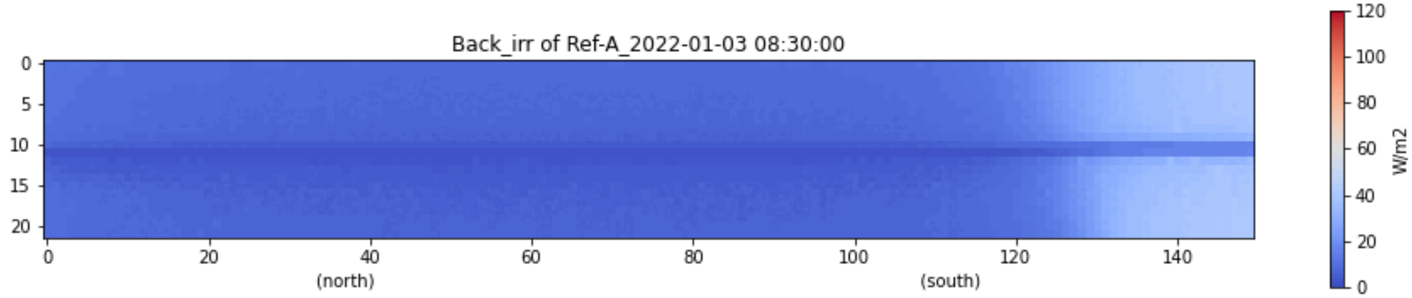
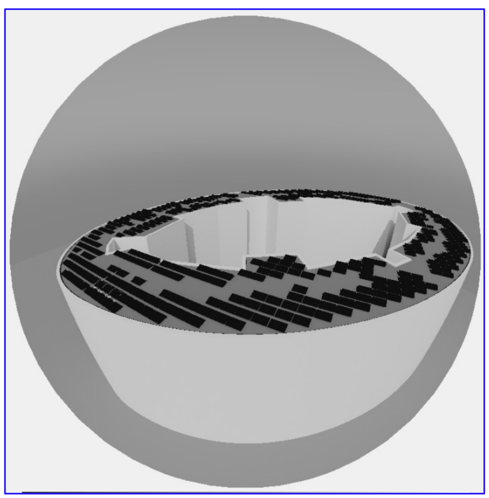
The sampling method works well for tracking system

- IEA PVPS Task 13 (Activity 2.3): PV Simulation Study of Bifacial Photovoltaic Systems on Single Axis Trackers



The method also applied in the simulation for another roof-top system (Tyyssija).



Anyone who is interested in our method can find the scripts from our Github website:

https://github.com/nercturku/BifacialRadianceSampling.git

Thank you!

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Team website

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Github

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Method

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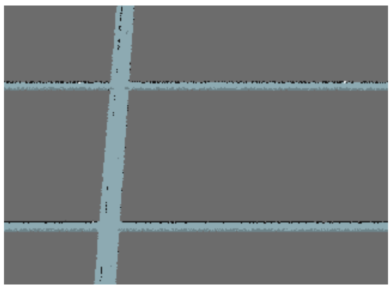
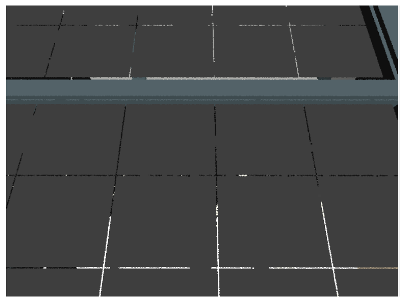
How to create PV modules in the model?

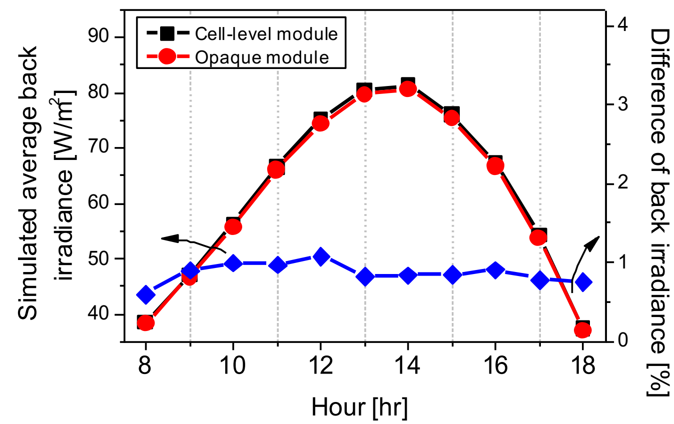
Opaque rectangular objects



Or

With cell-level features





From on-site photo:

- Glass-glass module could be semi-transparent

From simulation:

- Back irradiance could be enhanced with transmitted light through the cell-level module
- Enhancement dependent on ground albedo

Cell-level module used

Mismatch loss from irradiance variation

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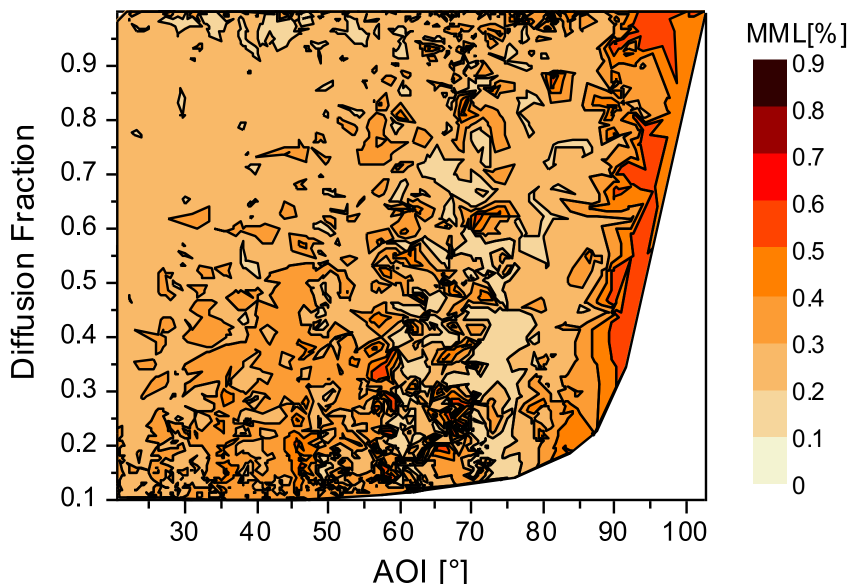
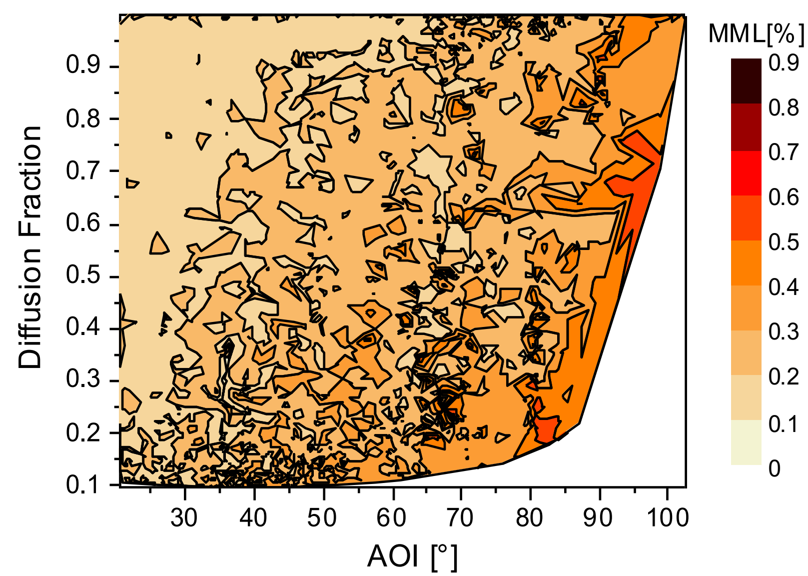
Dependence on sun position and diffusion fraction

MML map for String 1



MML map String 2



- Simulation for the period of one year
- Filtered from outliers
- AOI calculated with solar position and module orientation

- For string2:
  - Stronger dependence of AOI: the higher AOI, the higher MML
  - Weak dependence of DF: the lower DF, the higher MML.
- String1 only shows highest MML with highest AOI and weak dependence of DF
- The trend of MML depends on connection configuration

Mismatch loss from module variation

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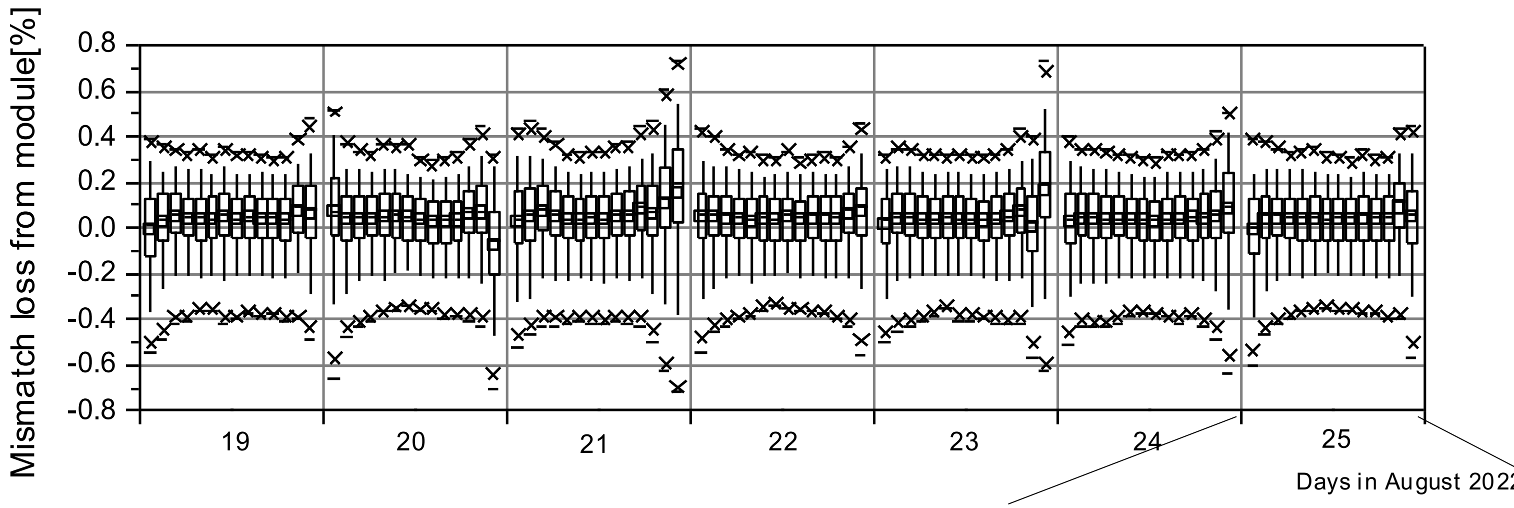
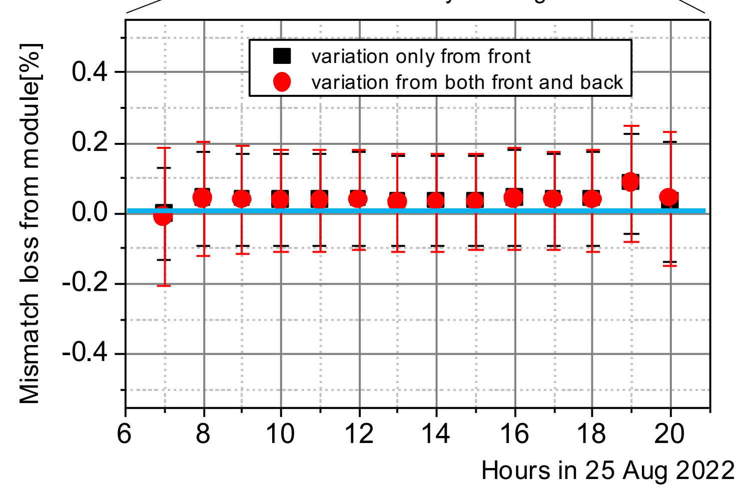
Dependence on time & Influence from back-side variation





- The expectation of mismatch loss is not highly sensitive to solar irradiance. Higher uncertainty in the early morning and late afternoon
- The expectation of daily loss is around 0.036%
- The non-uniformity of backside increases the uncertainty of MML slightly from 0.13% to 0.14%
- In our case, MML from module is very little.