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AgriPV: what light should be shared between agriculture and solar panels?

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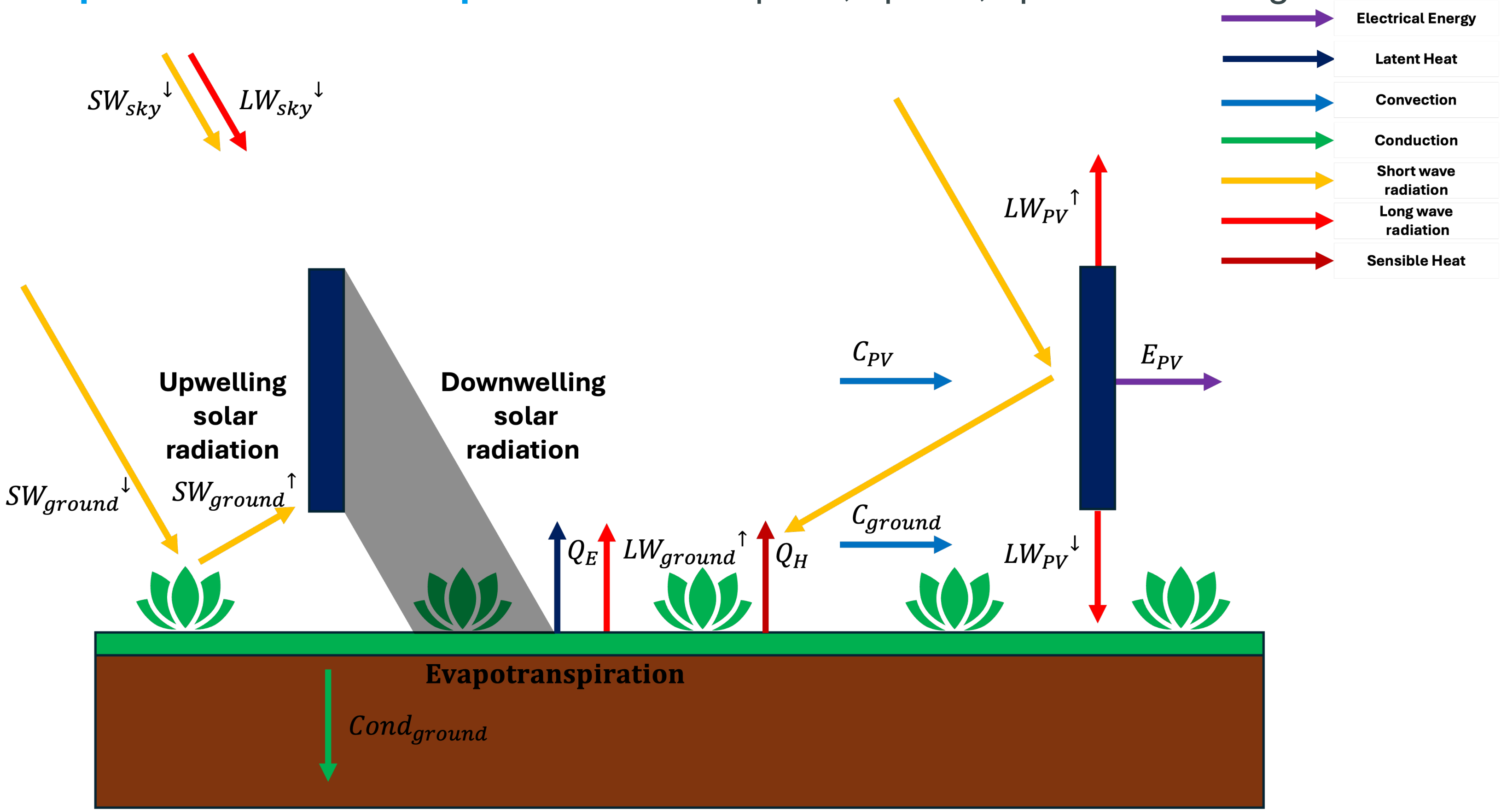
Challenges of AgriPV modeling

Short wave radiation is the primary driver of synergy between **Crop production** and **Photovoltaic production** but **there is a need to improve it modelisation**:

- Shading projection and **conservative assumptions** remain the norm
- Need to **improve the optical model in multiple domain**: temporal, spatial, spectral and angular



Dual-land use and co-dependent yields

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Climate Change

- Water Stress
- Heat wave
- Extreme climate event

Impact →

← Mitigation

Microclimate Evolution

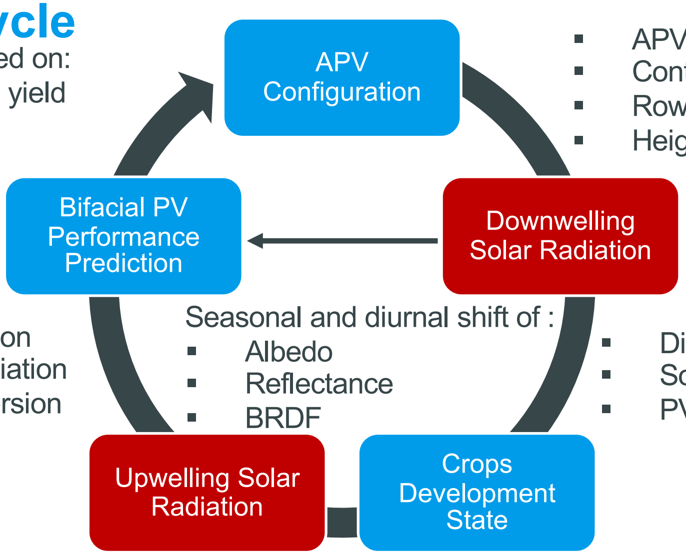
- **Solar radiation**
- **Temperature**
- **Evapotranspiration**
- **Water use efficiency**

For other components defining the microclimate, similar cycle can be represented

Solar radiation cycle

Optimization based on:

- Agronomical yield
- PV yield



- APV classification
- Controllability
- Row spacing
- Height

- Upwelling solar radiation
- Downwelling solar radiation
- Photo-electrical conversion

Seasonal and diurnal shift of :

- Albedo
- Reflectance
- BRDF

- Diffuse ratio
- Solar position
- PV structure shading

Agronomical Yield

Photovoltaic Yield

What is the response of an Agrivoltaics system to reflectance evolution, how does it affect the bifacial energy gain/bifacial optical gain?

Channay Pilot site (Côte d'Or, France)

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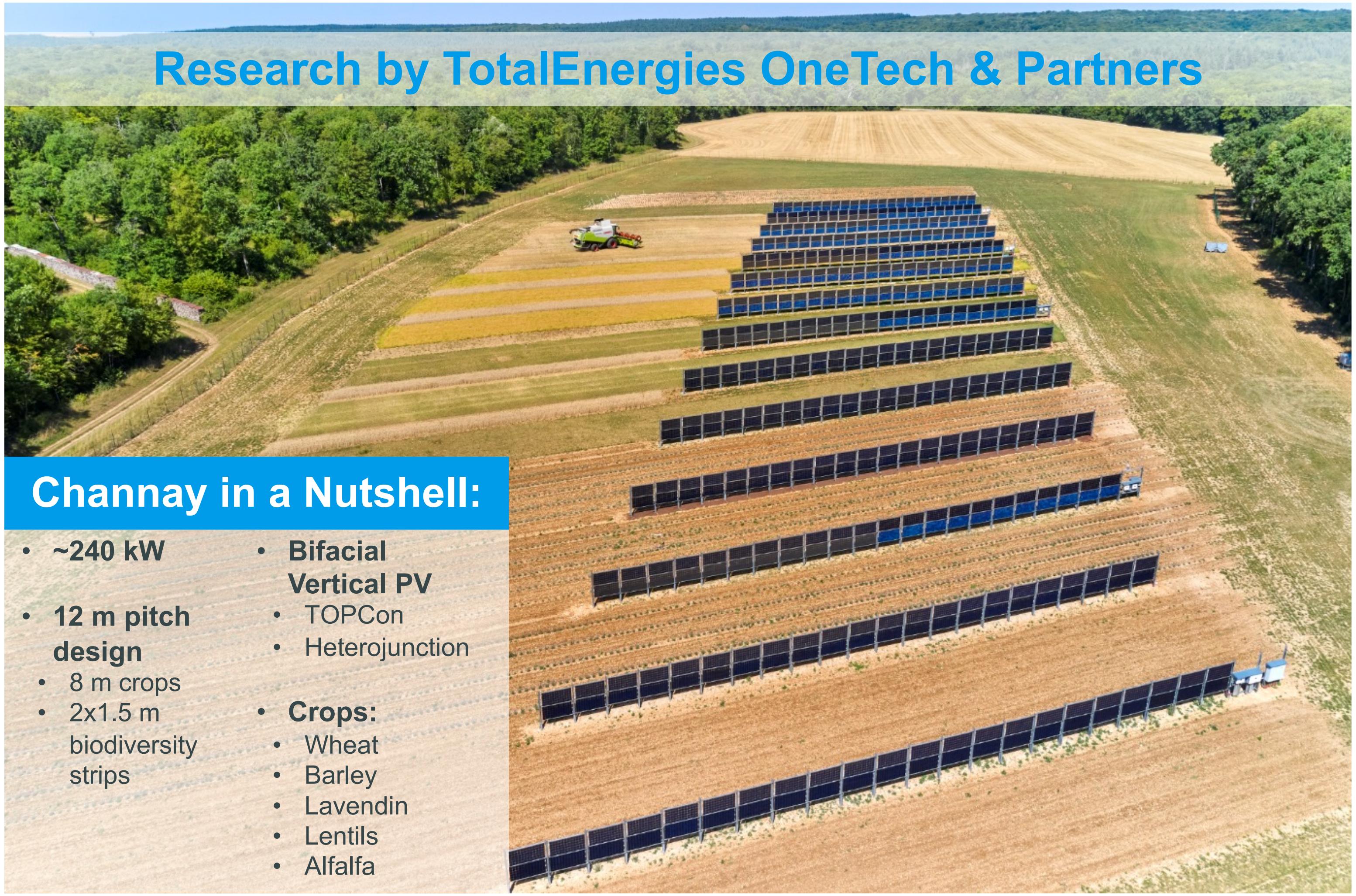

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Agronomics: Yield, phenology (also looking at remote sensing), weather monitoring, remote sensing for crops health monitoring. Yield modeling (using own developed software)

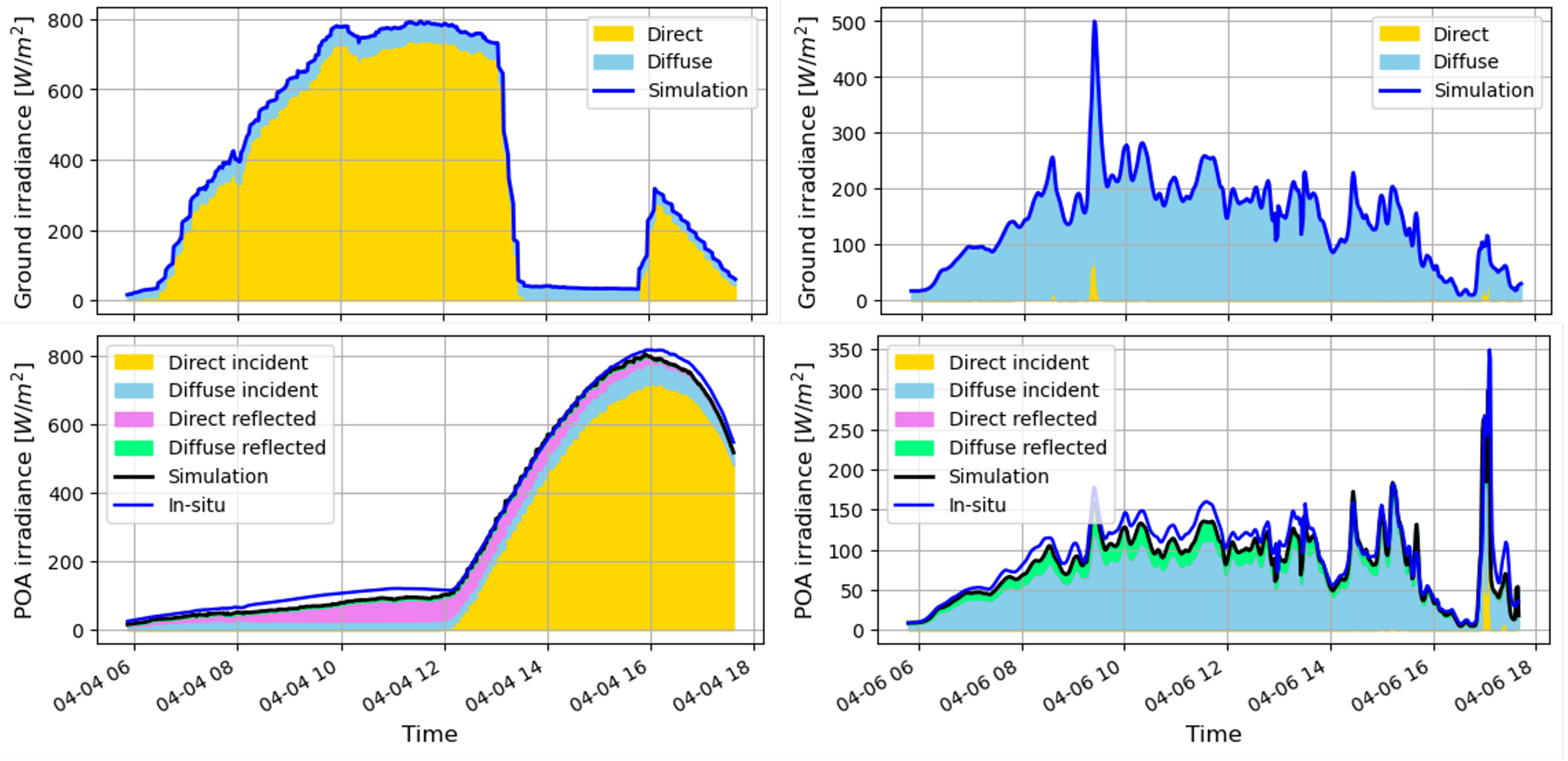
Soil: temperature & hydric tension, microbial biomass and diversity, soil chemical & physical fertility, remote sensing for water stress monitoring

Biodiversity: eDNA indicators monitoring, bees monitoring

Photovoltaics: Performance analysis & Modeling (using own developed software)

System analysis: techno-economic assessment, carbon diagnosis and life cycle assessment.

Synergies comprehension



- Crops and PV module **share the incident irradiances** (Direct and Diffuse)

- From the point of view of PV production, **synergy at the irradiance level is the reflected components**

Ground irradiance distribution

Motivation

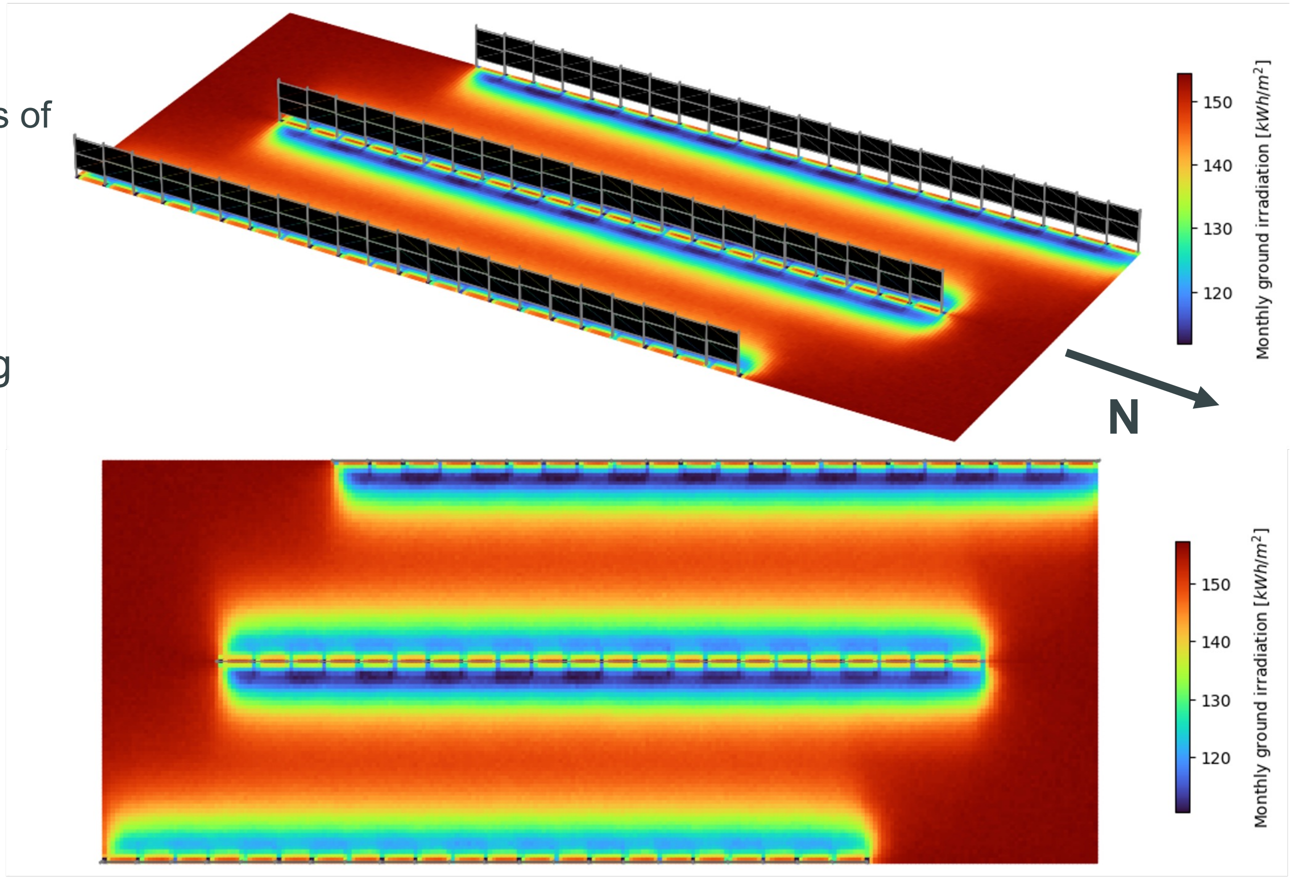
- Improving the estimation of **incident solar radiation** on:
  - arbitrary orientation and elevation
  - incorporating **spectral** and **angular** distributions
  - **dealing with geometric** effects, based on **temporal** variabilities of atmospheric and ground conditions

Ray-tracing based methodology

- **Separate time-varying conditions from geometry** using the matrix flux method

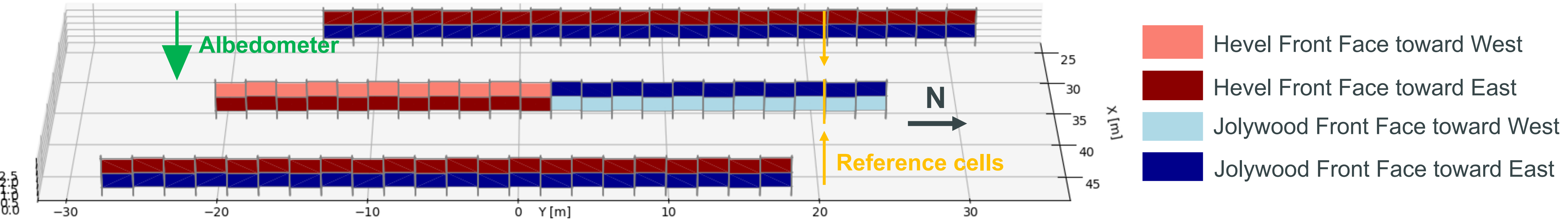
- Cumulative sky allow to provide Ground irradiance distribution for **arbitrary period**

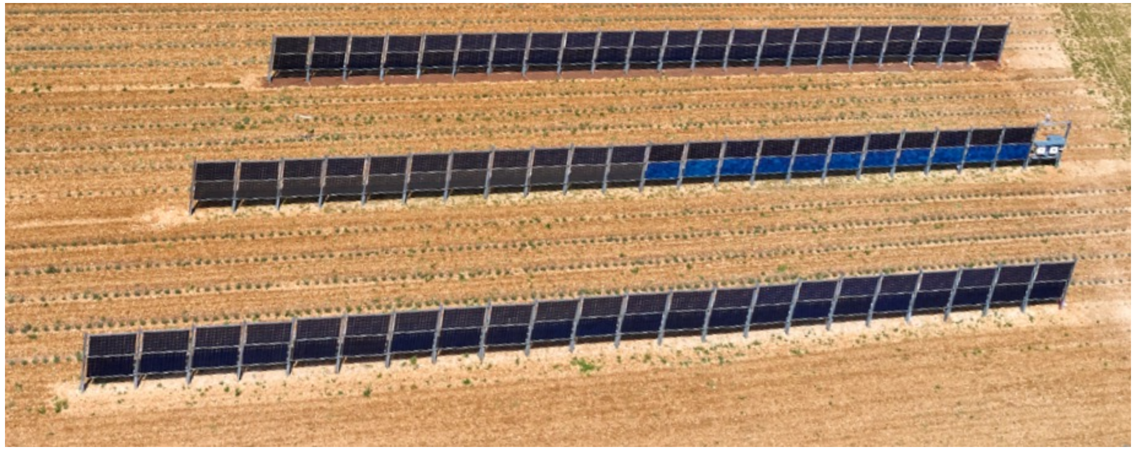
May 2023 – 1 minute resolution basis aggregated



PV module irradiance distribution

Simulation model - Channay





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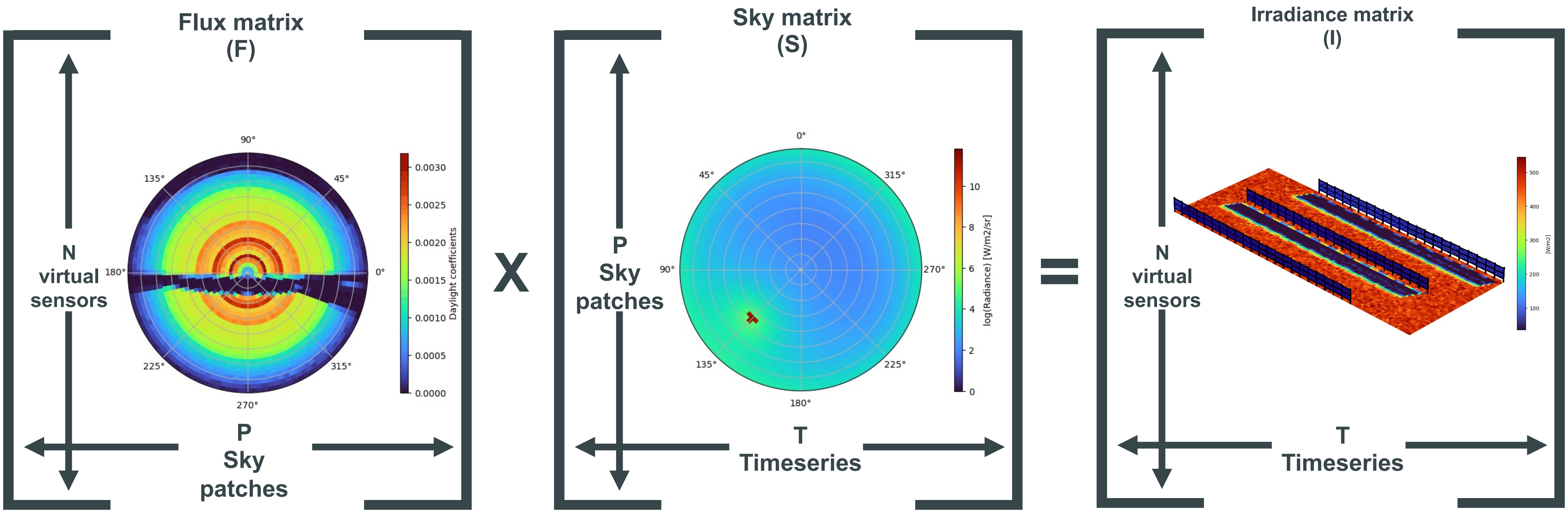
Flat terrain:

- Separated optical properties for East/West Side and Top/Bottom
- Additional division for Jolywood/Hevel for monitored row
- Reference cell are replicated

Transfer function approach

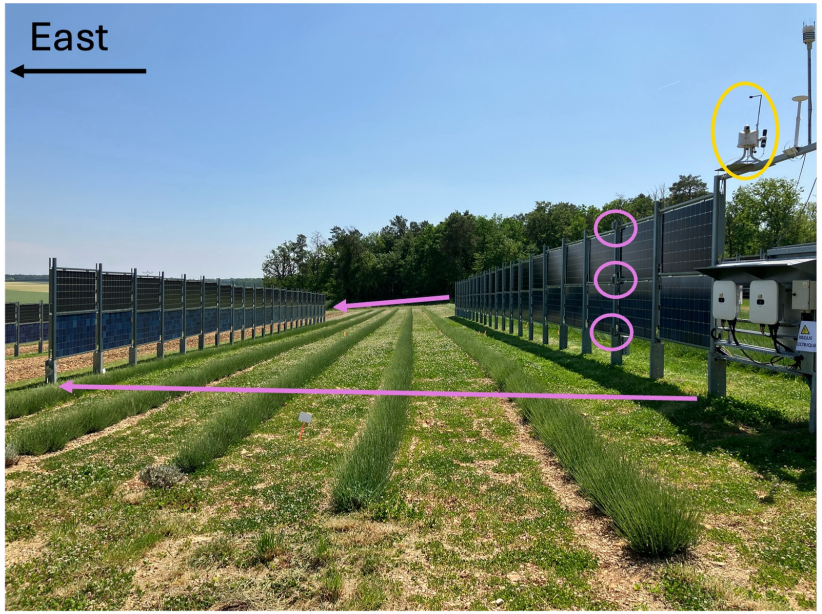
Matrix based equation: FS=I



<u>Advantages:</u>

- 1-minute basis temporal resolution
- High spatial resolution: Sub-PV cell resolution and 0.5mx0.5m grid for Ground
- Potential of pre-computed simulations: What-if analysis and custom tracking algorithm

In-situ measurements



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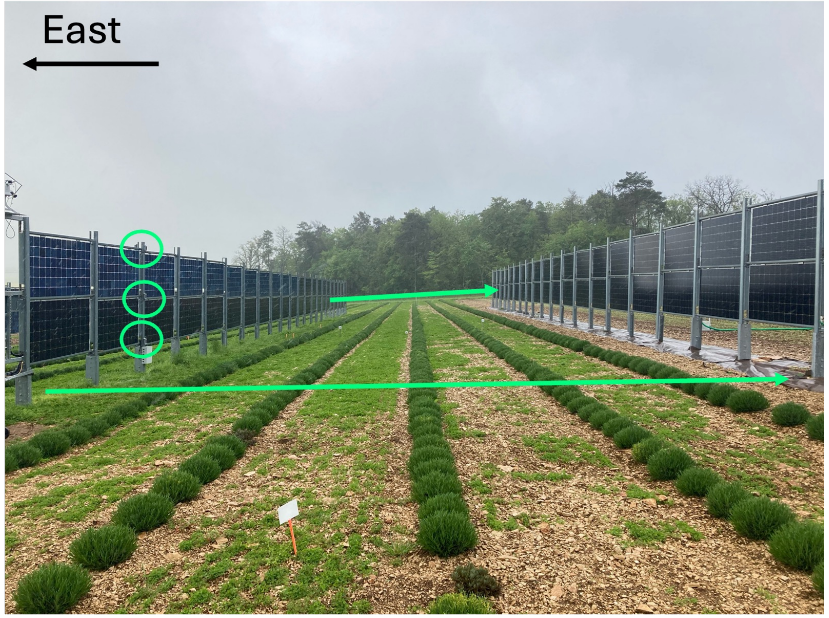

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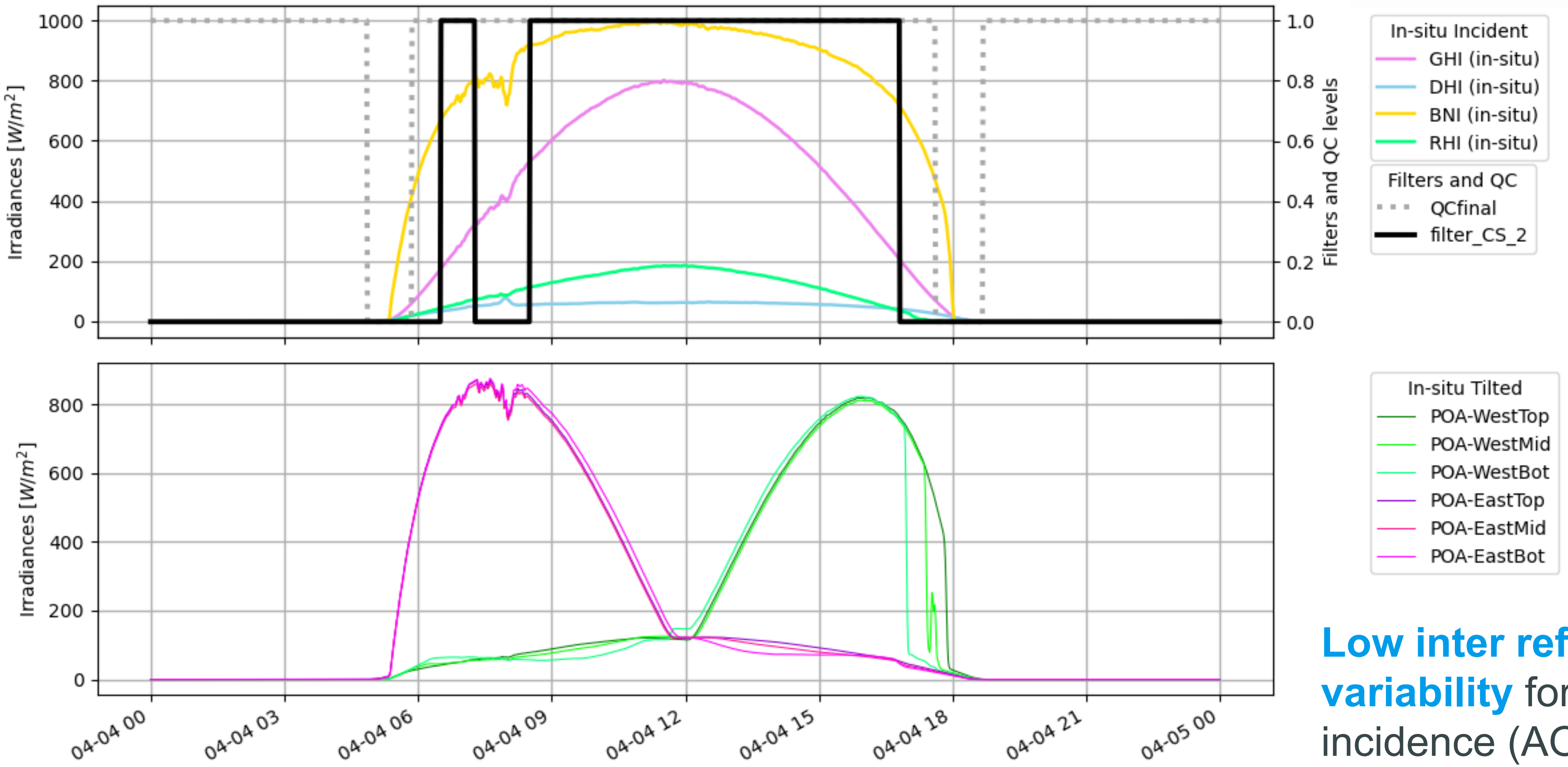
Objectives:

- Evaluate error metric of optical models against in-situ measurement
- Evaluate the relevant level of detail in sensitivity studies

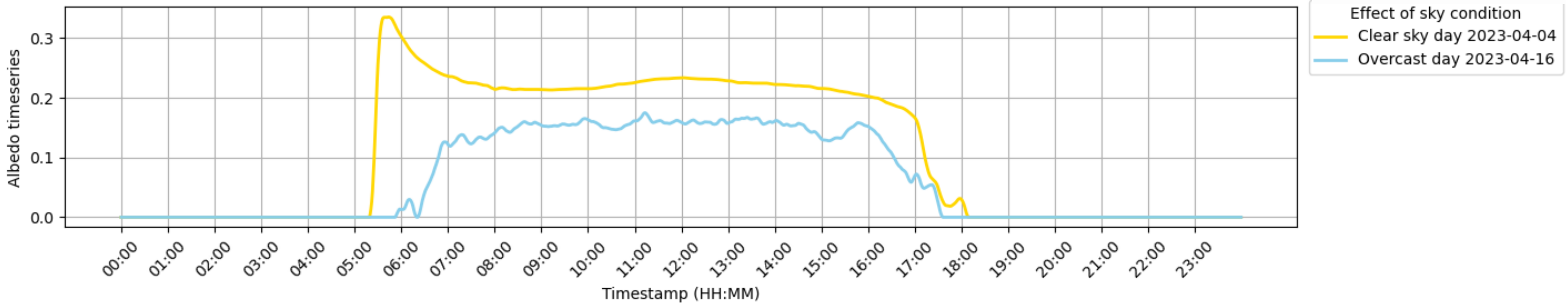
Element	Specification	Measurement and notes
Pyrheliometer	Kipp & Zonen PH1 (Razon+)	Beam normal irradiance (BNI), the sensor is mounted on a dual axis tracker
Pyranometer	Kipp & Zonen PR1 (Razon+)	Diffuse horizontal irradiance (DHI) using a shadow ball, Global horizontal irradiance (GHI) is calculated using the closure equation
Pyranometer	Kipp & Zonen SMP10	Reflected horizontal irradiance (RHI) thus forming an albedometer using the calculated GHI
Reference cells	IngenieBuro Si-I-420TC-T (x6)	Global tilted irradiance (GTI) facing toward East and West orientation for three elevation levels: Top, middle and bottom
Temperature probe	Lufft WT1 (x15)	Cell temperature, 2 in Landscape modules are covered per bypass diode (6 measurements on a transect) and at least 2 modules per technology are covered with a sensors (2 measurements on a transect)
Temperature probe	Pt1000 (Vaisala WXT530)	Ambiant temperature
Ultrasonic wind sensors	Vaisala WXT530	Wind speed and Wind direction

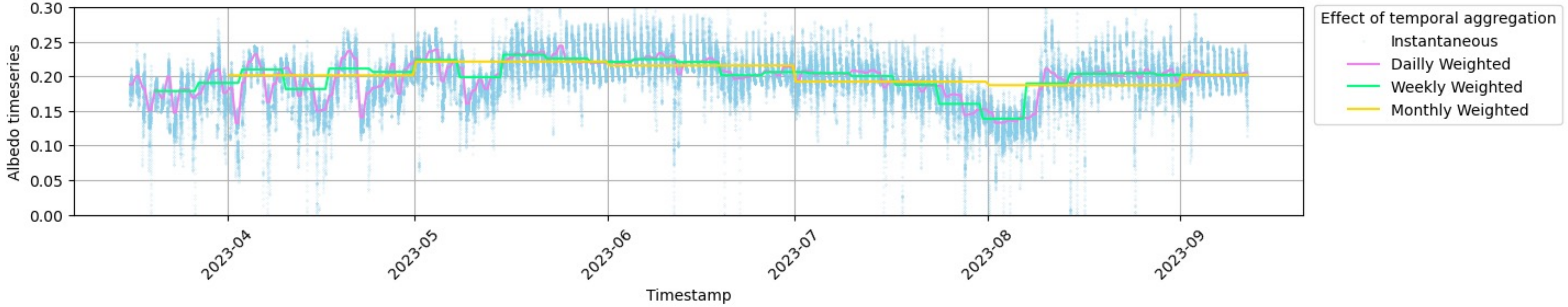
Pyranometric measurements



Low inter reference cell variability for angle of incidence (AOI) < 90°

Albedo

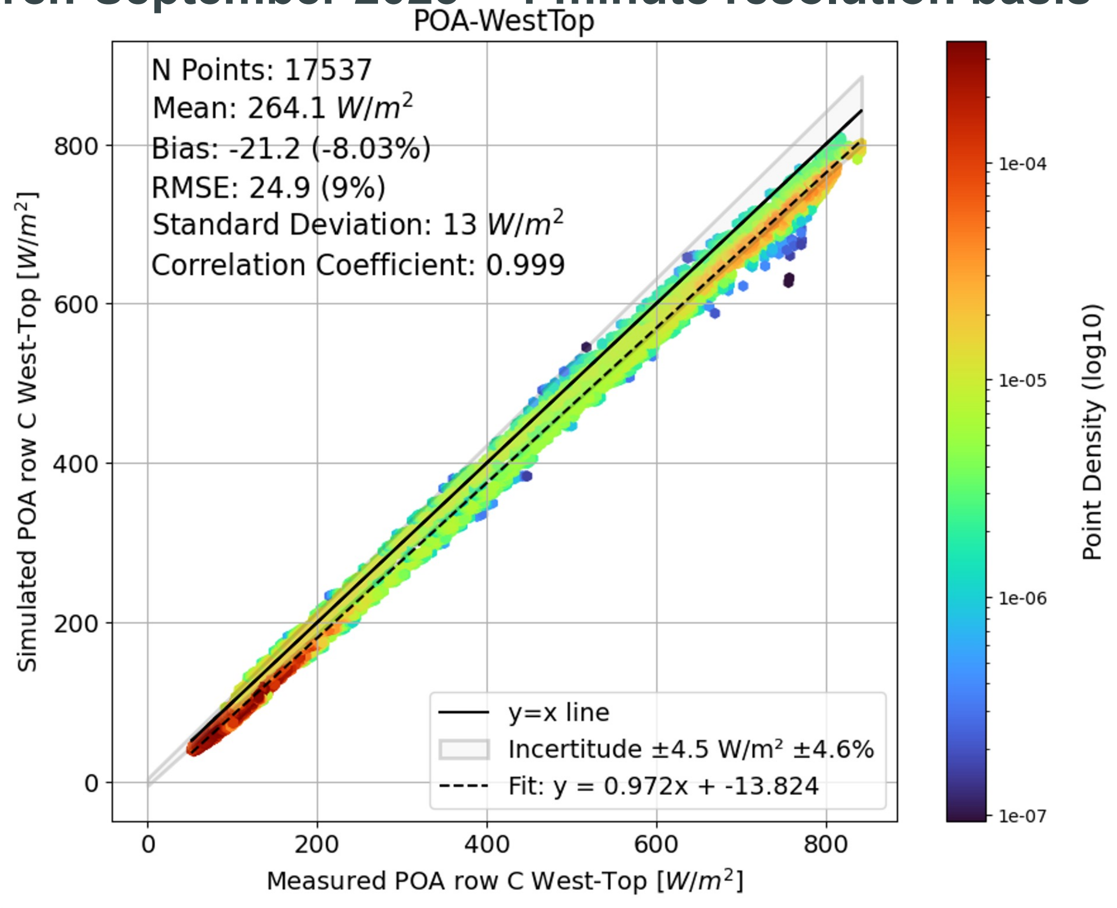


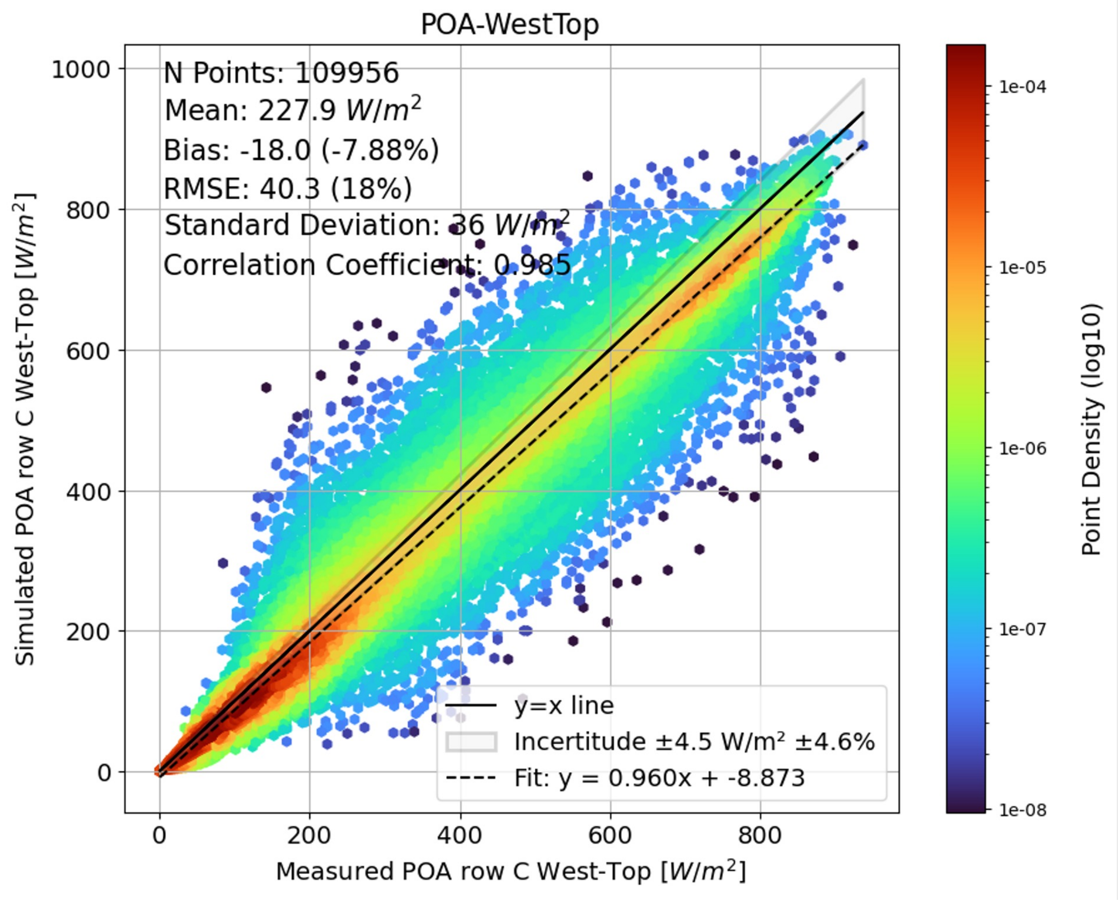


Multi-scale temporal and angular variability

Validation

March-September 2023 – 1 minute resolution basis





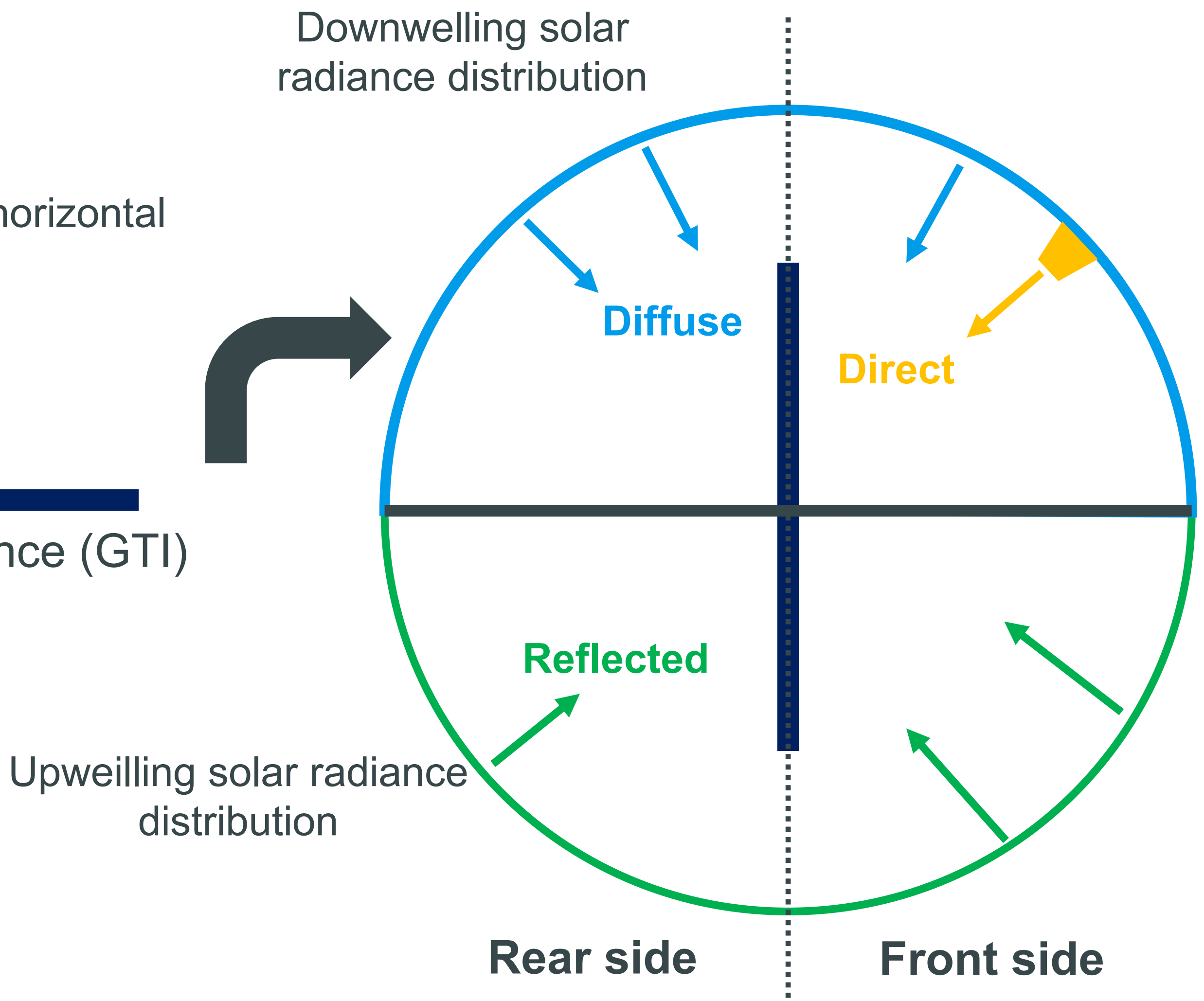
Clear sky and all sky **separated validation** allow to investigate **root causes of errors**

Irradiance components

Goal is to evaluate bifacial gain against an equivalent monofacial configuration

Reference position: horizontal

Global tilted irradiance (GTI)



Front side global tilted irradiance

G_{front} = **Dir** + **Dif** + **Ref**

Rear side global tilted irradiance

G_{rear} = **Dif** + **Ref**

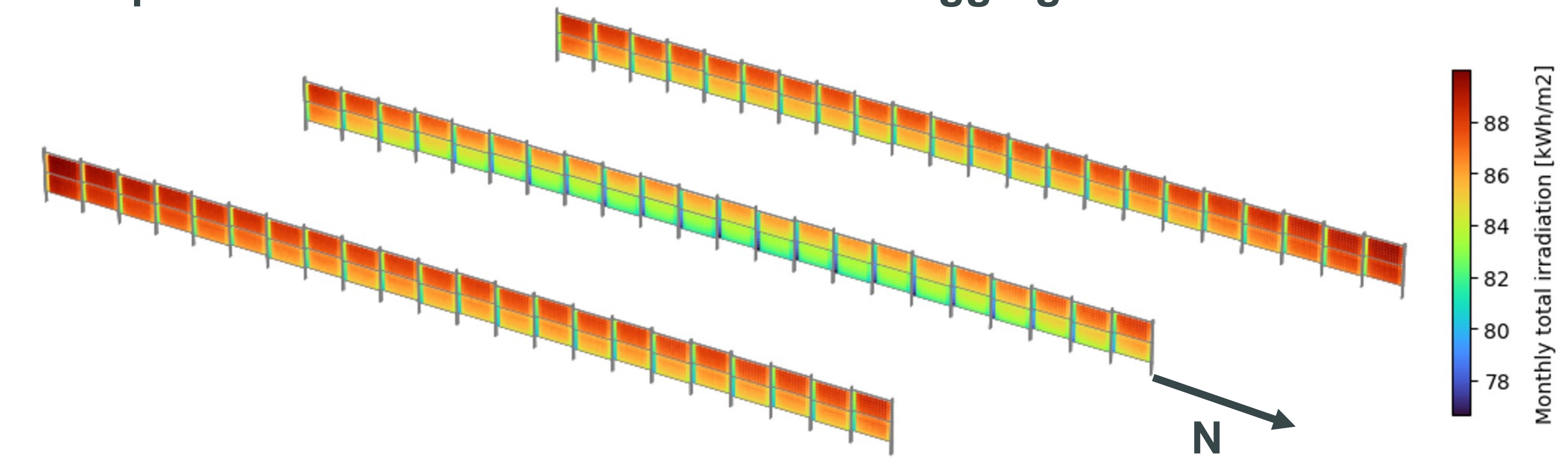
Direct tilted irradiance (**Dir**)

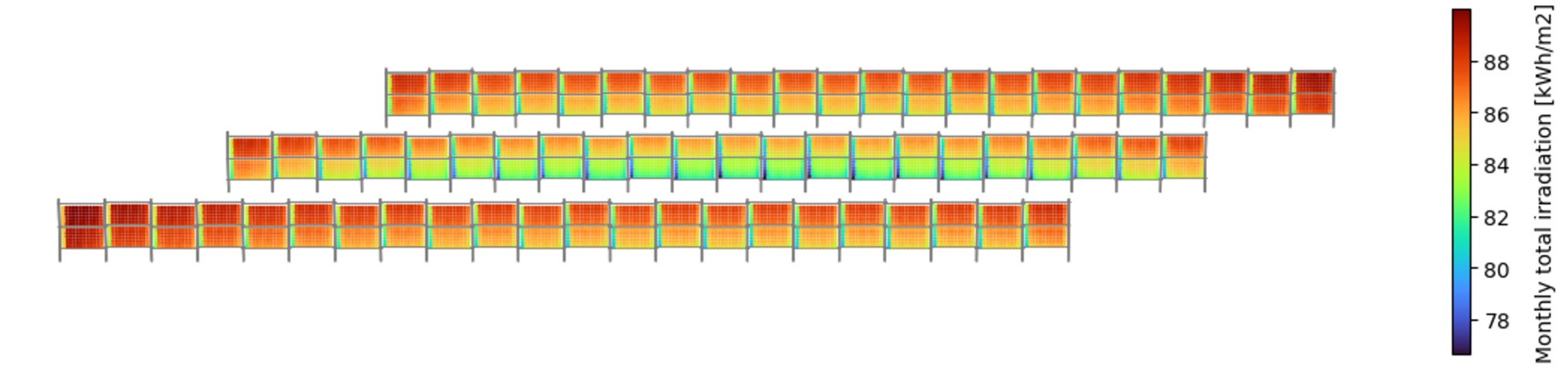
Diffuse tilted irradiance (**Dif**)

Reflected tilted irradiance (**Ref**)

Total irradiation

April 2023 – 1 minute resolution basis aggregated





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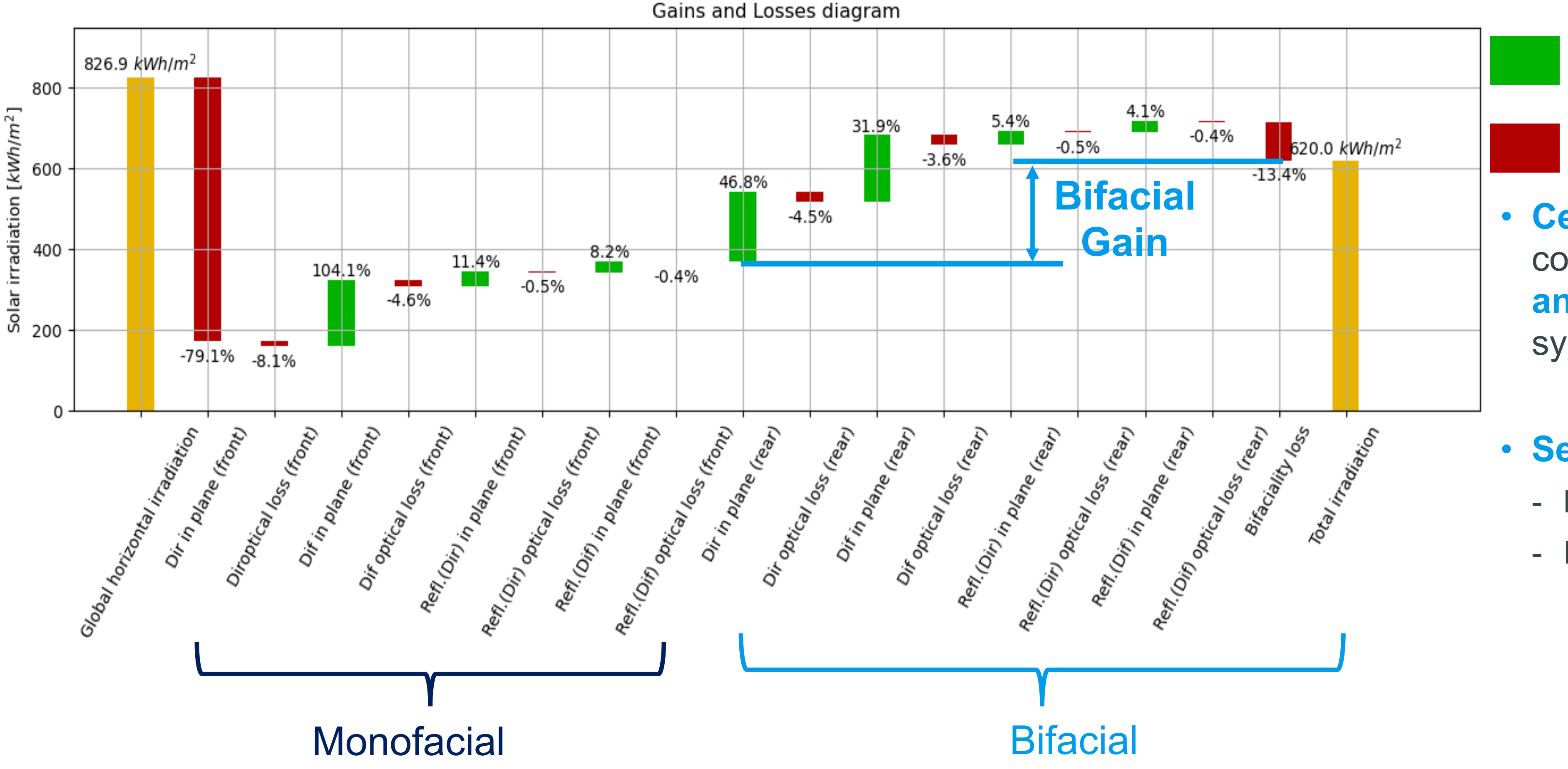
$$G_{\mathrm{total,i}} = G_{\mathrm{front,i}} + \phi_{\mathrm{Bifi}} G_{\mathrm{rear,i}}$$

- Front irradiance (global tilted)
- Rear irradiance (global tilted)
- Bifaciality of the cell

Didactics approach applied for Bifacial AgriPV

March-September 2023 – 1 minute resolution basis



- **Cell to System** (CTS) allow comprehensive and **systematic analysis** of a plurality of APV systems

- **Separated optical losses**:
  - Front and Rear
  - Incident and reflected components

AgriPV at Sirta

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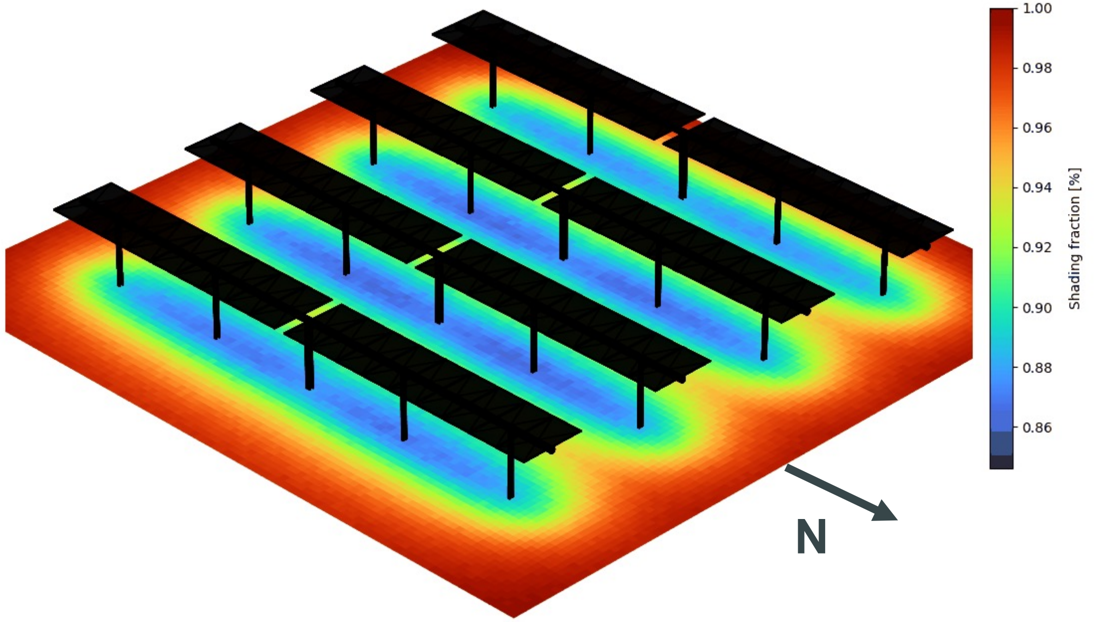
Ground shading with tracker

20/05/2024 – 5 minutes resolution basis



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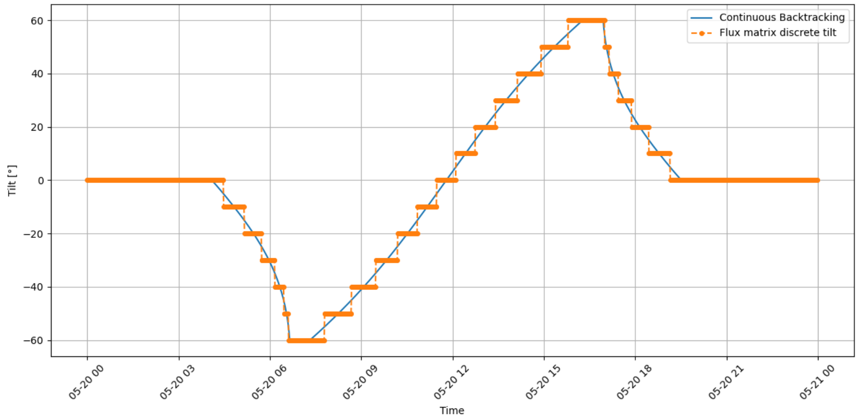
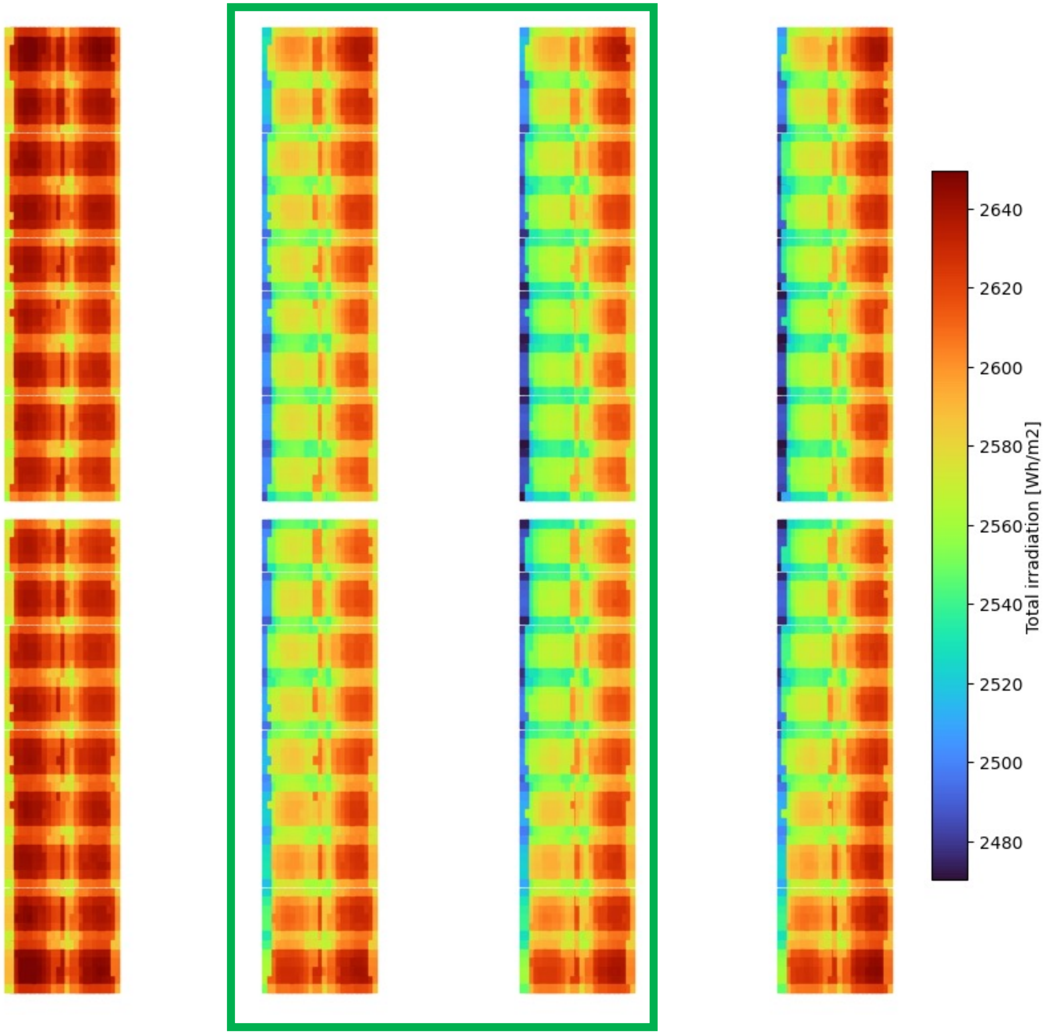


- Transition from a fixed system to a tracker requires discretizing the angular trajectory: **opto-geometrical separation**
- A look-up table and a nearest interpolation allow to generate **time-varying irradiance distribution**

From PV irradiation to PV performance

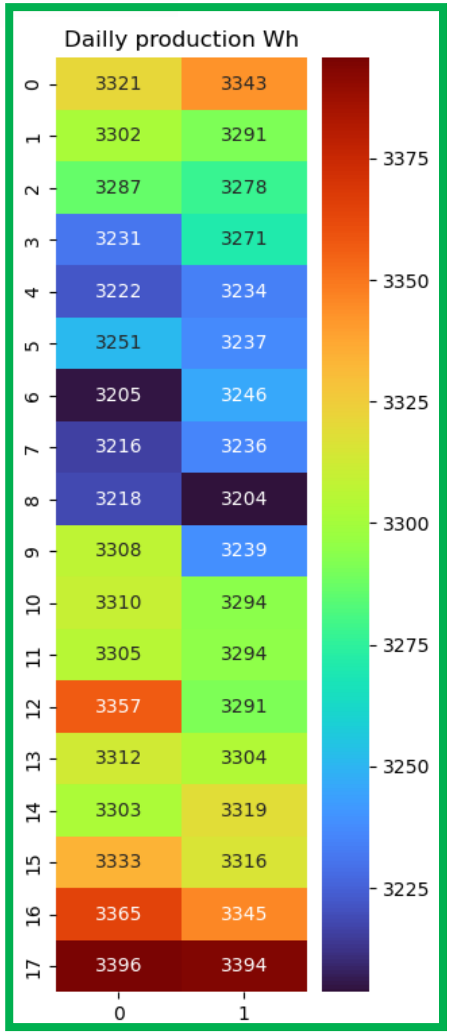
20/05/2024 – 1 minute resolution basis agregated

Module level power electronics

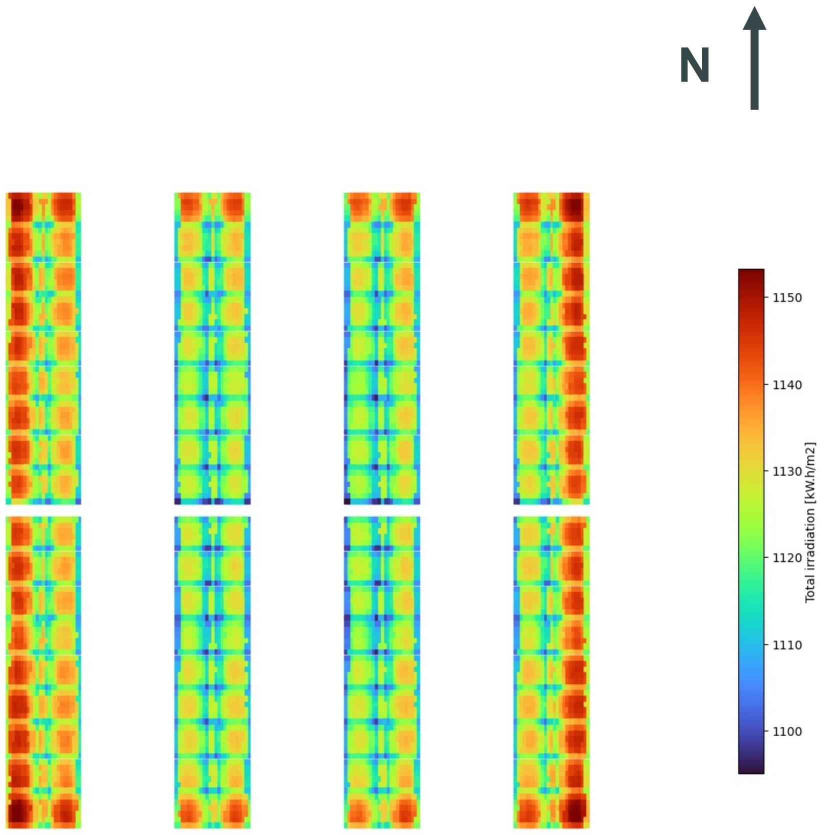


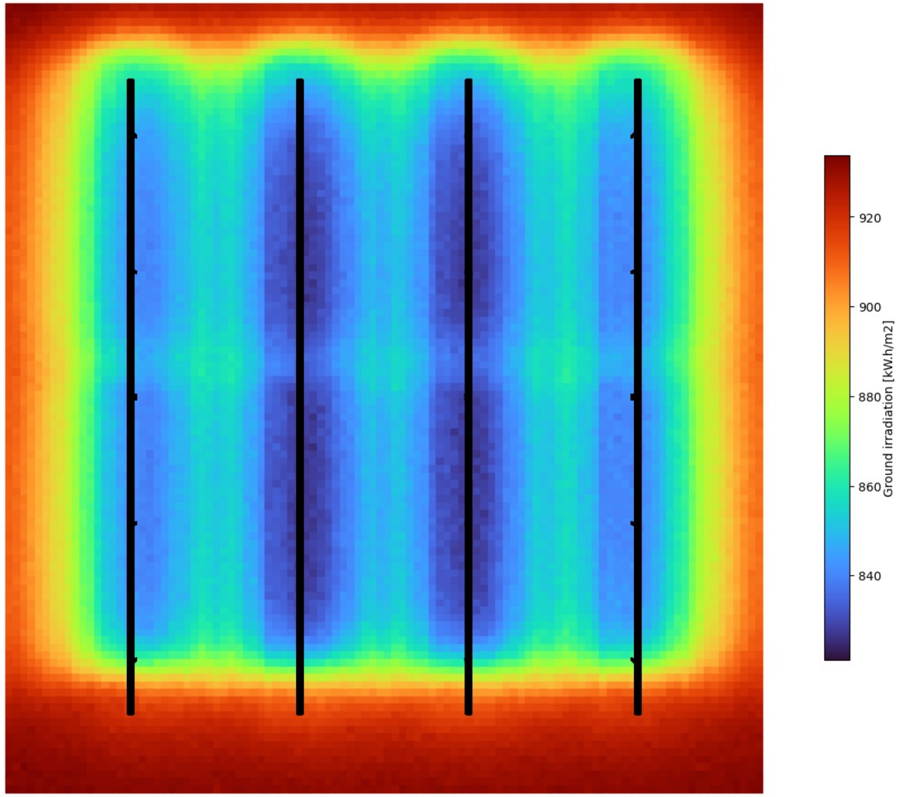
Objectives

- PV production depend upon **irradiance distribution** and operating temperature
- Conversion from irradiance to Direct current power is a **non-linear process**
- Instrumentation allow to account for intra-module variability: **Edge-effects**



Seasonal expectations with satellite data





- Irradiance source: **CAMS Radiation**
- **1 minute resolution** basis integrated over the period **April to October 2023**
- **Standard backtracking** algorithm

Conclusion & Perspectives

- Proposed methodology allows accurate evaluation of each irradiance component.
- Better understanding of the balance of irradiance.
- Validation show a good agreement between simulations and measurements

- Sensitivity analyses will make it possible to assess the limits of these approaches.
- Spectral and angular impact need to be evaluated (Sky and ground)

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