Vertical Agrivoltaics system: What solar radiation to share between agriculture and PV modules?

Arthur Poquet, Dr. Etienne Drahi, Dr. Jordi Badosa and Prof. Philippe Blanc

2024 European PVPMC Workshop

Copenhagen, Denmark

Agenda

1. Introduction
2. Methodology
3. Results
4. Conclusion

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Introduction

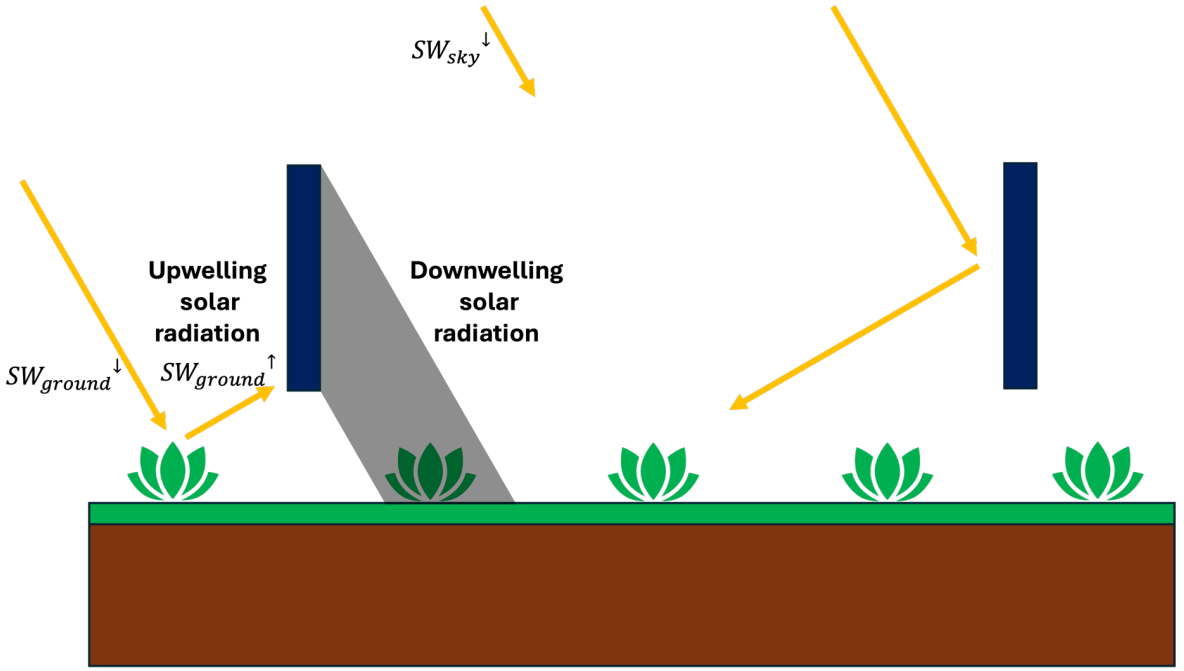
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Challenges of short-wave solar radiation modelling

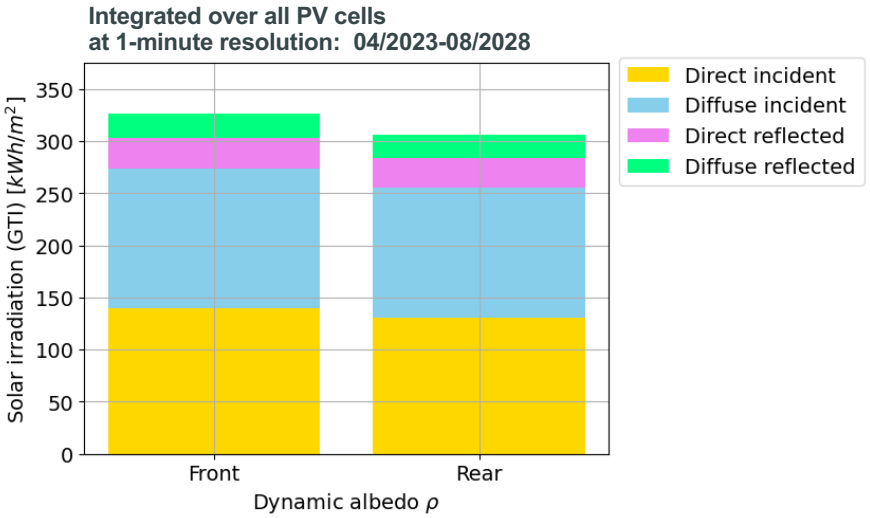
- Short wave radiation is the primary driver of synergy between **Crop production** and **Photovoltaic production**

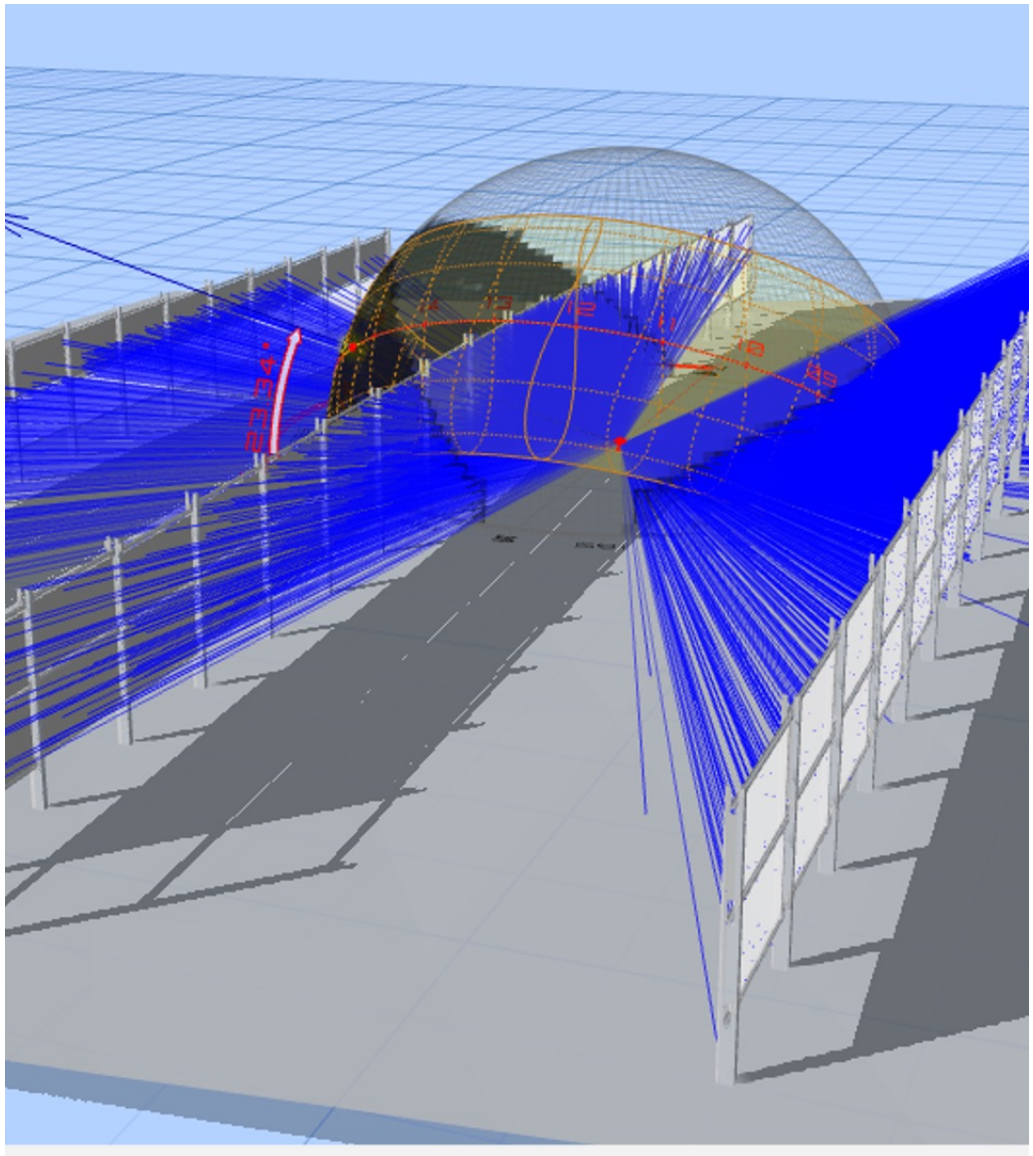
- But **there is a need to improve it modelisation**:
  - Shading projection and **conservative assumptions** remain the norm for Crops simulation
  - Modelling errors originate from **both upwelling and downwelling** for bifacial simulation
  - Need to **improve the optical model in multiple domain**: temporal, spatial, spectral and angular



Irradiance components
PV specific

- **Ray-tracing** models **lack understanding** in providing the global titled irradiance
- Conversely, **view-factor** models have been able to provide a detailed understanding **although quite restricted**
- **Scientific question**: How can we achieve the level of understanding of model view-factors with the level of flexibility of ray-tracing?





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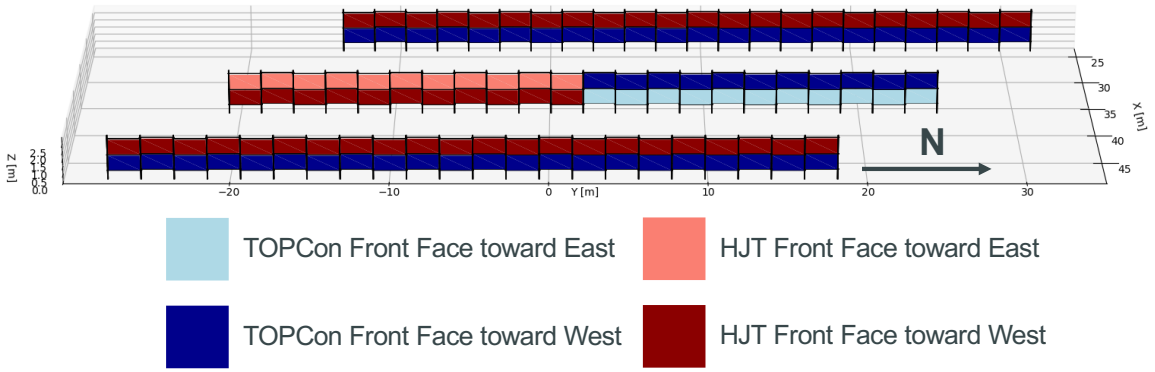
Methodology

Credit https://drajmarsh.bitbucket.io/shading-box.html

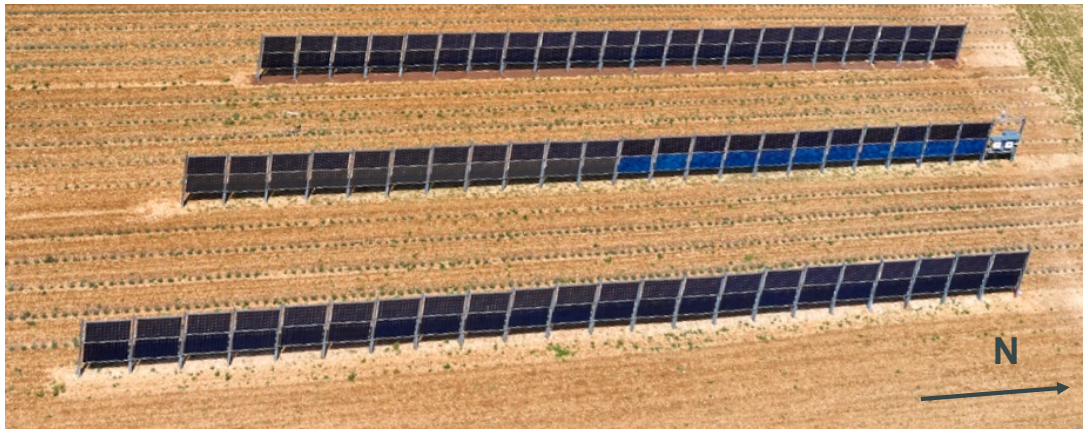
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Simulation model



Channay, France (Coordinates: 47.891°N, 4.295°E)

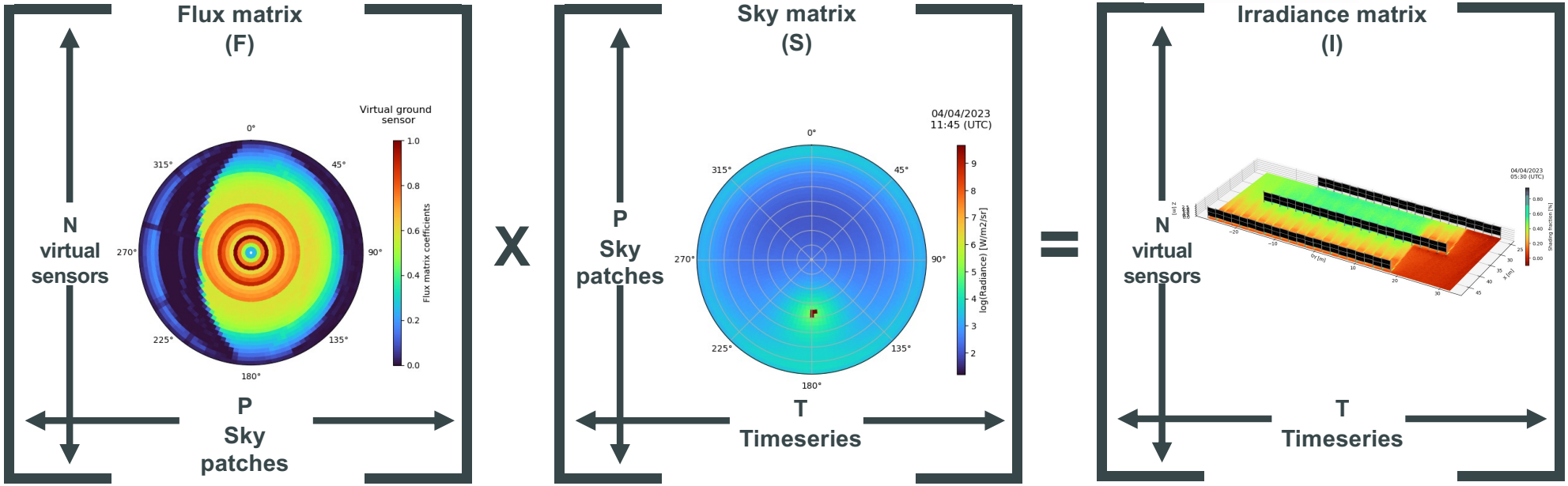


- SolarOPS: Advanced yield estimation tool
- 3D geometry is generated arbitrary using a **hybrid approach** between:
  - **Parametric models**: PV modules, frames, torque-tube…
  - **CAD-based components**: Specific structures
- Front and rear faces have distinct **optical loss** parametrizations

A. Florakis et al., 2023, "SolarOPS: A versatile PV system simulation software," presented at 16th PV Performance Modeling Workshop, Salt Lake City, USA. doi: 10.13140/RG.2.2.16350.61761

Matrix based ray-tracing

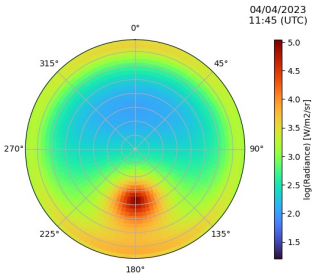
Matrix based equation: FS=I



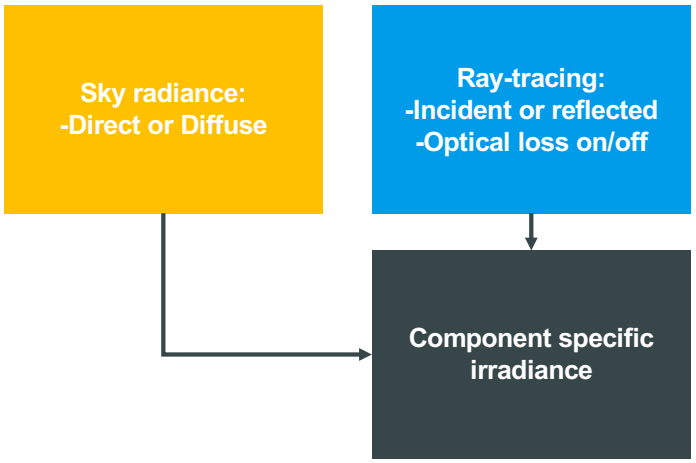
- Matrix based ray-tracing separate:
  - **Opto-geometric properties** of the system
  - **Temporal variation of the sky** (Perez's sky model)

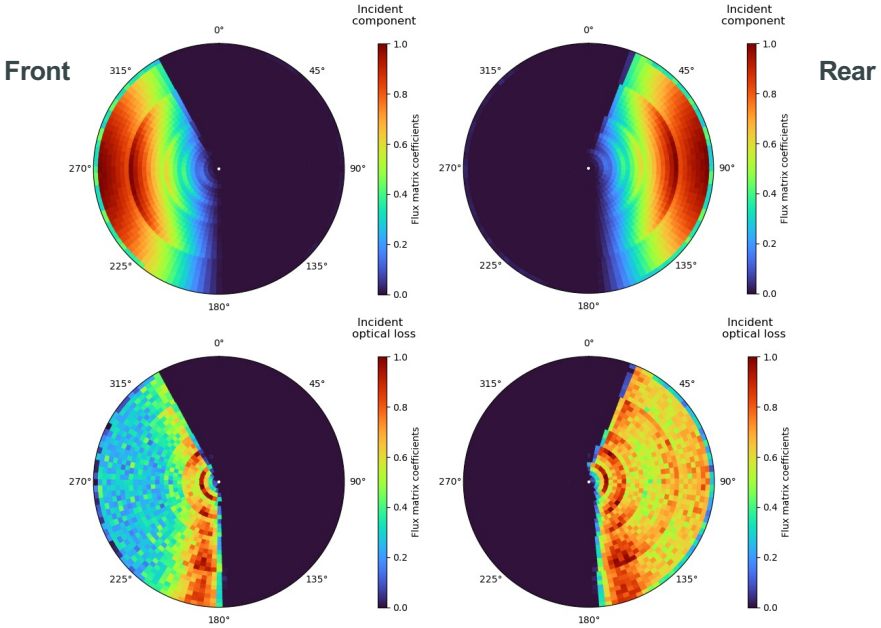
R. Perez et al., 1993, "All-weather model for sky luminance distribution-Preliminary configuration and validation", Solar Energy, Volume 50, Issue 3, doi:10.1016/0038-092X(93)90017-I

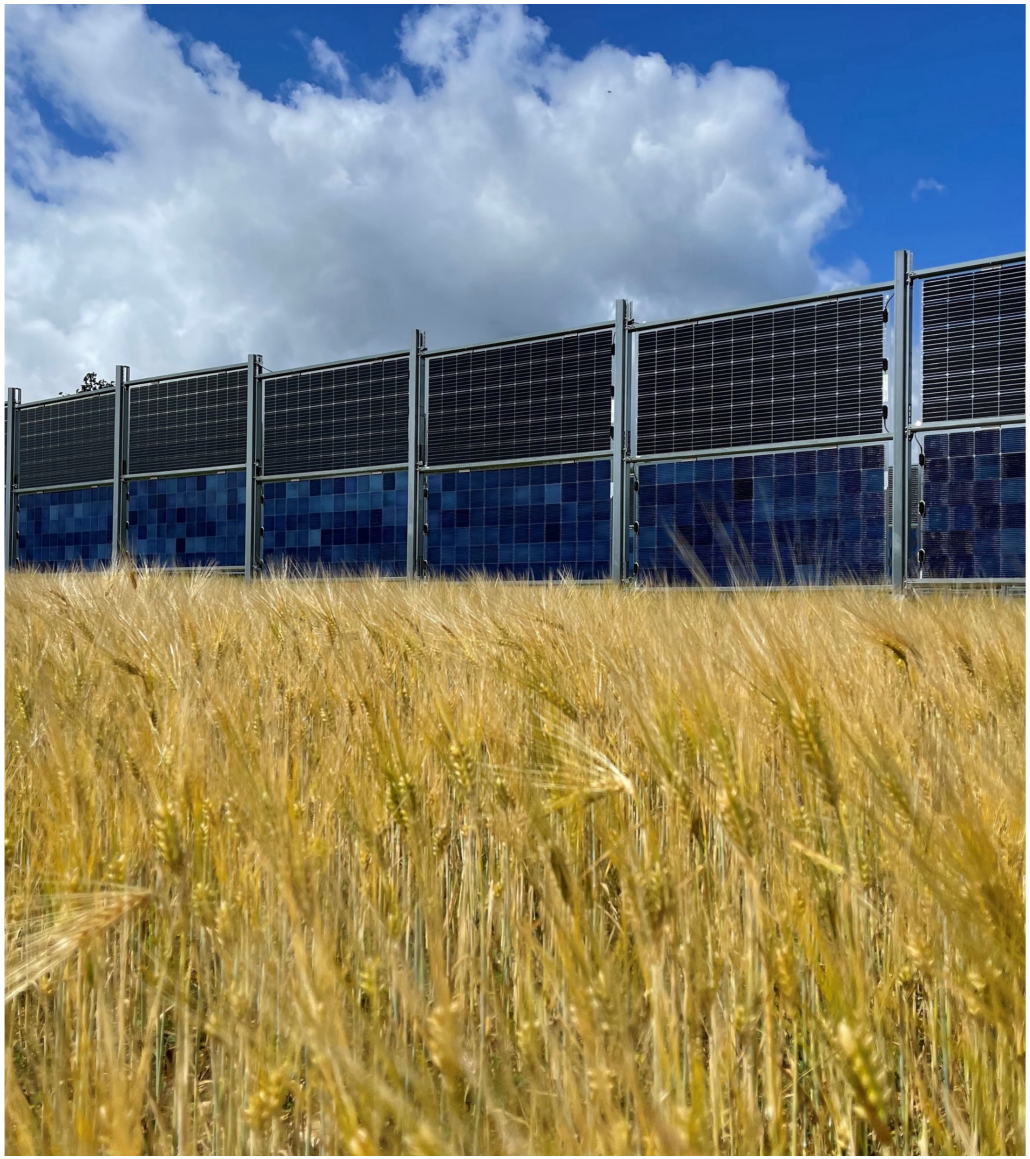
Modelling workflow



- A difference between two simulations allows **each component to be isolated**:
  - Direct and Diffuse: RADIANCE can provide both components separately
  - Incident and Reflected: Number of bounces (1-5)
  - Optical losses: W/O front and rear surfaces







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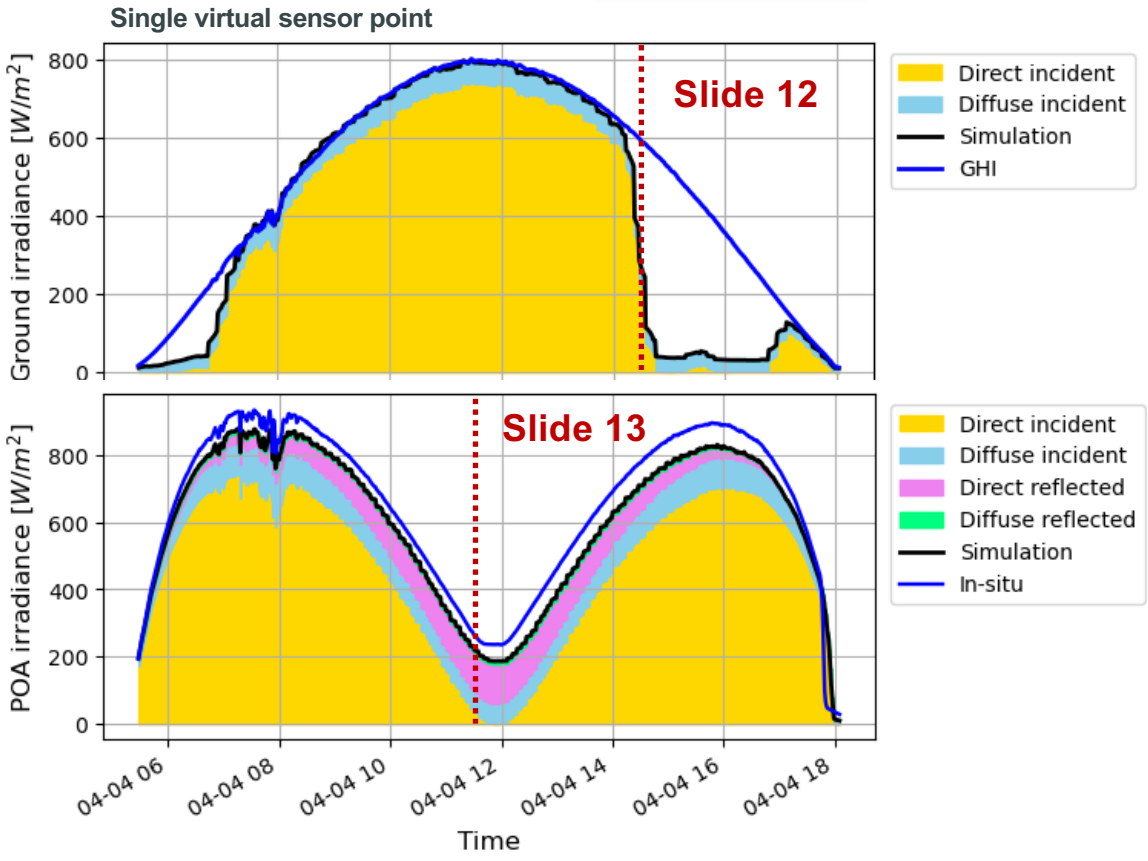
Results

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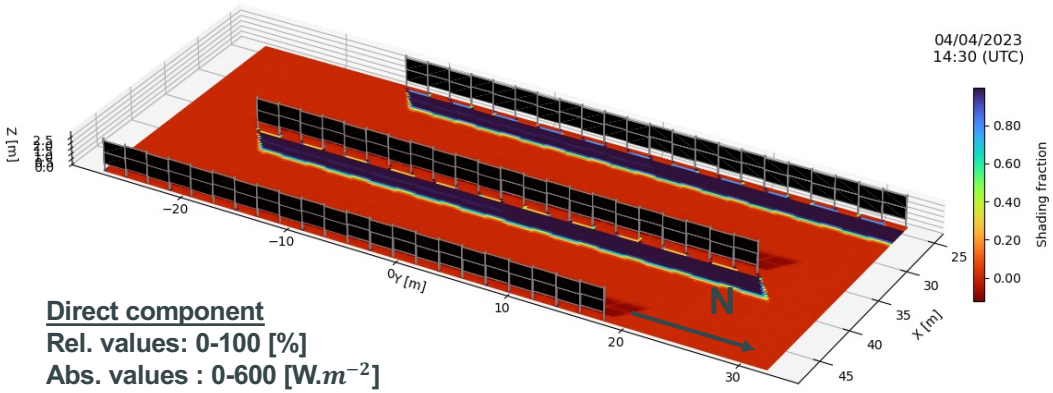
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Spatio-temporal variability
Point-based

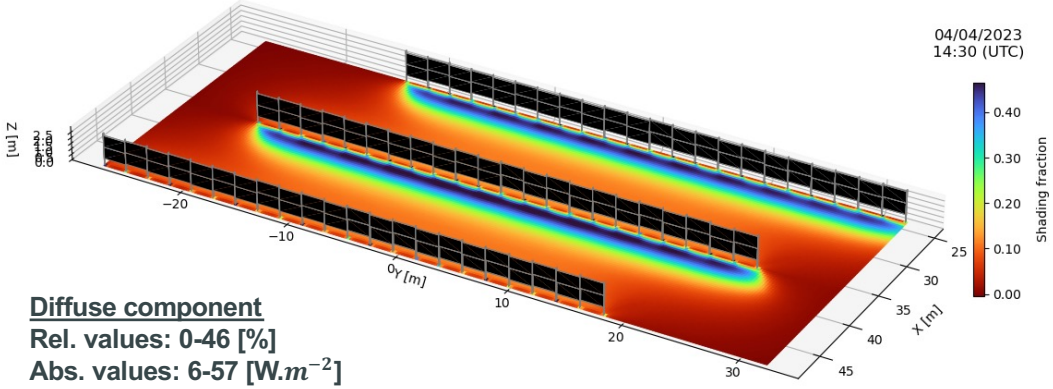
- **Complex** to account for both **spatial** and **temporal variability**.
- Ground irradiance temporal variability is mainly **geometric**
- Global tilted irradiance (GTI) from both sides exhibits **temporal variability of relative contributions**
  - Direct incident is dominant most of the day
  - Direct reflected become important at solar noon



Ground irradiance components
Spatial distribution



Direct component
Rel. values: 0-100 [%]
Abs. values : 0-600 [W.m^{-2}]



Diffuse component
Rel. values: 0-46 [%]
Abs. values: 6-57 [W.m^{-2}]

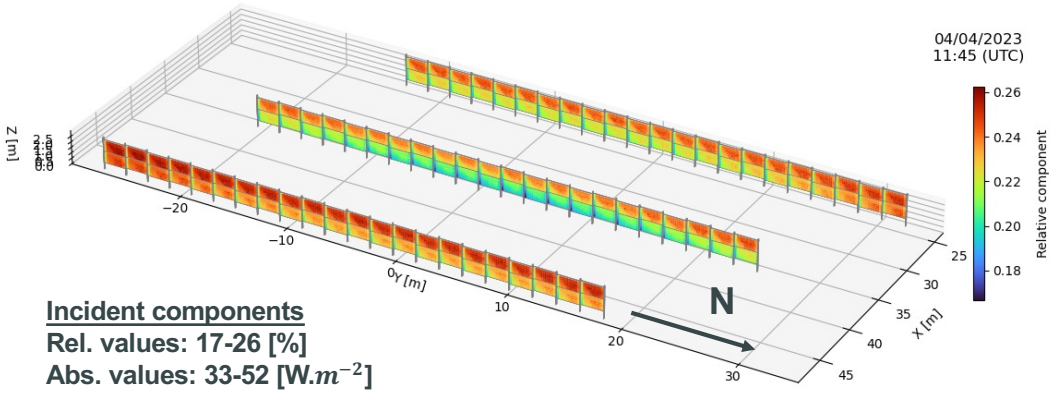
- Two **theoretical cases** can be envisaged:
  - Purely direct illumination: “Black-sky”
  - Purely diffuse illumination: “White-sky”
- Usually, it is a **combination** of these two situations
- The limitations of these results are:
  - Direct component is **distributed over sky patches**
  - Sky radiance is **not isotropic**: i.e. partial cloud condition

$$SF = \frac{GI_{ref} - GI_{x,y}}{GI_{ref}}$$

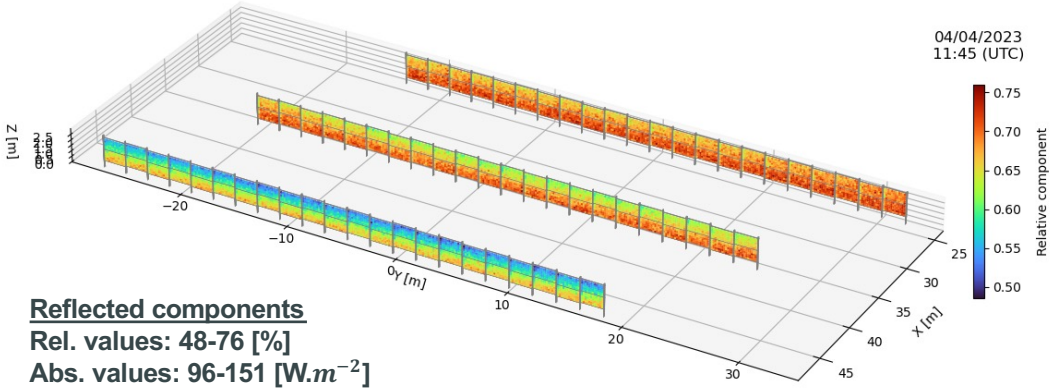
- Where:
  - SF: Shading fraction
  - $GI_{x,y}$: Ground irradiance

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PV irradiance components
Spatial distribution



Incident components
Rel. values: 17-26 [%]
Abs. values: 33-52 [W.m^{-2}]



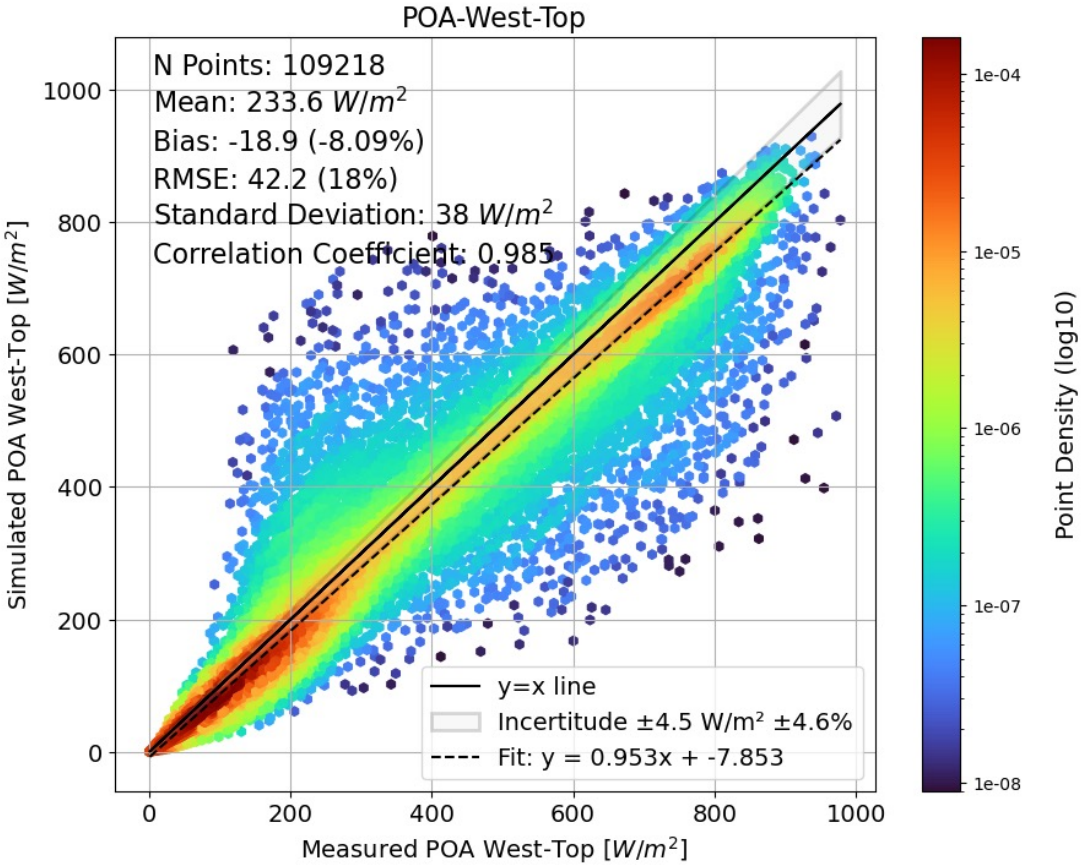
Reflected components
Rel. values: 48-76 [%]
Abs. values: 96-151 [W.m^{-2}]

- Vertical PV is **sensitive to reflected components**
  - Structure suppresses the incident direct component
  - Reflected components can represent more than 60%
- Reflected components **non-uniformity** depends on:
  - Shadow on the ground, sky radiance…
  - Lambertian reflection corrected by optical losses

$$RC = \frac{G_{component}}{G_{total}}$$

- Where:
  - RC: Relative component
  - G_{total}: Total irradiance (Front & Rear)

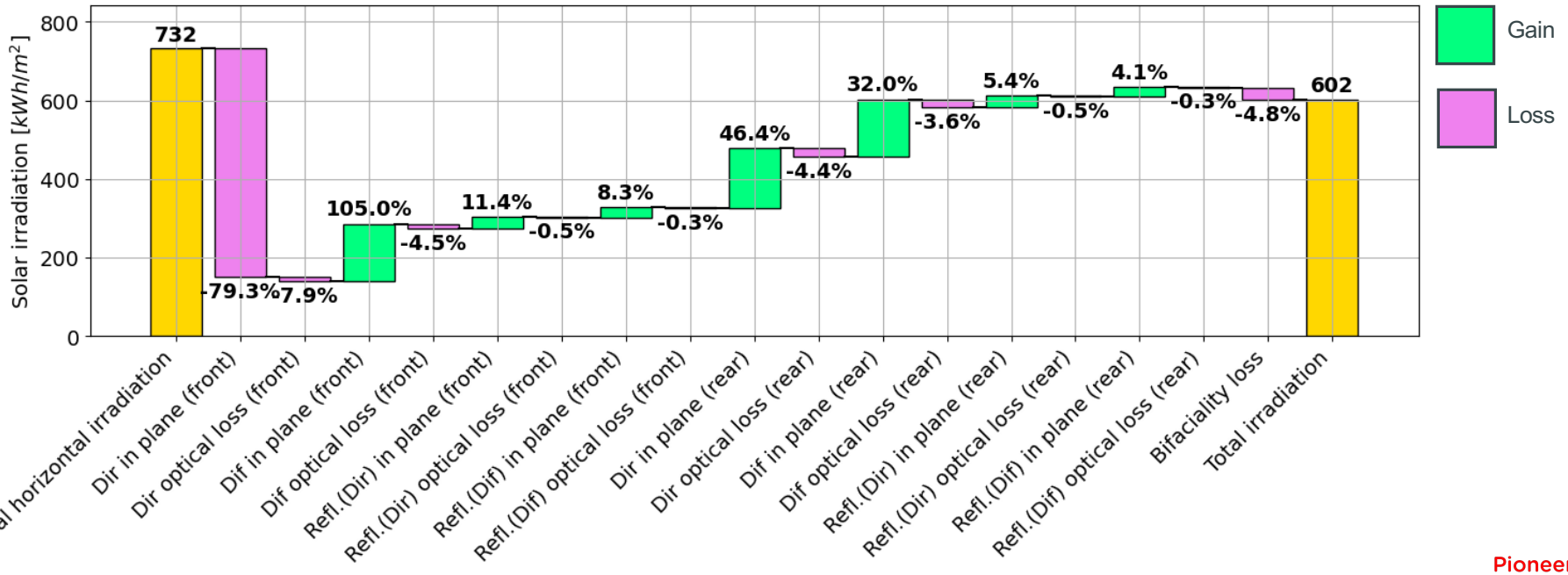
Point based validation



- Validation period: March-September 2023
- Temporal resolution: 1-minute basis
- Simulated GTI of reference cell is compared with IngenieBuro Si-I-420TC-T measurement
- Filtering procedure
  - Quality check flagging and 60-min sliding window
  - Solar Zenith Angle > 80°

Waterfall diagram
Vertical PV total irradiation

April-August 2023, 1 minute resolution basis





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Conclusion

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Conclusion

- Separating time-varying sky and ground distributions from optical and geometrical properties enable **deeper analysis**
- 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**



Contact:
arthur.poquet@totalenergies.com
arthur.poquet@minesparis.psl.eu

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