SOLARGIS

Comparative analysis:
Validating PV simulation uncertainty against field measurements

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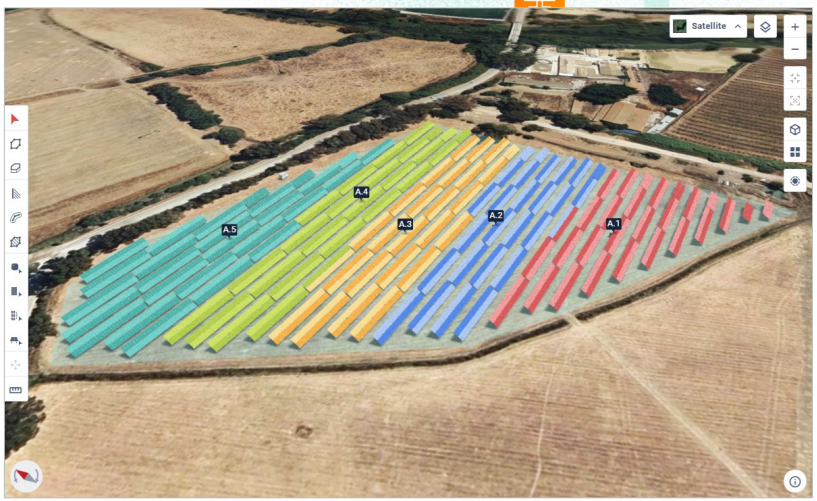
Solargis Evaluate

Cloud-based software solution providing site assessment, PV system design, energy yield simulation and analysis in one place

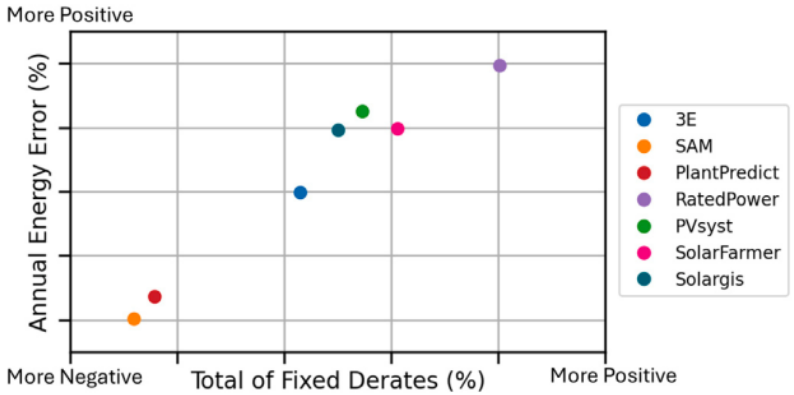
- Data trusted by financial stakeholders
- 30+ years of 15-minute Time Series data
- Charts and visualizations
- 3D Energy System Designer
- PV simulation based on ray tracing and Perez all-weather sky model
- Compare multiple PV energy yield simulations
- Bankable report



PV Simulation Uncertainty

- Key to build trust in the simulations and underlaying data
- Helps to understand risks arising from the use of simulation results
- Project financing, planning O&M, fitting the electricity demand, performance evaluation, …

- Differs for various simulation tools

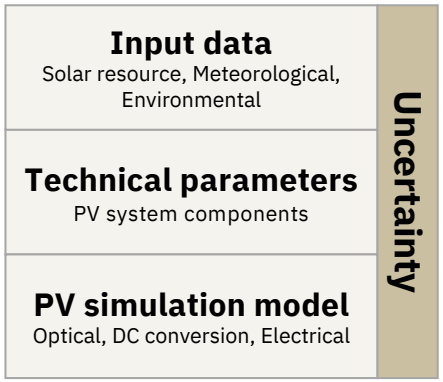


Deville et al. 2026: Feature review of photovoltaic modeling software utilizing blind performance assessment
https://www.sciencedirect.com/science/article/pii/S0038092X25009703

PV Simulation Uncertainty

End-user uncertainty of PV simulations

- Input data uncertainty,
- Simulation model complexity (simulator uncertainty) ,
- Technical parameters (PV system components specification uncertainty)

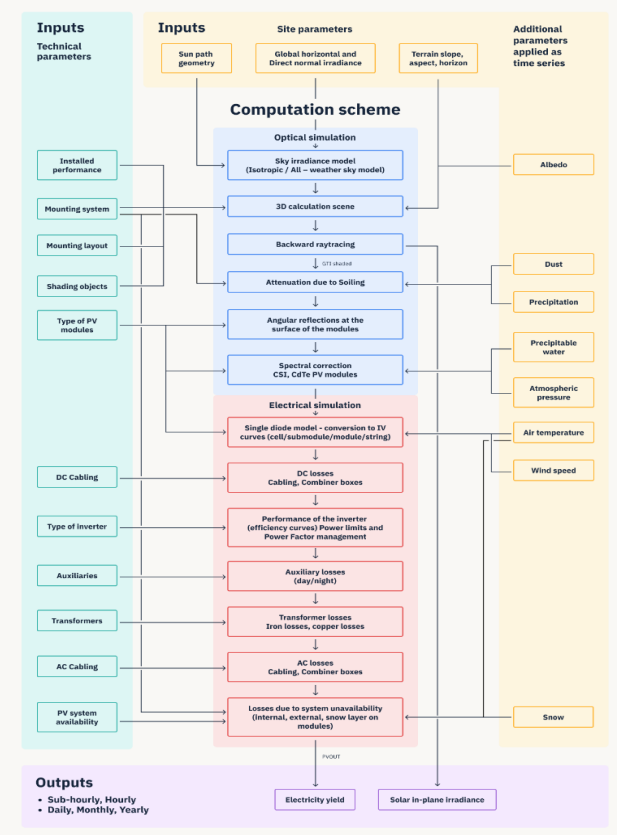


Application determines acceptable uncertainty

- Energy system design and yield modeling
- Performance evaluation
- Real-time monitoring
- Forecasting
- ...

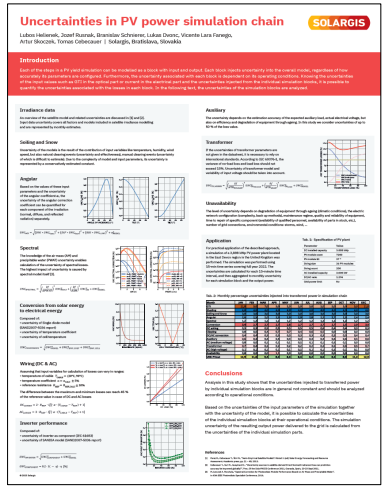
PV simulation uncertainty framework

Solargis Evaluate PV simulation Engine



- The PV simulation chain is composed from several simulation blocks
- Each block contributes uncertainty into the whole chain
  - Model used in block
  - Uncertainty of configuration (settings, parameters)
  - Operational conditions, sensitivity to inputs (nonlinearities)
- Deriving uncertainty for each simulation block
  - Uncertainty calculation
  - Qualified uncertainty estimate (e.g. GTI)
- Result - quantification of monthly uncertainties
  - Combines partial uncertainties

$$UNC_{\mathrm{PVOUT}} = \sqrt{UNC_{\mathrm{GTI}}^2 + \sum UNC_{\mathrm{BLOCKS}}^2}$$



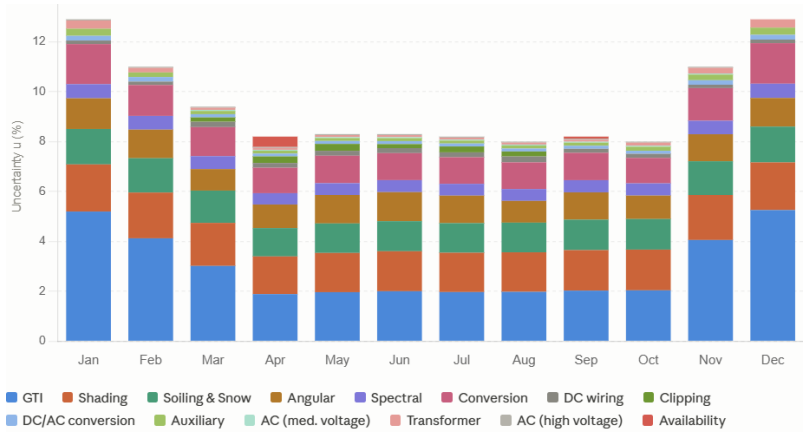
Helienek, L. et al. (2023). Uncertainties in PV Power Simulation Chain. 1-6. 10.1109/PVSC48320.2023.10359583.

PV simulation uncertainty framework

Example of monthly uncertainty PV simulation uncertainty

PV power plant in East Devon, United Kingdom

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
GTI	11.0	9.0	7.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	9.0	11.0
Shading	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Soiling snd Snow	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Angular	2.6	2.5	2.0	2.5	2.9	2.9	2.8	2.2	2.7	2.3	2.4	2.4
Spectral	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Conversion	3.4	2.7	2.7	2.7	2.8	2.7	2.7	2.7	2.7	2.5	2.9	3.4
DC wiring	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.6	0.4	0.4	0.3	0.3
Clipping	0.0	0.0	0.4	0.7	0.7	0.4	0.6	0.5	0.0	0.0	0.0	0.0
DC/AC conversion	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Auxiliary	0.6	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.5	0.6
AC (medium voltage)	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Transformer	0.7	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.7
AC (high voltage)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Avaliability	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UNC PVout	**12.9**	**11.0**	**9.4**	**8.2**	**8.3**	**8.3**	**8.2**	**8.0**	**8.2**	**8.0**	**11.0**	**12.9**



Note: Each component is rescaled, so the bar height equals the actual combined uncertainty.

Main contributions to monthly uncertainty:

- Solar radiation (measured/satellite-based GTI)
- Environmental factors (shading, soiling)
- Angular and spectral losses
- Conversion of solar to electrical energy

Lower contribution:

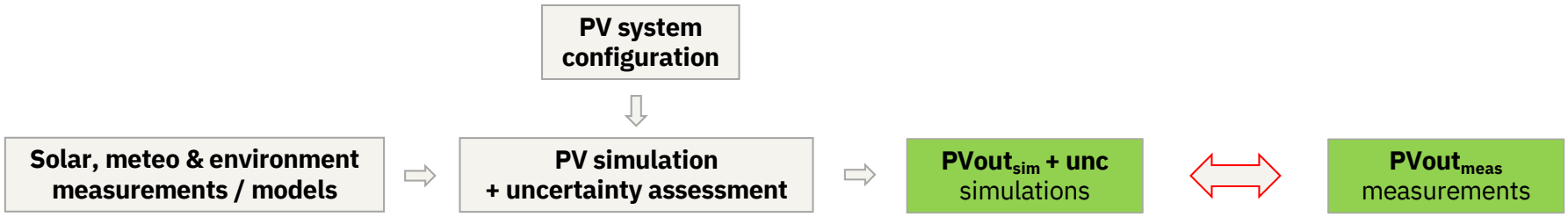
- Electrical simulation

PV Simulation Uncertainty

Goal of presentation

- Comparison of:
  - PV simulation **$PVout_{sim}$** + monthly uncertainty
  - with **$PVout_{meas}$** real-measurements

- Understand sources of discrepancies between simulations measurements



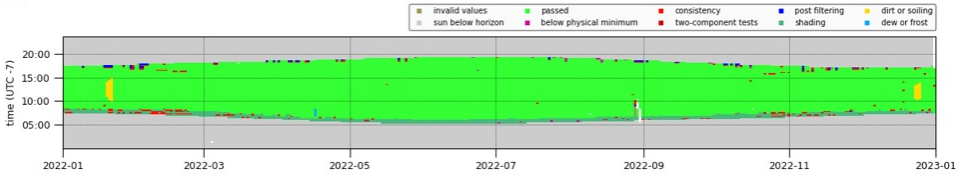
Results

Test site 1 - Gantner Instruments outdoor test facility, USA, Arizona

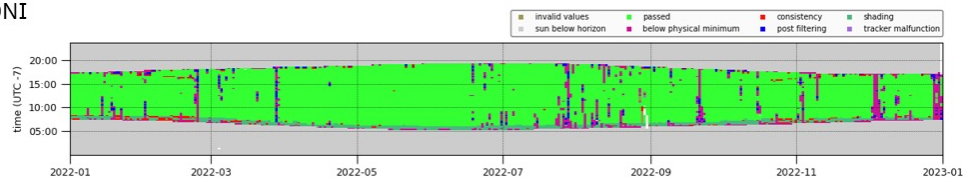
- Dry, dust, high temperatures
- Analysis based on on-site measurements:
  - GHI, DNI, TEMP and WS, QC'ed, harmonized
  - PVOUT from 2 PV CSi modules, fixed tilt 33 deg, azimuth 180 deg
- Data availability – year 2022, 15-minute time step
- QC results – few minor events detected and flagged out
- Uncertainty at the level of DC cabling (MPPT regulator)

Measurements QA results

- GHI



- DNI

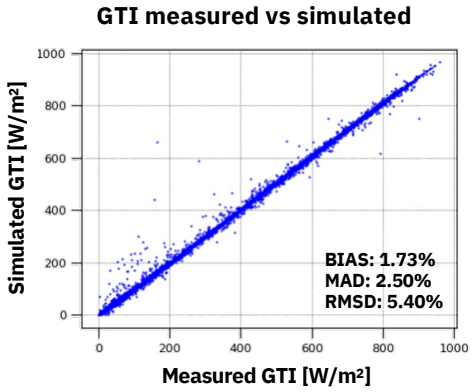


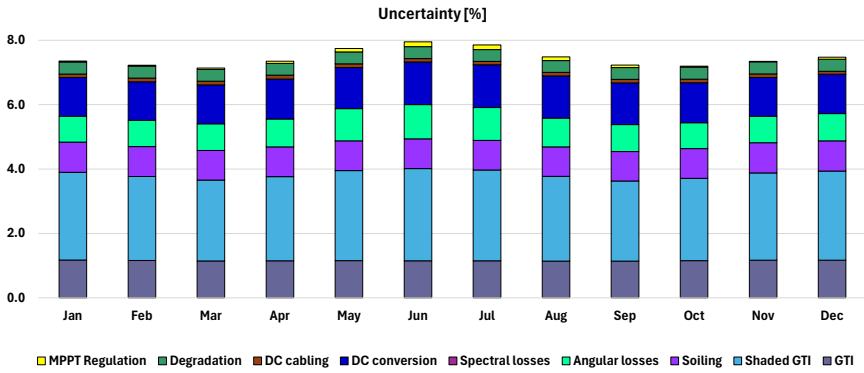
Test site 1 - Arizona

- PV simulation **PVout$_{meas}$**

- Uncertainty calculation (80% occurrence)
  - Estimation of **input GTI uncertainty**:
    - Qualified estimate, based on:
      - Sensor characteristics
      - Arrangement of measurement scene (shading seen by pyranometer vs. shading seen by test module)
      - QC and harmonization methods
      - Remaining issues in measured GTI
  - Estimation of **simulation uncertainty**:
    - Each simulation step separately
    - Based on actual input data (nonlinear)
  - **Combined monthly uncertainty** **PVout$_{meas}$ ±unc**

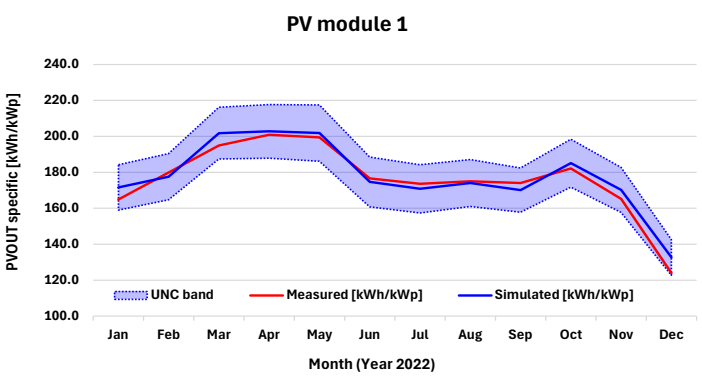
- Comparison with measured **PVout$_{meas}$** values

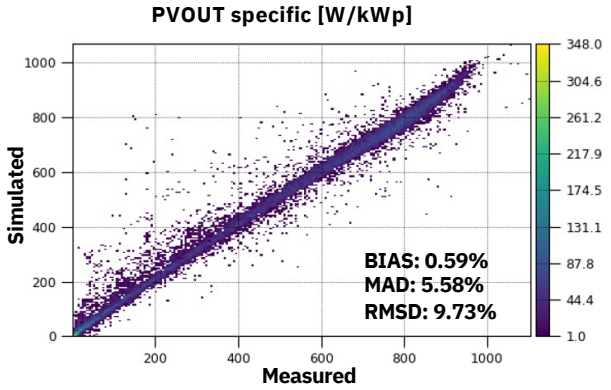


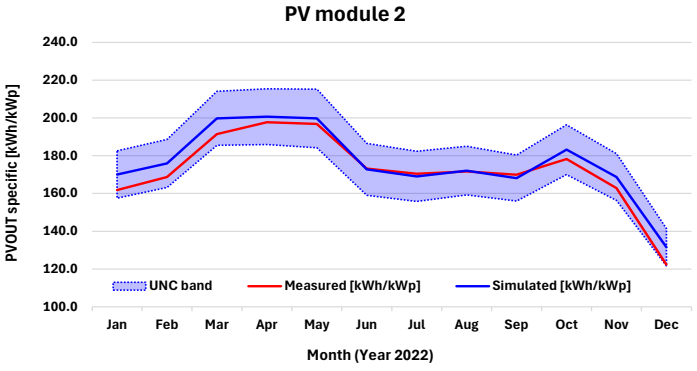


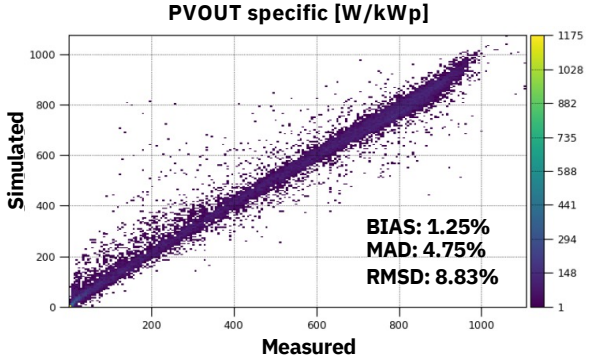
Note: Each component is rescaled, so the bar height equals the actual combined uncertainty.

Test site 1 - Arizona





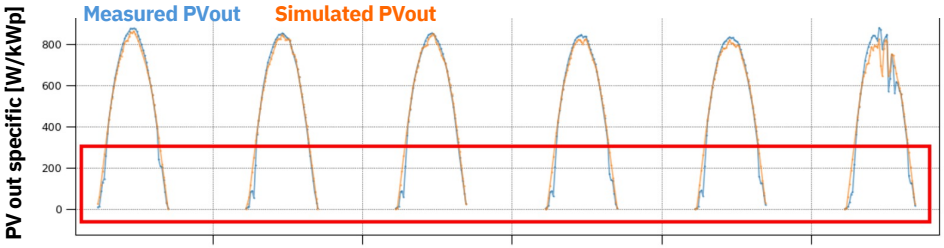


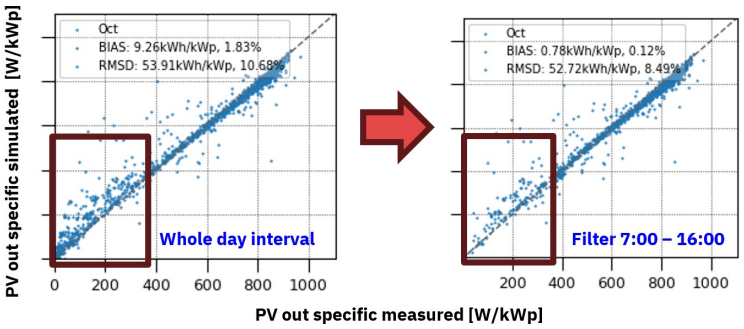


Test site 1 - Arizona

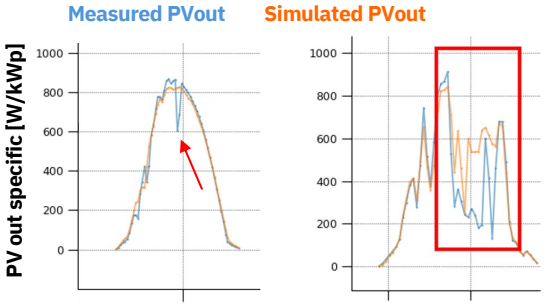
- **What could be wrong? Examples...**

Shading recorded by PV module, but not by GHI pyranometer

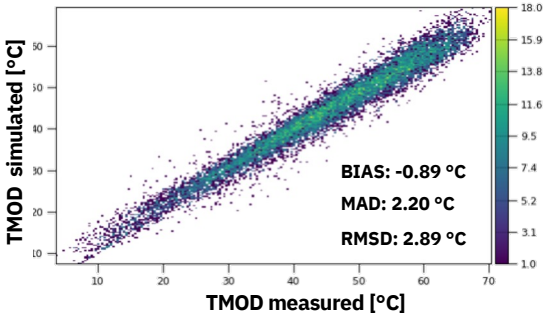




Random events on the site, human operation?



PV module temperature modelling TMOD (daytime)

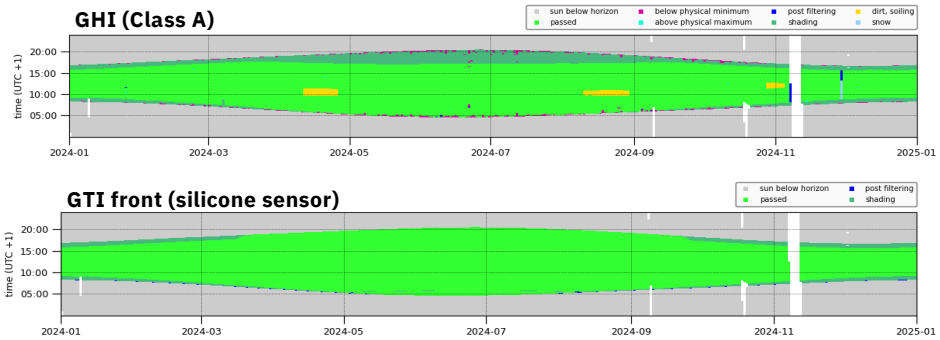


Test site 2 - Sedrun Solar outdoor test facility, Switzerland

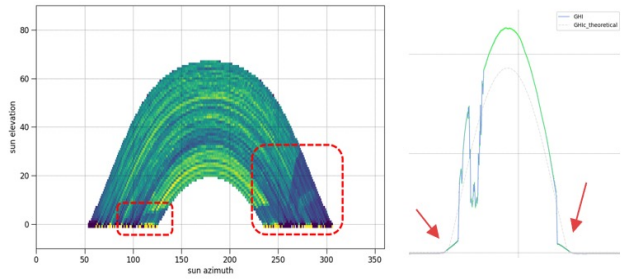
- Mountains, high altitude, higher uncertainty, snow, challenging conditions
- Analysis based on on-site measurements:
  - GHI, RHI (Class A), GTI (silicone sensor), TEMP and WS, QC'ed, harmonized
  - PVOUT from bifacial CSi module, fixed tilt 65 deg, azimuth 155 deg
- Data availability – year 2024, 1-minute time step
- QC results – snow, shading, RHI misalignment
- Uncertainty at the level of DC cabling (MPPT regulator)

Source: Sedrun Solar, ZENDRA (ALPIN QUATTRO ®), Gantner Instruments

Measurements QA results

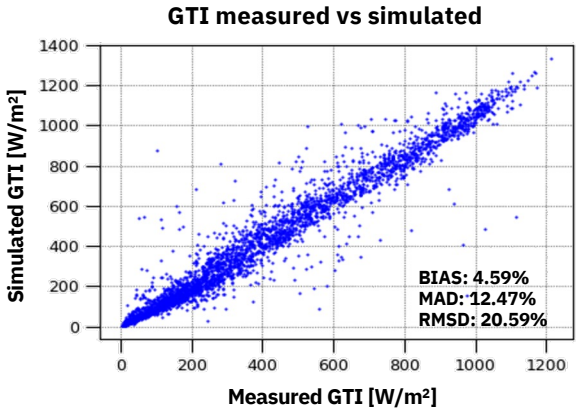


Horizon and construction shading

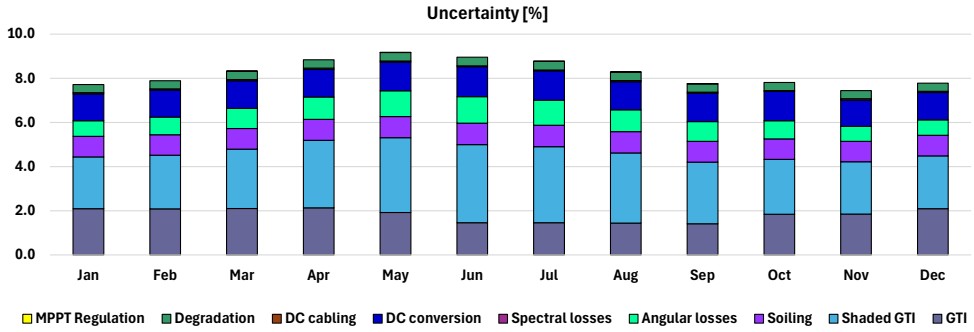


Test site 2 - Switzerland

- Estimation of **input GTI uncertainty**:
  - Challenging conditions in alpine climate
  - Reliability of measured values, what also affecting simulation with the measurement data
  - High albedo periods (snow), reflections

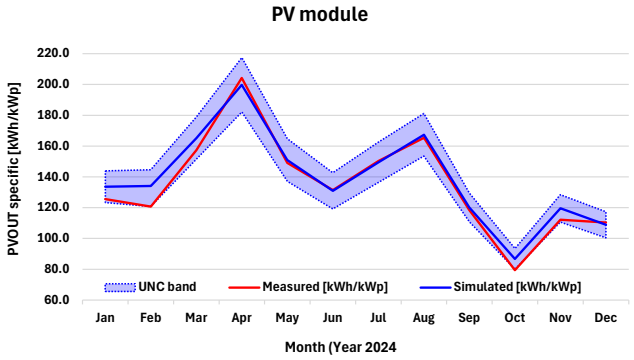


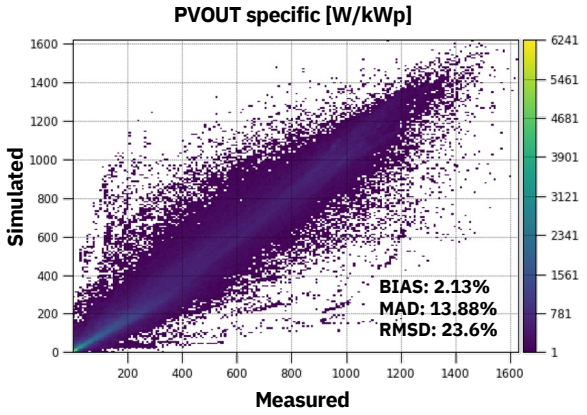
- **Combined monthly uncertainty** $PVout_{meas}$ **±unc**



Note: Each component is rescaled, so the bar height equals the actual combined uncertainty.

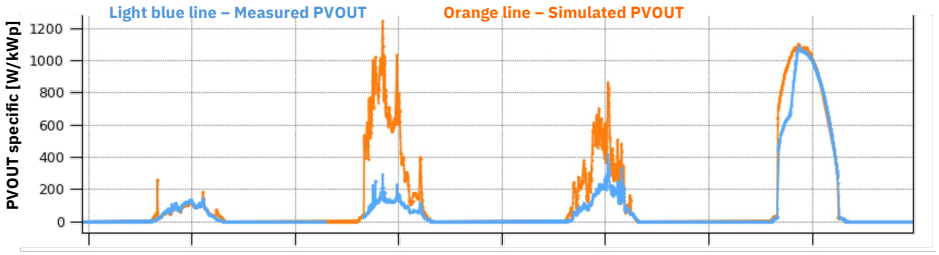
Test site 2 - Switzerland





- **What could be wrong? Examples...**

Snow/frost on PV modules, but not on pyranometer (flagging uncertainty)

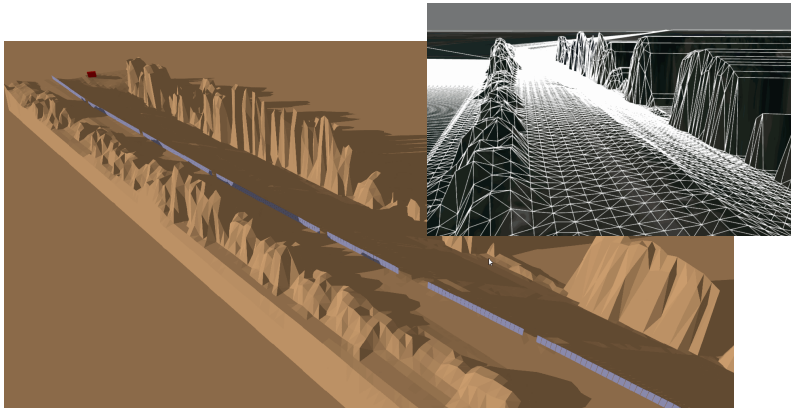


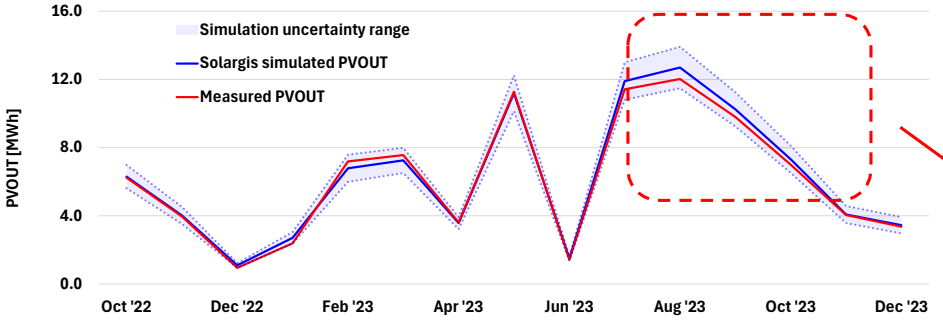
Other challenges:

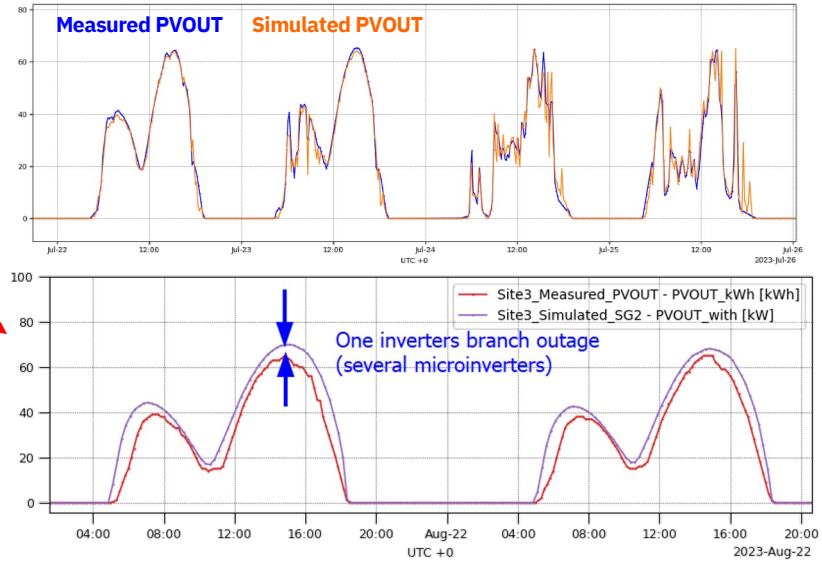
- Albedo
- Shading
- Temperature sensor “insulated” by snow

Test site 3 – Vertical bifacial installation, France

- Temperate climate, LIDAR surface model
- Analysis based on on-site measurements:
  - GHI, TEMP and WS, QC'ed, harmonized
  - PVOUT from bifacial vertical CSi modules
  - Data availability – 14 months, 10-minute time step
  - UNC for simulation chain up to LV power output – additional uncertainty of LIDAR to be considered (3D modelling)

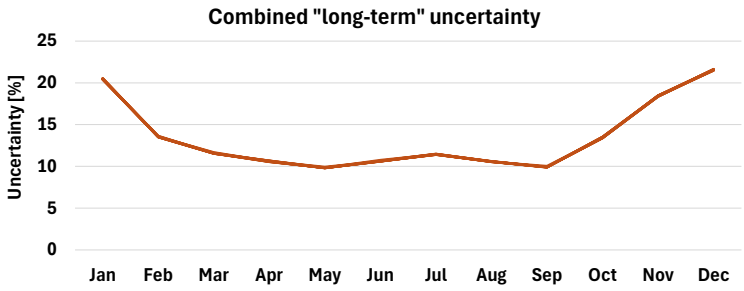




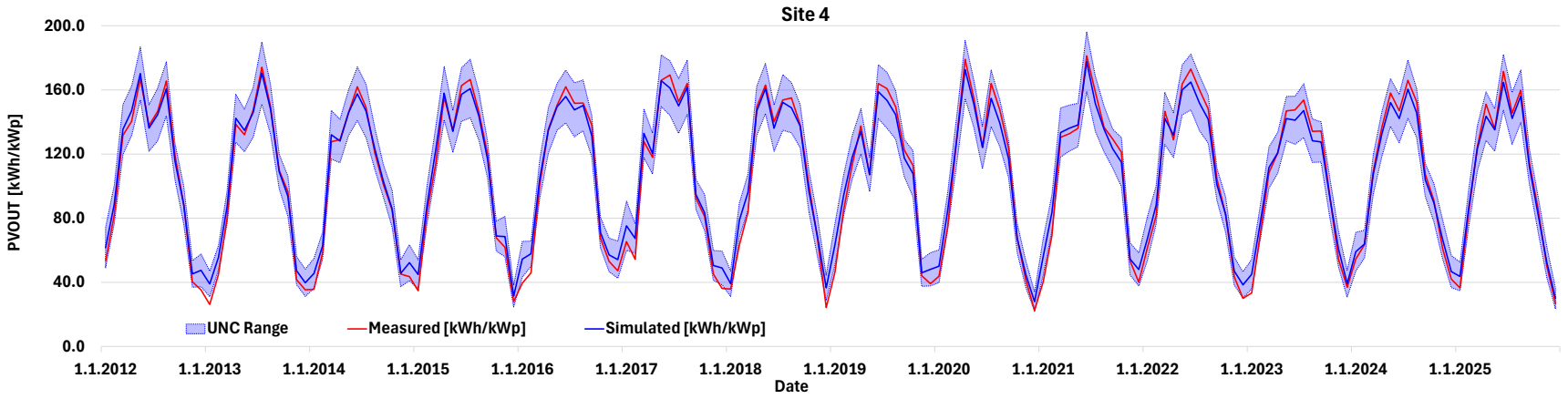


Test sites 4, 5 – Industrial ground-mounted, fixed-tilt, Slovakia

- Continental climate, long term operation
- Analysis based on:
  - Input satellite data for simulation
  - PVOUT measured by electricity meter
  - Data availability – 14+ years, 15-minute time step
  - UNC for simulation chain up to grid connection point

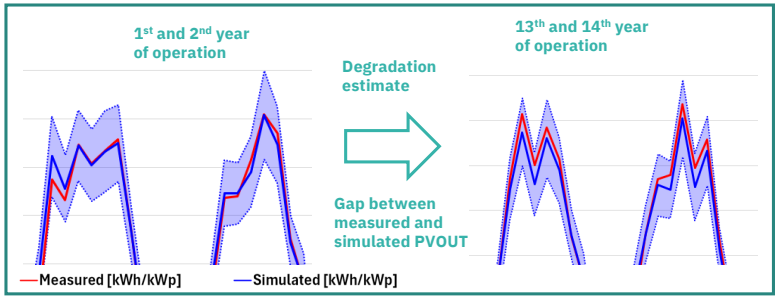


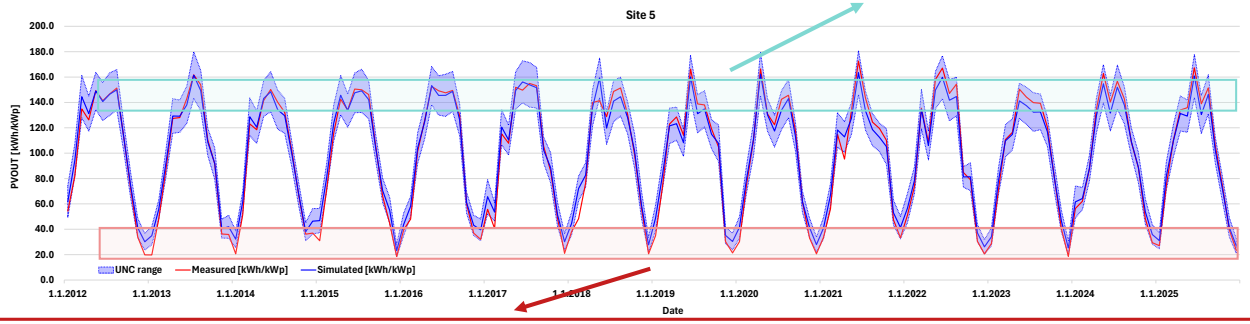
additional uncertainty given by degradation estimate

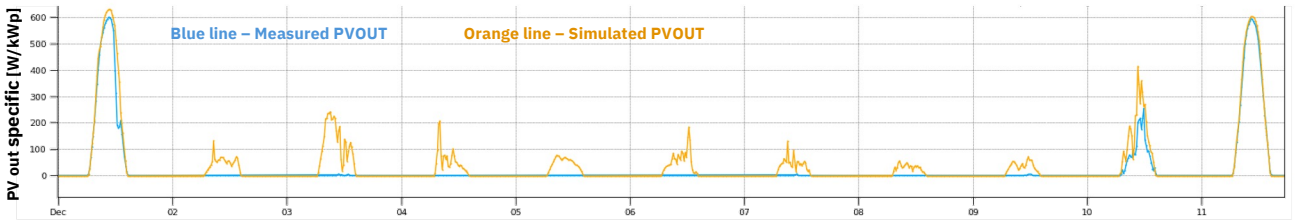


Test sites 4, 5 – Industrial ground-mounted, fixed-tilt, Slovakia

- Site 5 – similar pattern of production and uncertainty as Site 4
- Observed abnormalities:
  - Representation of snow in satellite data (challenge in snow losses model and uncertainty of this model)
  - Conservative estimate of PV power degradation
  - Production outages (unavailability)







Typical winter situation

- Cold days, TEMP below 0 °C
- Modules covered by snow
- GTI+TEMP not so strong to slide/melt snow

Summary and Conclusions

Conclusions

- Simulation chain and accuracy confirmed with real PV power production
- Sensitive to good quantification (mostly) of inputs like shading, albedo, snow, system specification, performance degradation ...
- Uncertainty concept verified on monthly scale, good base for future development
- Uncertainty of simulation as tool for monitoring - any deviations of production outside uncertainty band can signalize operational issues

Future work

- Improvement in uncertainty of optical part of modelling chain (biggest contributors):
  - Shading
  - Snow losses
  - Soiling losses
- Higher granularity (daily uncertainties)
- Relations between aggregations – daily / monthly / yearly
- Uncertainty of simulations for portfolios
- Cure real pain – get more data for validation & publication

Thank you.

Tomas Cebecauer
CTO

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