How Hybrid Forecasting Improves Earnings of Utility Scale Energy Assets

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Gantner Instruments
Global Leader in Utility-scale PV/ESS Monitoring & Control

$$\text{LCoE } (\$/\text{MWh}) = \frac{\text{CapEx} + \text{O\&M}}{\text{Energy yield}}$$

- Latest projects:
  - 500 MW, PV cluster, Germany
  - 300 MW, Denmark
  - 300 MW, Angola
  - 230 MW, Poland
  - 180 MW, Spain
  - World's largest PV diesel hybrid plant in Sudan
- Serving > 54 countries
- Certified for Cybersecurity and flexible energy management

We enable effective energy generation in Solar, BESS, Wind, Hybrid, Gensets, and P2X.

Source: Gantner Instruments Environment Solutions, an ISO 9001 & ISO 27001 certified company

Why PV forecasting is needed

- PV forecasts translate expected solar production into operational and market decisions.
- They support reserve management, storage dispatch, ramp management, congestion management, trading, maintenance planning and risk management.

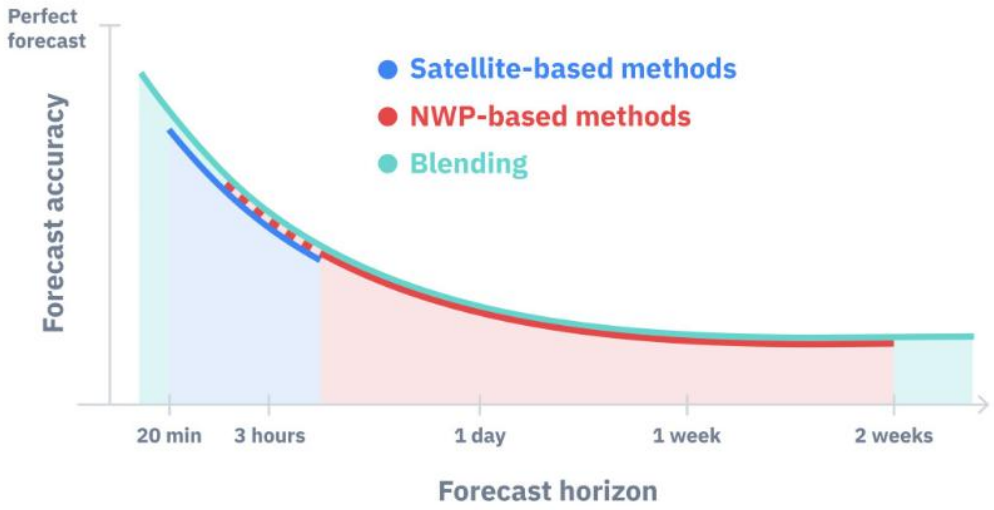
Time horizon	Typical grid activity	Main value of PV forecast
Seconds to 15 minutes	Reserve management, storage optimization, ramp management, market position adjustment	Respond to fast PV changes and protect grid stability
15 minutes to 6 hours	Deviation management, congestion management, balancing, secondary reserves, intraday trading	Reduce imbalance exposure and adjust flexible resources
Day ahead	Scheduling, BESS planning, transmission congestion management, trading strategy	Improve market bids, dispatch planning and penalty avoidance
1 to 3 days ahead	Maintenance scheduling, reserve planning, severe weather alerts, hedging	Prepare operations and reduce weather related risk

Forecast → Schedule quality → Imbalance exposure → Earnings

Hybrid forecasting combines strengths

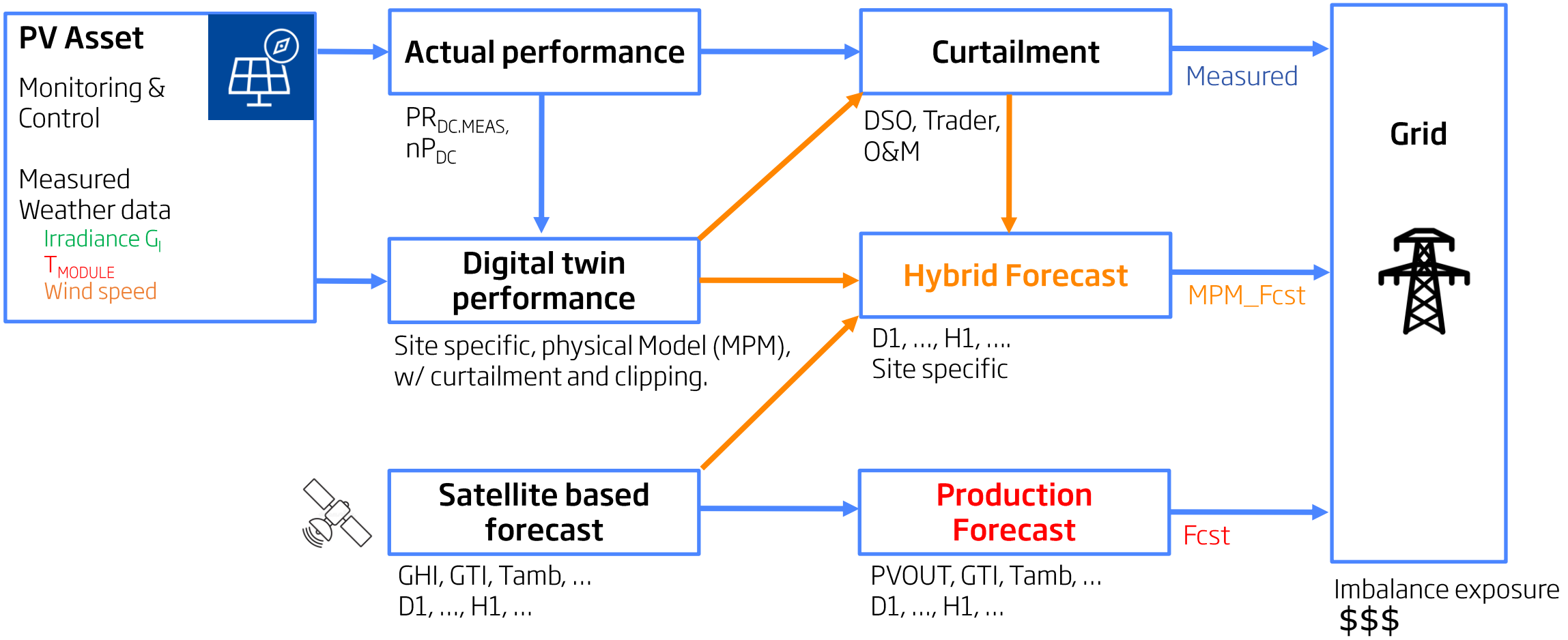
Combining weather forecasts with plant data can make forecasts more accurate than using either one alone.

- Limitation of standard forecasts
  - Generic models may miss local site behavior
  - Extreme weather can amplify forecast error
  - Standard forecasts may not fully capture plant-specific production response
- Why hybrid forecasting helps
  - Combines weather-based forecasts with real plant data
  - Adapts the forecast to the specific PV asset
  - Reduces deviation between forecast and actual production
  - Hybrid forecasting connects physical modeling with real operating data



Weather forecast + plant data + physical model → localized generation forecast

What We Mean by Hybrid Forecasting

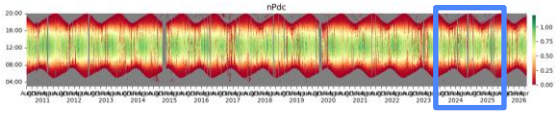


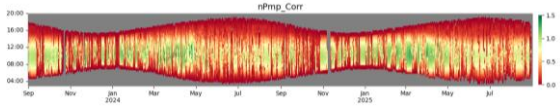
What is the Mechanistic Performance Model (MPM)?
The MPM assigns a meaningful normalized coefficient to expected performance behavior to fit observed measurements with understandable loss coefficients;
Requires only a few days of training data.

SAT Forecast data: 15 min resolution, Measurement data: 1min , Filter for normalized values >5%

Sites overview

Normalized Power





Type	OTF4, Arizona	Sedrun Solar, 18 MWdc Switzerland	Northern Europe 10 MWdc with Curtailment
Climate	Desert, clear, high-irradiance location	Alpine, cloudy, high-altitude (2,100 m) region, frequent snow, high albedo	Variable weather, temperate oceanic climate
PV technology	c-Si, Mono-facial	c-Si, Bifacial	c-Si, Bifacial
Tilt / Azimuth	33° / 180	65° / 155°	25° / 180°
Sensors	c-Si, Pyranometer, 1min data logging	cSi, Pyranometer, Albedo, 10 Hz – 1 min Data logging	c-Si, Pyranometer
Installation date	2010	2023	2022
Forecast source	SOLARGIS mono-facial	SOLARGIS mono-facial	SOLARGIS

Forecast performance at desert site conditions

Hybrid forecast, 15 min data, Sep 2023 to Aug 2025

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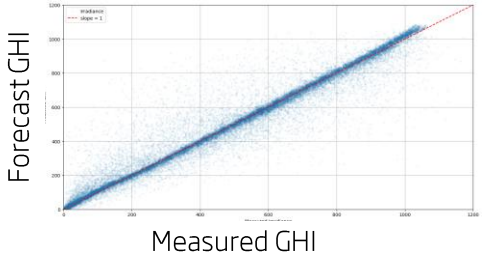
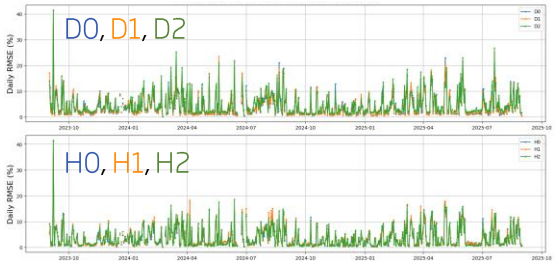
Forecast GHI vs. measured GHI



Daily GHI RMSE by forecast horizon



NRMSE [%] of GHI

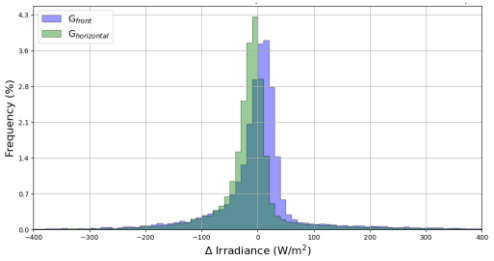
Gh_D0	Gh_D1	Gh_D2	Gh_H0	Gh_H1	Gh_H2
4.00%	4.17%	4.68%	3.44%	3.63%	3.64%

MAPE [%] of GTI

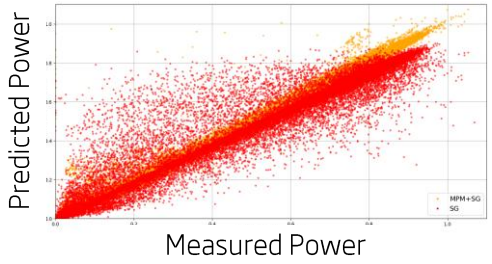
GTI_H0	GTI_H1	GTI_H2	GTI_D0	GTI_D1	GTI_D2
4.31%	4.16%	2.91%	2.17%	2.40%	1.57%

Distribution Irradiance forecast error

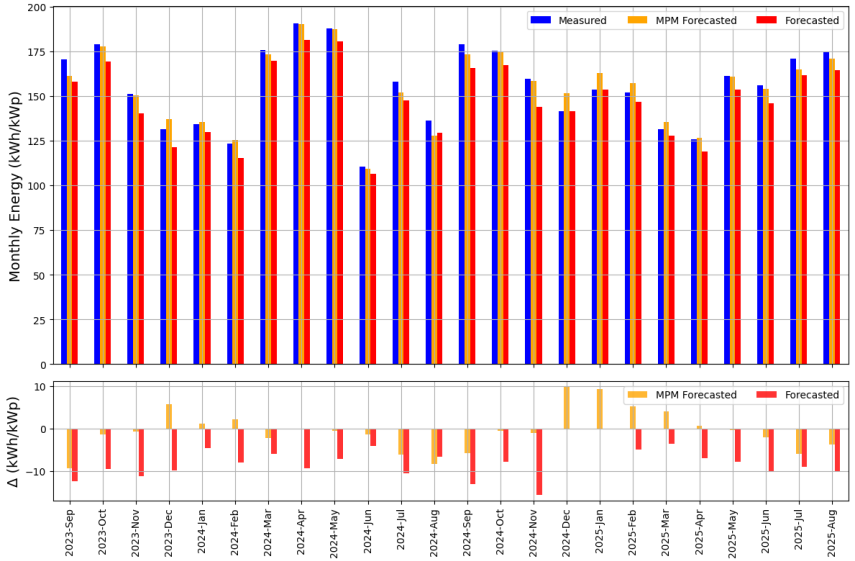
Front, Horizontal vs. Measured



Power: Fcst, MPM_Fcst

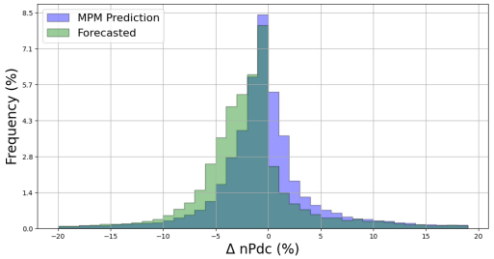


Monthly Energy: Measured, MPM_Fcst , Fcst



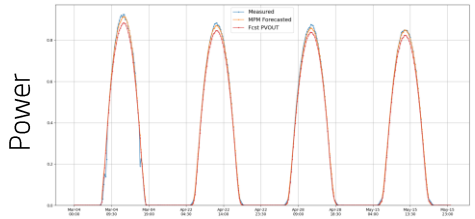
Distribution of Power Forecast Error :

Fcst, MPM_Fcst vs. Measured



Prediction accuracy, Spring

Measured, Fcst and MPM_Fcst

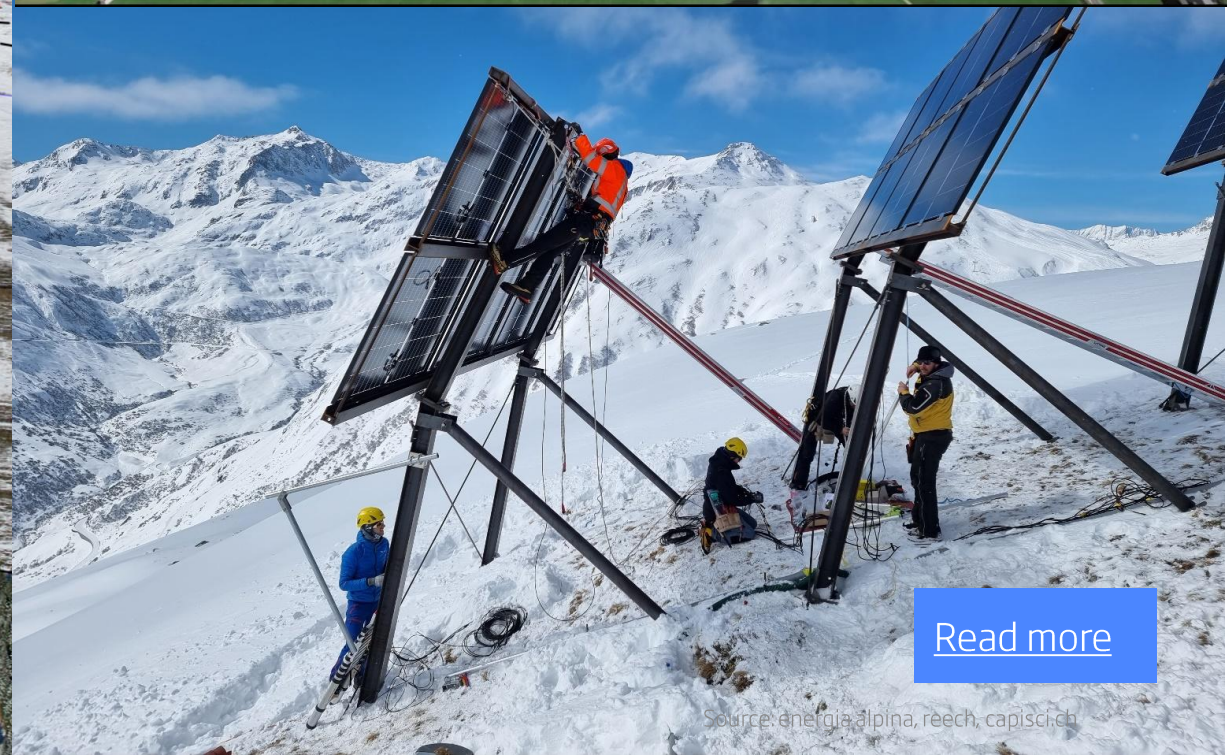


Annual Energy prediction error: 5% → 1%

Energy MAPE Model / Forecast	15 m	Daily	Monthly
MPM_Model	16.9 %	2.7 %	1.6 %
MPM_Fcst	25.3 %	5.2 %	2.7 %
Fcst	27.9 %	6.8 %	3.9 %

Alpine Site Sedrun Solar

ZENDRA

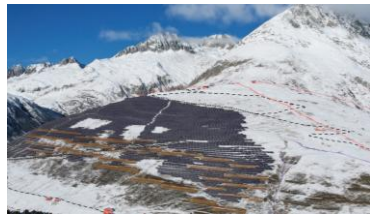


Read more

Source: energia alpina, reech, capisci.ch

Forecast performance under alpine site conditions

Hybrid forecast, 15 min data, Sep 2023 to Aug 2025



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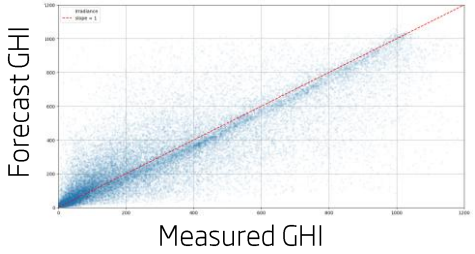
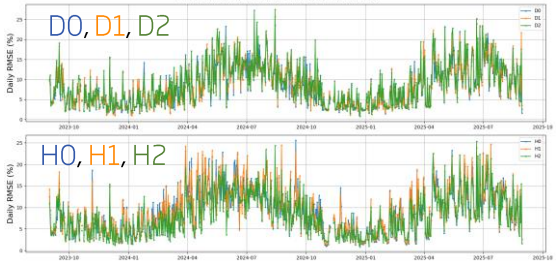
Forecast GHI vs. measured GHI



Daily GHI RMSE by forecast horizon



NRMSE [%] of GHI

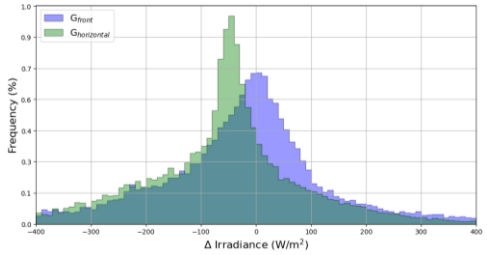
Gh_D0	Gh_D1	Gh_D2	Gh_H0	Gh_H1	Gh_H2
8.15%	8.37%	8.76%	8.72%	9.14%	8.25%

MAPE [%] of GTI

GTI_H0	GTI_H1	GTI_H2	GTI_D0	GTI_D1	GTI_D2
22.52%	23.63%	22.15%	21.20%	20.67%	20.14%

Distribution Irradiance forecast error

Front, Horizontal vs. Measured



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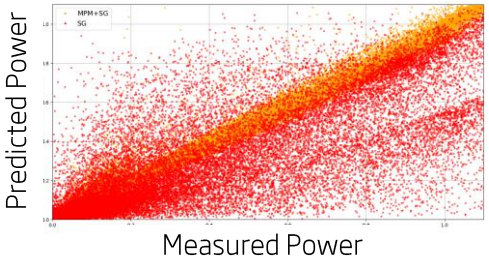
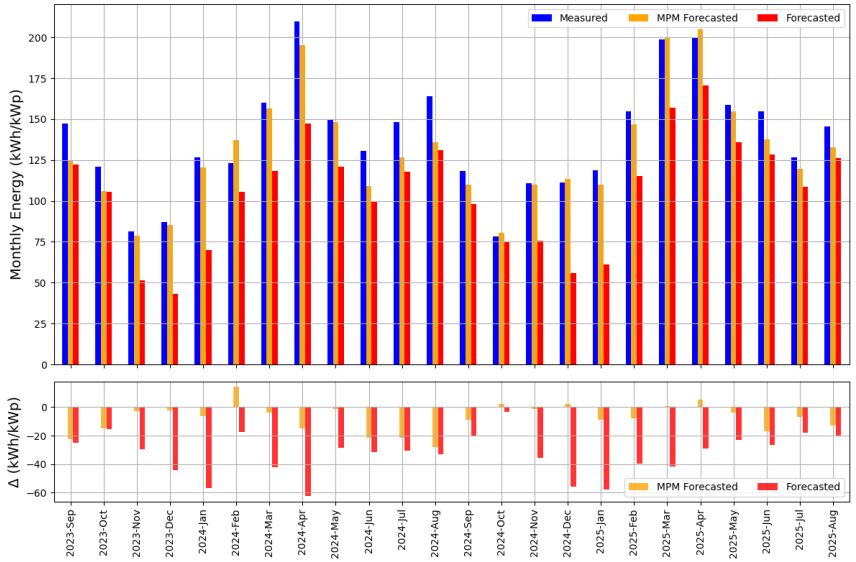
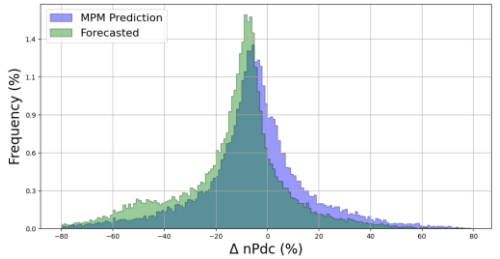


Monthly Energy: Measured, MPM_Fcst , Fcst



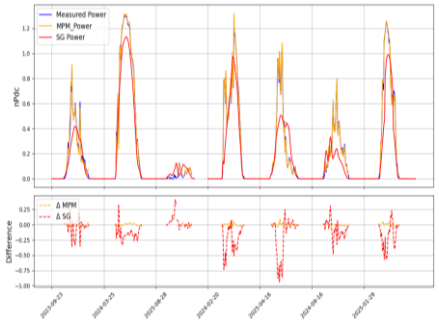
Distribution of Power Forecast Error :

Fcst, MPM_Fcst vs. Measured



Prediction accuracy, Winter

Measured, Fcst and MPM_Fcst



Annual energy prediction error: 23% → 5%

Energy MAPE Model / Forecast	15 m	Daily	Monthly
MPM_Model	11.9 %	7.5 %	3.9 %
MPM_Fcst	79.1 %	24.6 %	9.7 %
Fcst	80.3 %	31.5 %	27.5 %

Why does forecasting still matter during curtailment?

Available energy must be forecasted

- Operators need to know potential production before curtailment is applied.

Curtailment requires planning

- Forecasts support congestion management, dispatch and reserve decisions.

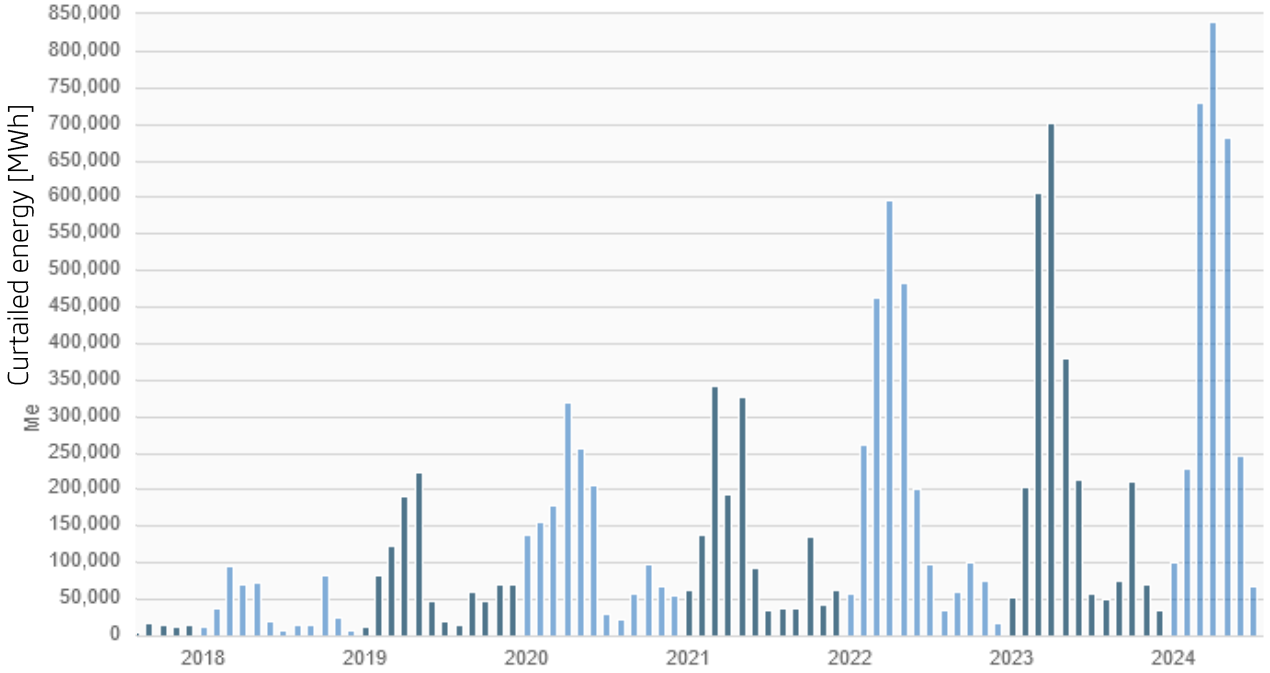
Storage does not remove forecast risk

- Battery power and capacity are limited.

Market positions still need adjustment

- Forecasts reduce deviations and imbalance exposure.

Wind and solar curtailment, California
Monthly curtailed energy shows increasing grid constraints



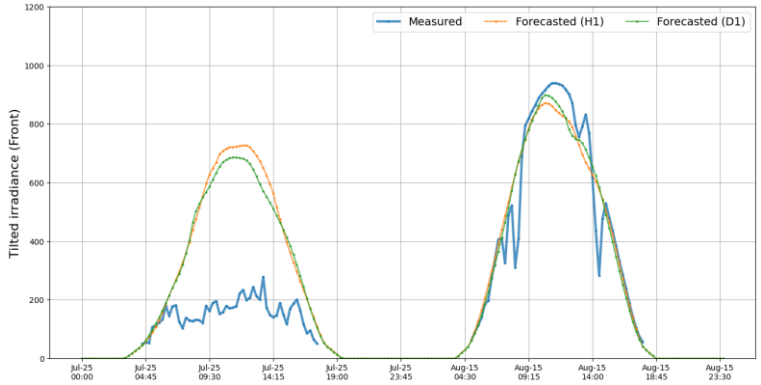
Higher curtailment makes forecast based operational planning more important.

Source: CAISO, Updates as of 8/6/2024, Link; Grid Status link

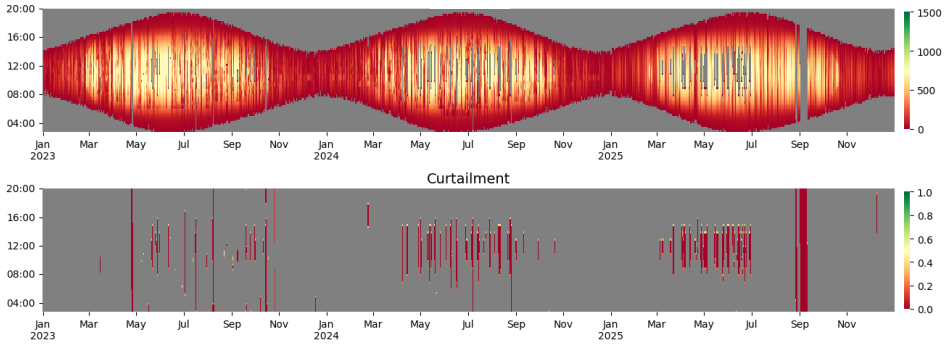
Forecast models must account for curtailed operation

10 MWdc Northern Europe site, Jan 2023 to Dec 2025

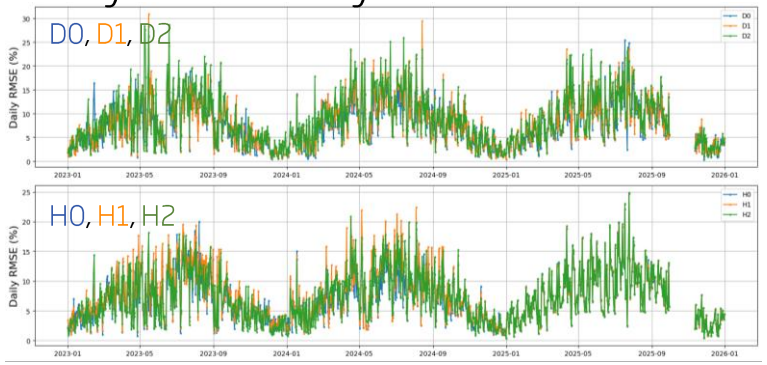
Measured production can differ strongly



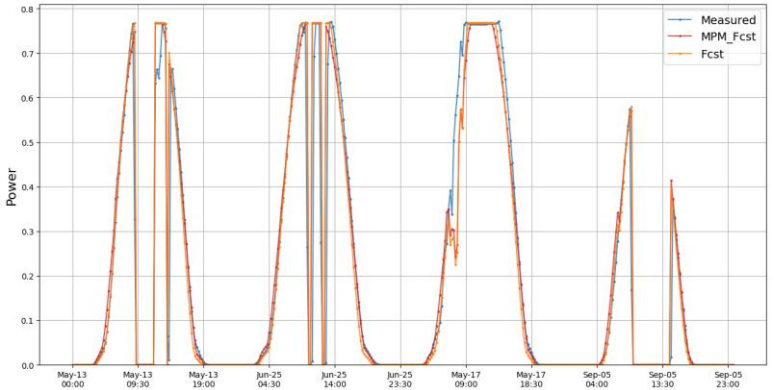
Predicted Power and Curtailment (2023 – 2025)



Daily GHI RMSE by forecast horizon



Forecast and MPM include curtailment and clipping



⚠️ Separate Curtailment losses by source:

Trader · DNO · O&M

More Details: PVSC and EUPVSEC 2026 conference papers.

Source: CAISO, Updates as of 8/6/2024, Link; Grid Status link

Summary

- Desert sites are predictable
  - Stable irradiance reduces forecast uncertainty
  - Annual energy error reduced from 5% to 1%

- Alpine sites need site specific modeling
  - Snow, high albedo and variable weather increase forecast error
  - Annual energy error improved from 23% to 5%

- Forecast error becomes economic exposure
  - Forecast deviations affect schedules, imbalance exposure, curtailment planning and storage dispatch
  - Better forecasts improve earnings predictability

Hybrid forecasting is most valuable where local site effects dominate standard forecast uncertainty.

A forecast is only useful when it improves the next decision.

Thank you very much!

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More information here:

https://www.gantner-instruments.com/company/research/analytics/

Source:
GI Weather prospecting, La Paz County, Arizona, PV ~1 GW, 18 km2,
ESS ~ 1 GWh, Hydrogen enabled by PV
Connected to Ten West Link 500 kV transmission line with two substations

Appendix

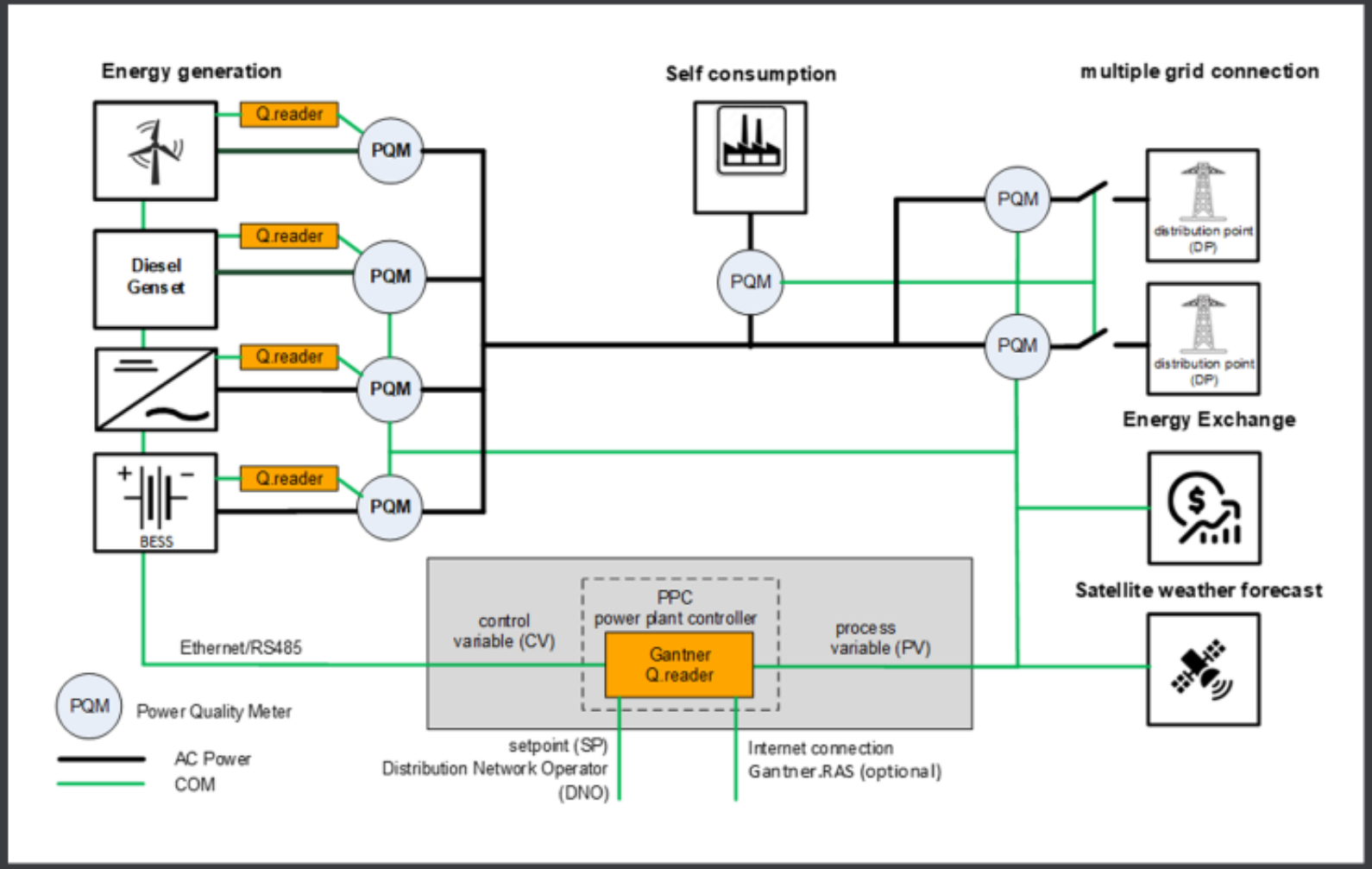
Q.reader PPC and BESS Controller

Certified Power plant controller "PPC" features

Gantner instruments | intelligence for energy

Main features

- Multi feeder, distribution point support
- Absolute production constraint
- Power gradient constrain
- Voltage and Frequency Control
- Active / Reactive /PF Power Control
- Power Factor Control
- Frequency Control
- Zero feed IN
- Self consumption optimization
- Battery Control "BESS"
- Data logging
- Browser based HMI
- Remote configuration by Gantner.RAS
- VDE-AR-N 4110, 4120, 4130



PV Yield assessment: Measured vs. Expected

String, MPP, Inverter DC, AC, Site level

Types: Fixed and tracked

Mechanistic Performance Model (MPM) for Large PV Arrays

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MPM assigns a meaningful normalized coefficient to expected performance behavior to fit observed measurements with understandable loss coefficients

$$MPM_{Param} = C_1 + C_2*(T_{MOD}-25) + C_3*Log_{10}(G_I) + C_4*G_I + C_5*WS$$

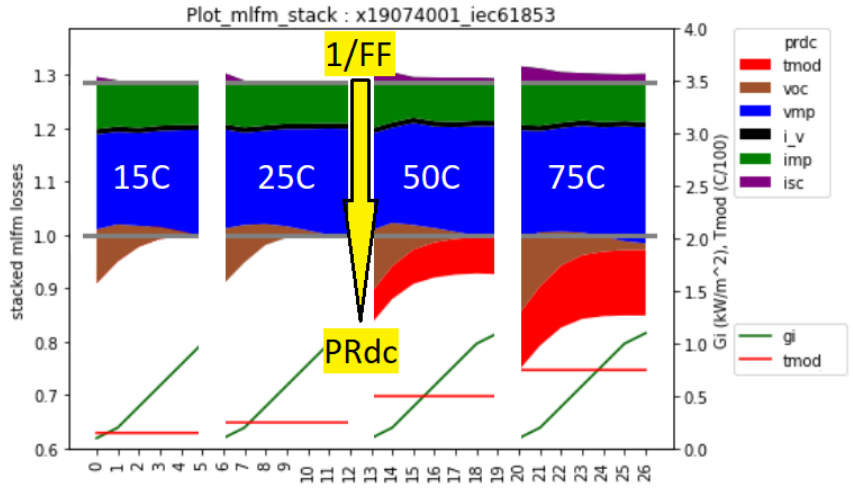
e.g., PR, nVdc, nIdc	Tolerance	Temperature	V_{OC} and R_{SHUNT}	R_{SERIES}	Wind

MPM Advanced

5 Coeff. for typical sites

MPM Professional

Covers also Clipping, Asym., Curtailment



MPM is best to:

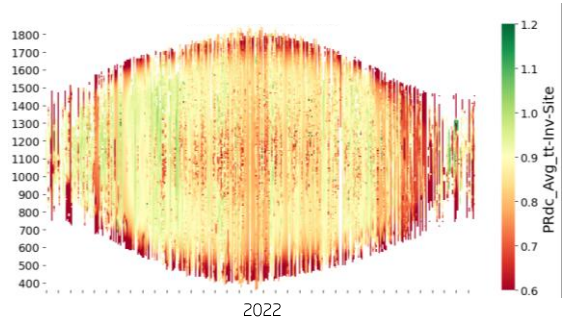
- Fit measured PR vs. Irradiance and Tmodule
- Look for discrepancies or poor-fit coefficients
- Predict performance

MPM Coefficients are meaningful, orthogonal, robust, and normalized; Inputs: G_I, T_{MOD}, WS, $P_{NOMINAL}$
Graph shows losses per component from 61853 matrices of only Isc, Imp, Vmp, and Voc. IV curves weren't provided.

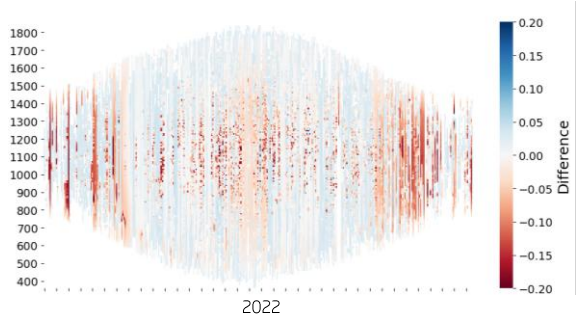
Delta and Distribution of nPdc
Fixed and tracked site, Europe

Site C
Fixed, 14.1 MW

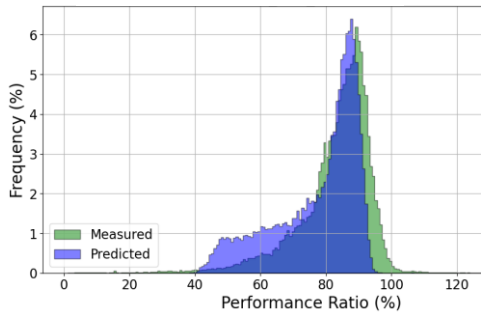
PRdc



Delta PRdc

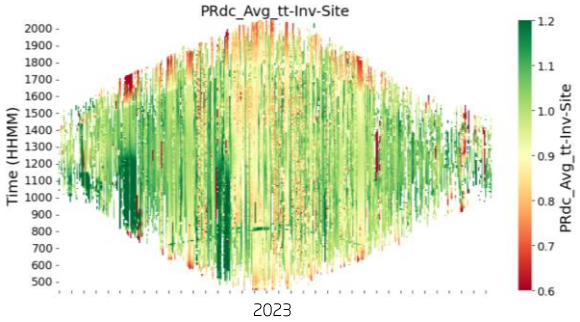


PRdc (Meas, pred)

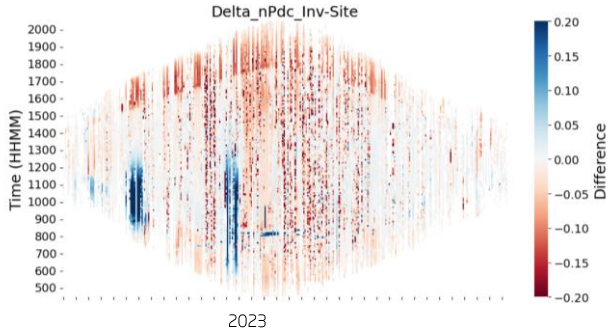


Site F
Tracked, 53 MW

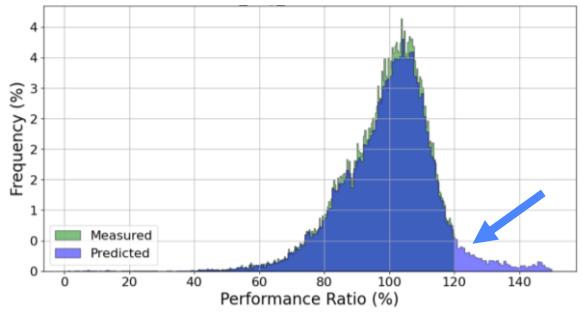
PRdc



Delta nPdc



PRdc (Meas, pred)



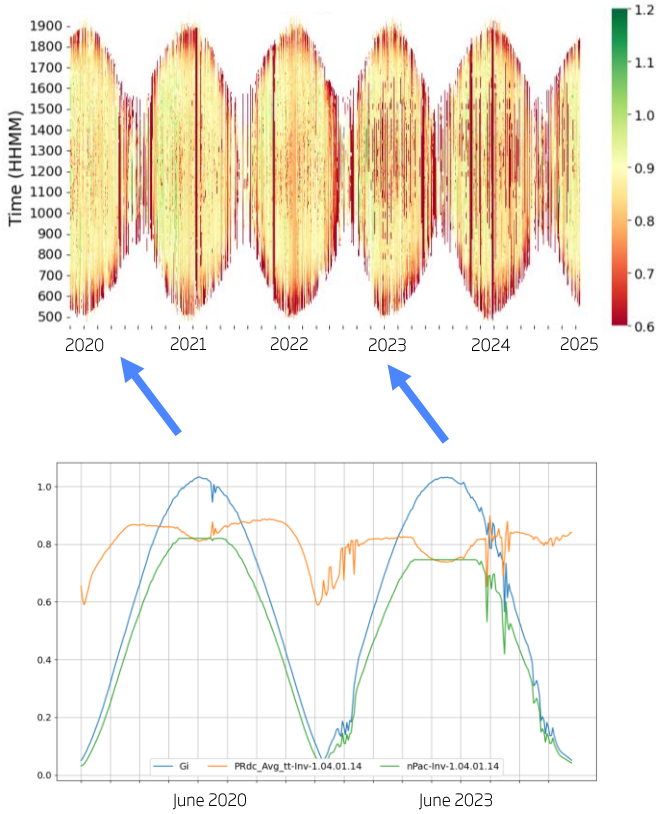
Low Irradiance

Good alignment for Measured and Predicted. Calculated for all Components and Site level.

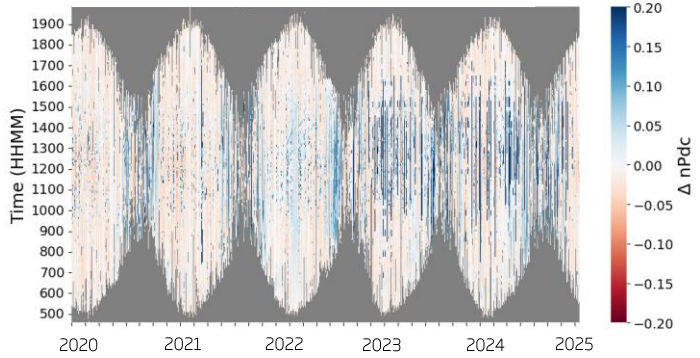
Applied for mono and bifacial technologies; fixed or tracked sites

Clipping: Instant detection and loss assignment
Site C, 14.1 MW, Europe, fixed, 5 years

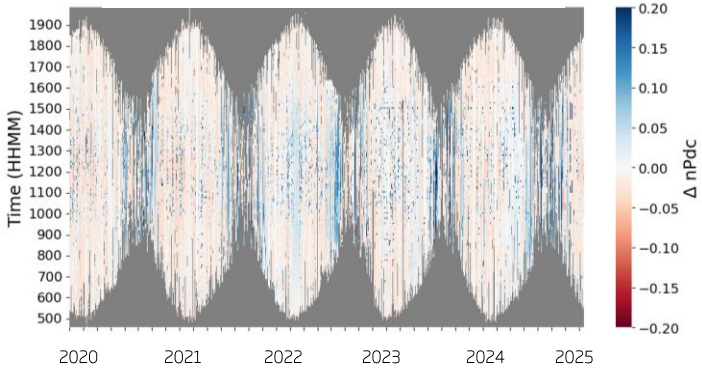
PRdc-Inverter-Site



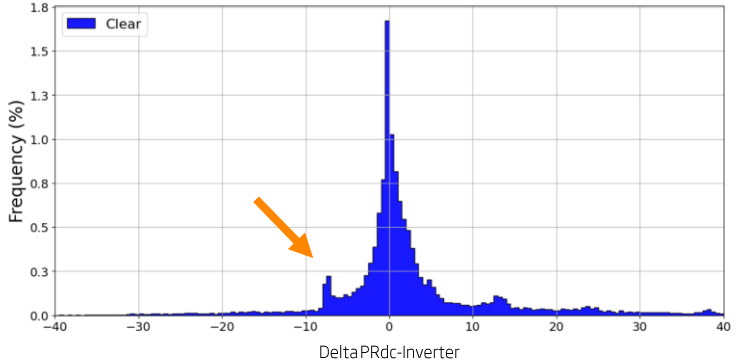
Delta nPdc-Inverter



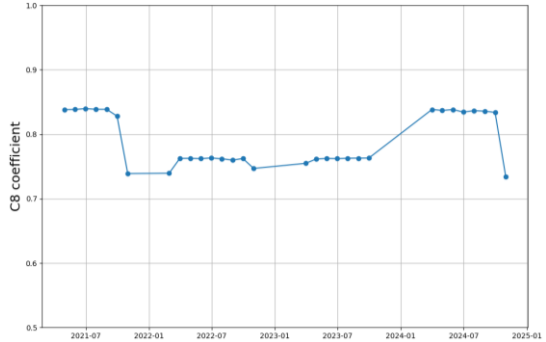
Delta nPdc-Inverter (no Clipping)



Delta (full period), Clear days



c_8 (clipping) (max. value, monthly)



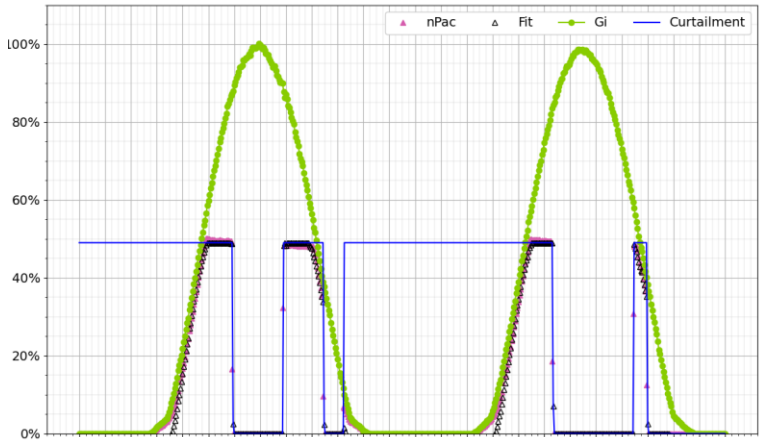
c_1 is constant, no degradation observed

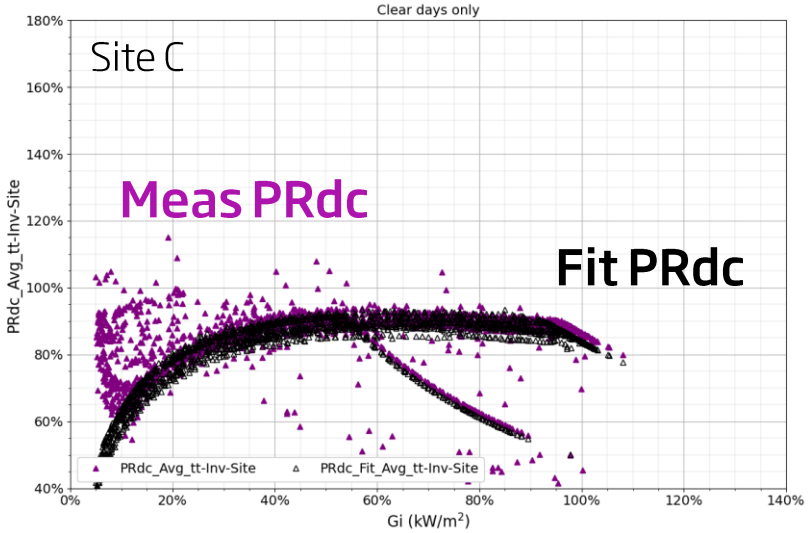
MPM coefficients can identify any change (clipping, curtailment, degradation, …)
Clipping losses are easy to calculate

Models have to deal with curtailment losses

Gantner instruments

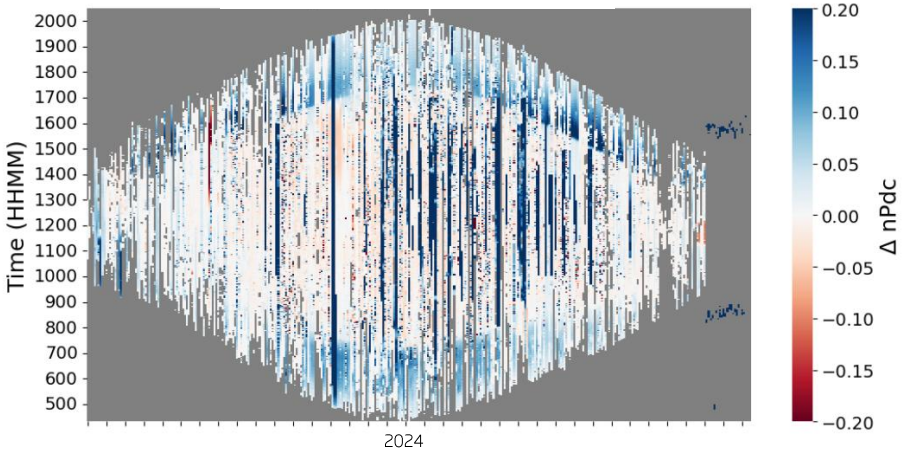
Curtailment Example, normalized



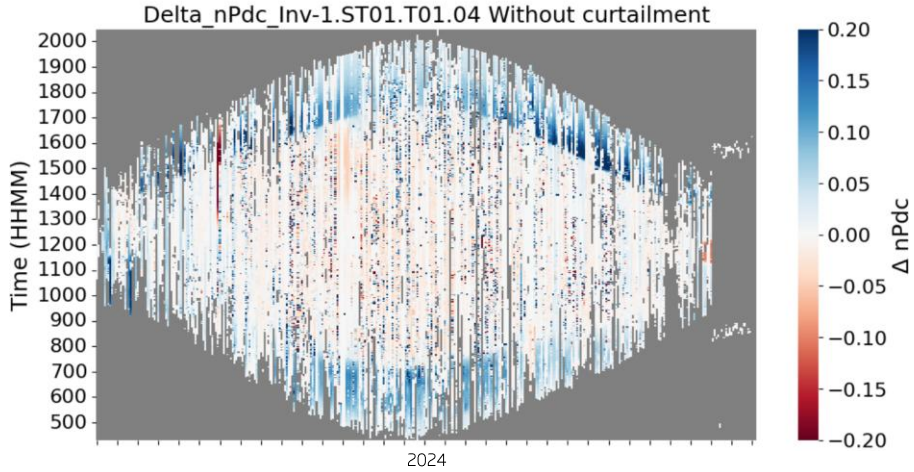


Site G, 5MW, tracked; Inverter power: 215 kW

Inverter With Curtailment

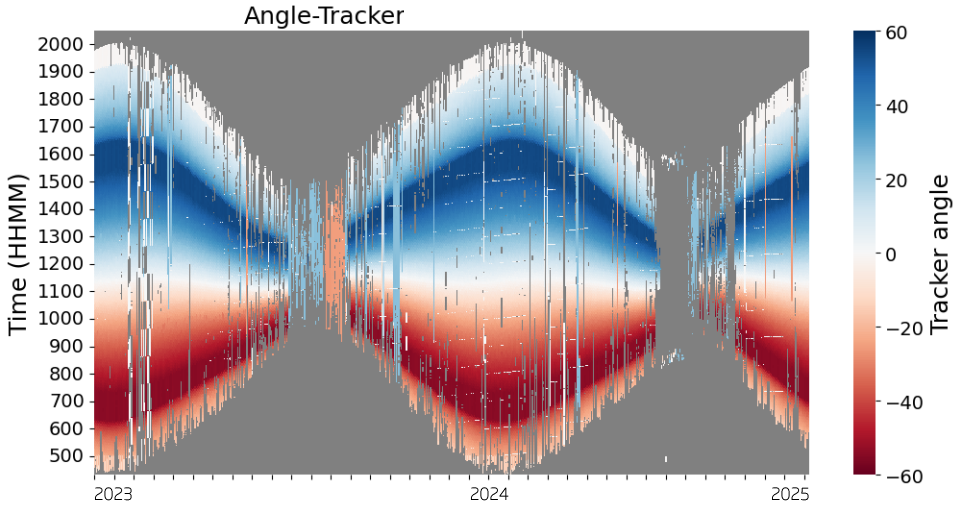


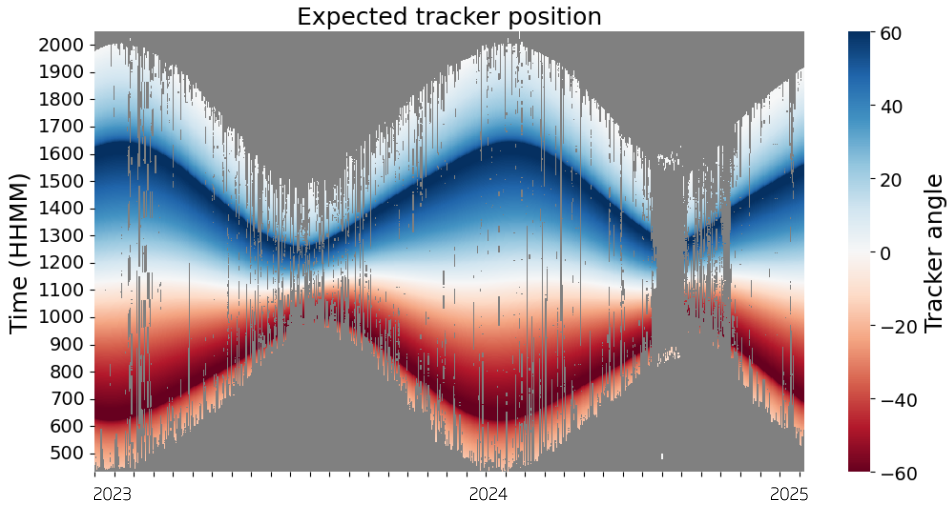
Inverter No Curtailment

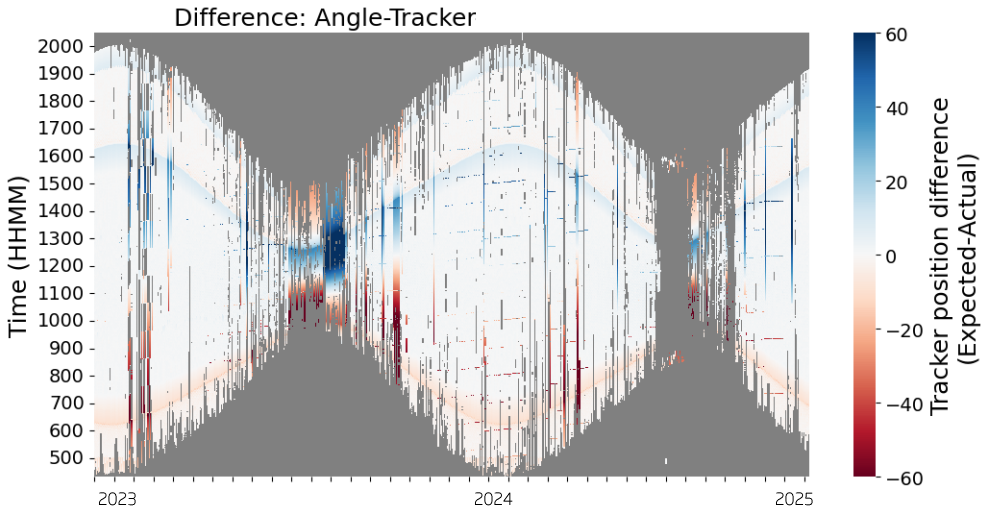


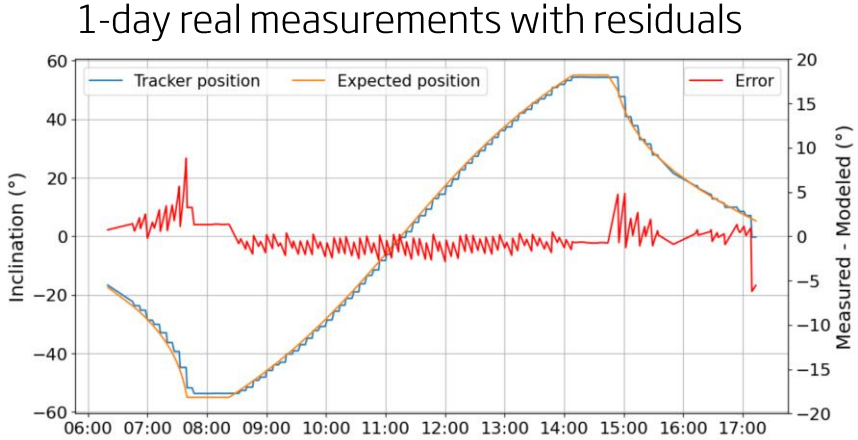
Separate curtailment losses based on source: DNO, Trader, O&M, ...

Finding gains in Tracker operation
Actual vs. Expected angle and residuals, Site G, Tracked, 10 MW_{DC}







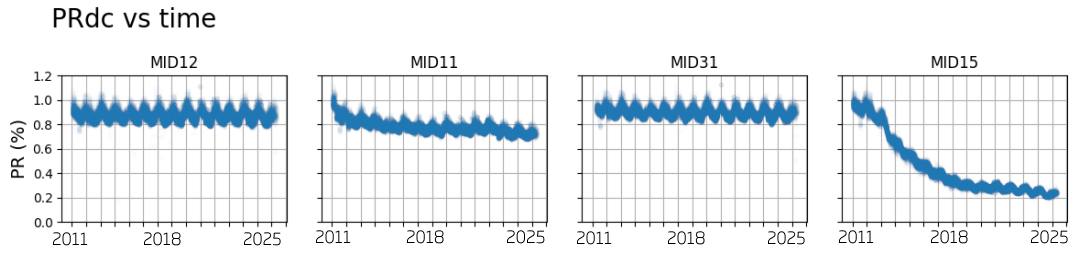


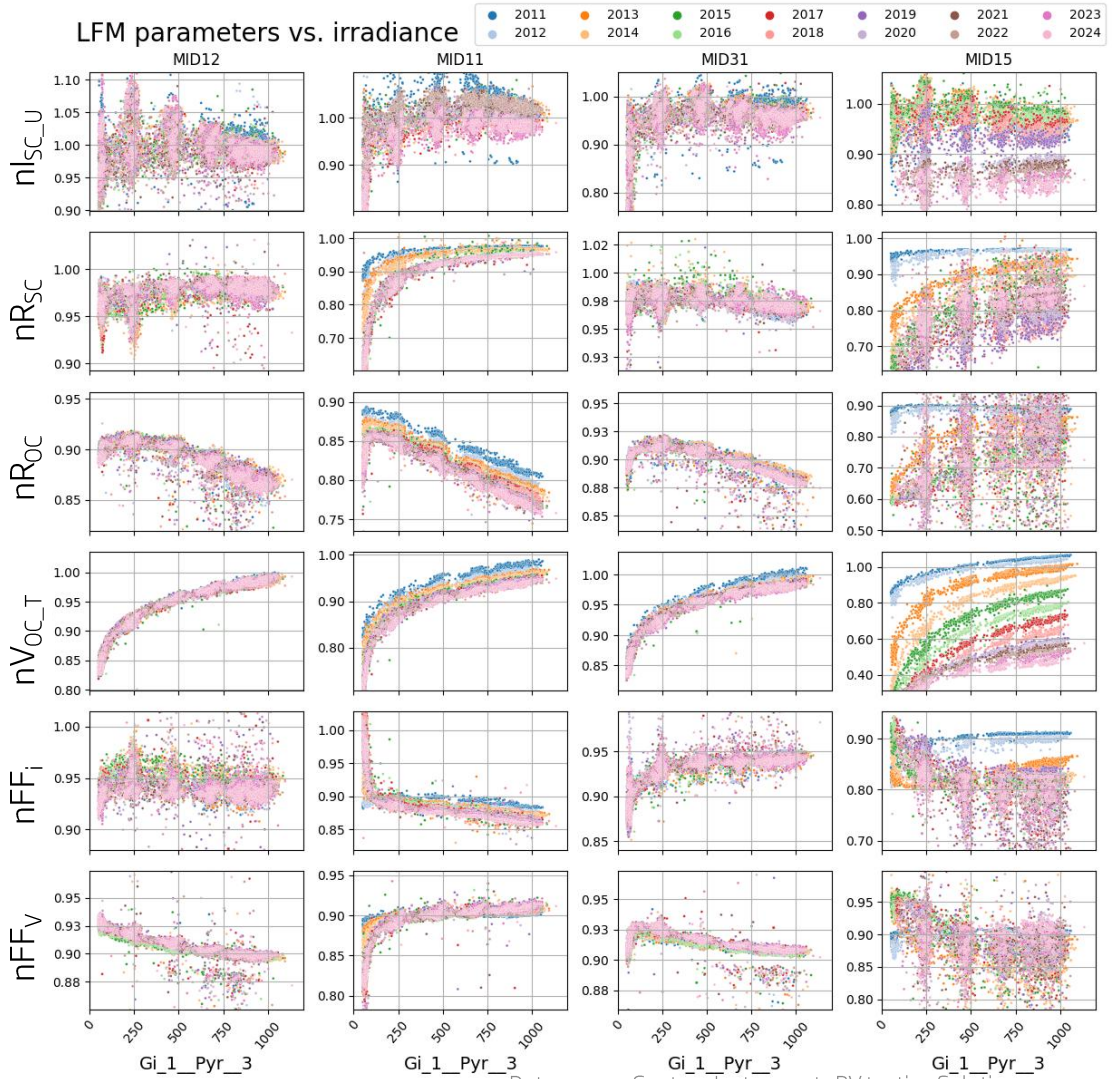
Actual vs. Expected degradation 2011 – 2025

- Independent PV Module testing
- 15 year, one of the longest outdoor test worldwide
- 1min resolution
- Losses based on Loss Factors Model (LFM), IVscans

Degradation:

- Very stable c-Si multi (MID12), c-Si HJT (MID31)
- Degrading – as expected: CdTe (MID11)
- Strongly degrading: CI(G)S (MID15)

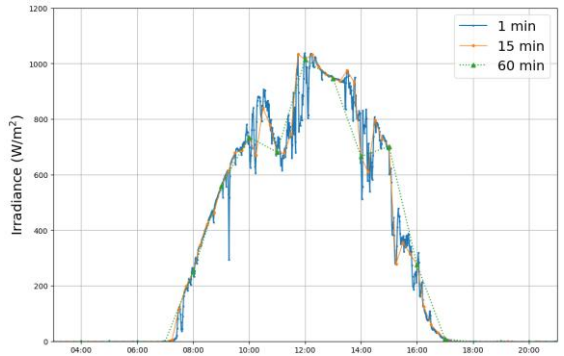




Data source: Gantner Instruments PV testing Solutions

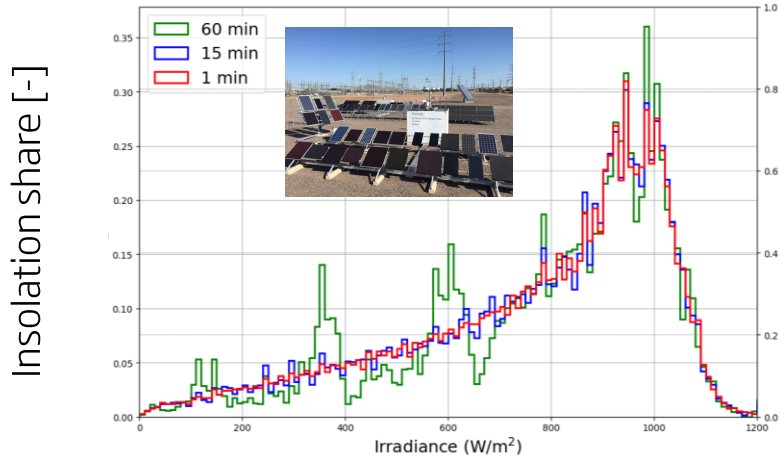
The Role of Data Acquisition (DAQ): Impact of sampling rates

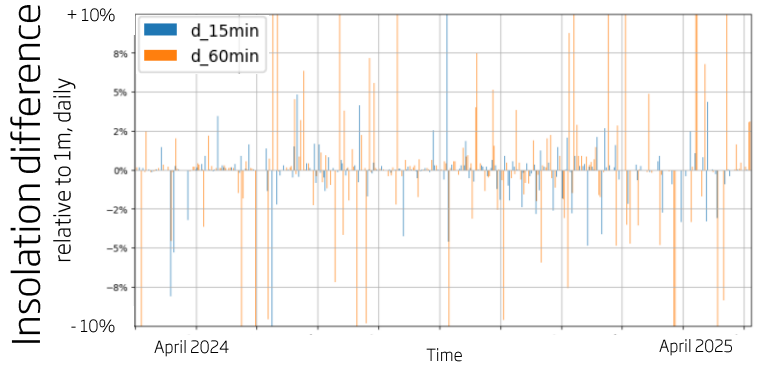
- Sampling rates:
  - 1 s
  - 1 min
  - 15 min
  - 1 h
- Important for:
  - High altitude/latitude
  - Hilly or shaded topologies
  - Tracked, curtailed systems
  - Variable weather



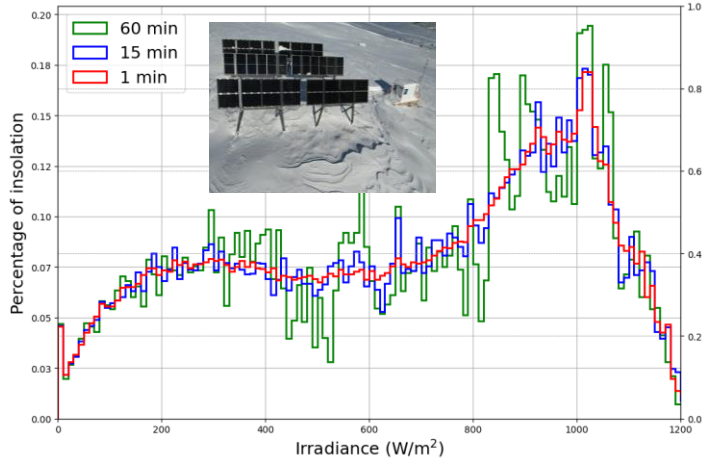
1 day in AZ/USA

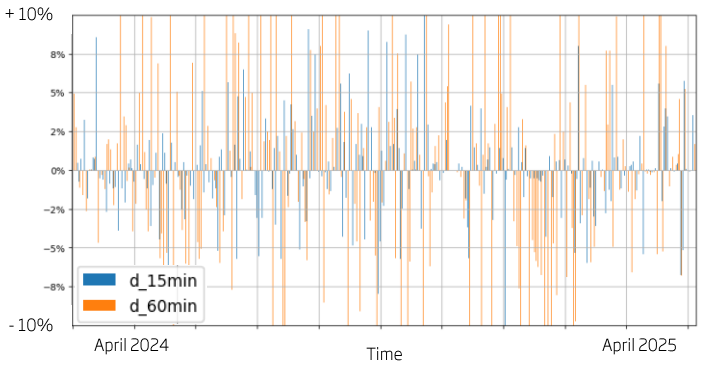
OTF4, Arizona, Desert, 1 year





OTF21, Switzerland, Alpine, 1 year





High resolution is needed for rapid insights and effective O&M

Data source: OTF04: Gantner Instruments testing facility, Arizona; OTF22, ewz Test facility Tschers, Surses, Switzerland