Data-driven predictive analytics & system monitoring workflows for streamlined utility-scale photovoltaic power plant failure diagnosis

PVPMC Workshop
Nov 8th, SUPSI, Mendrisio, Switzerland

Jürgen Sutterlüti et. al.
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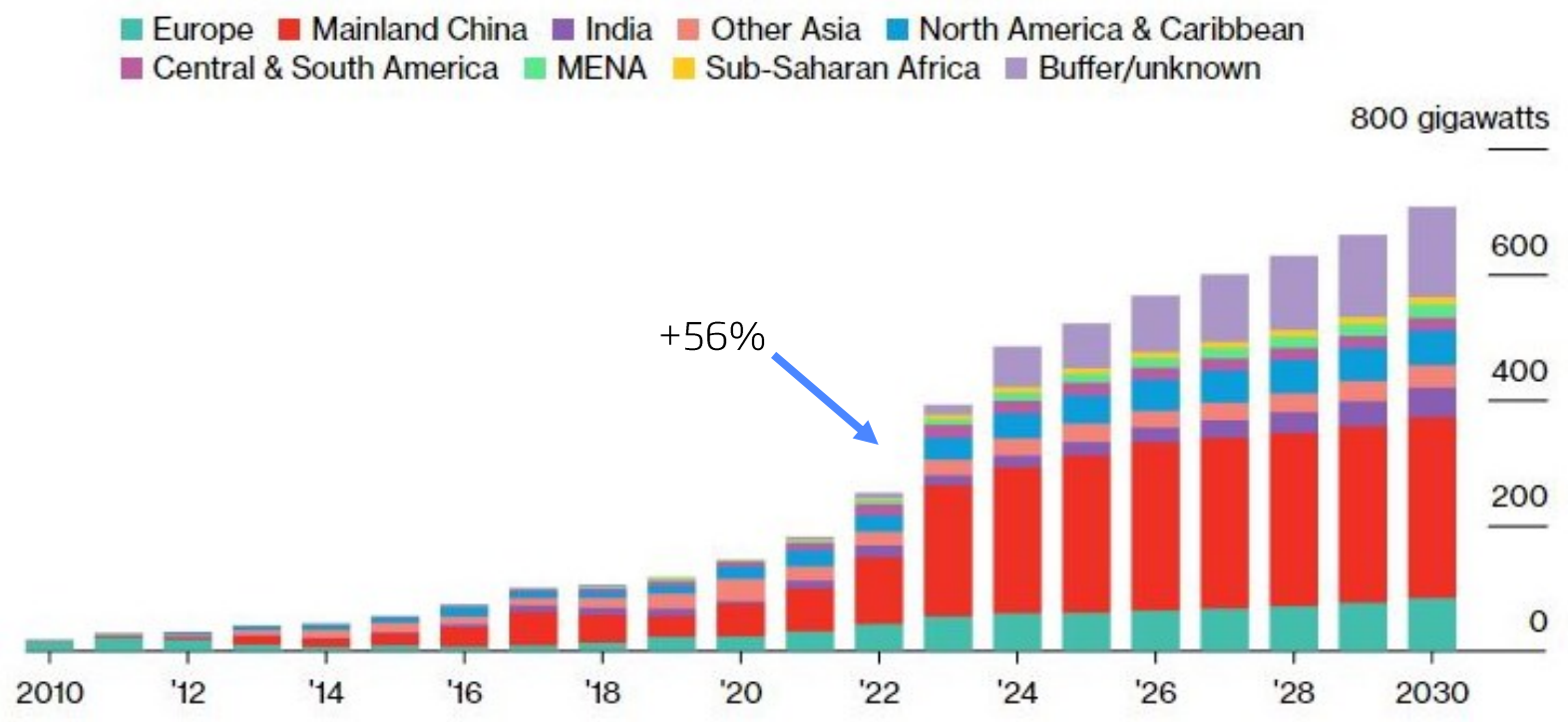
Installing the next TW PV Capacity

- 392 GW PV Installation in 2023, +56%
- 14.5ctUSD/Wp: Cheap PV Modules
- 570 GW Polysilicon supply
- PV and ESS combined

- Margins:
  - Under pressure across the PV value chain
  - Competition is intense
  - High module inventory in Europe and other large markets

Global PV installation, expected in 2023 [GW]



Reliable Information about Energy generation is key

Predictable Energy Output makes a huge difference in earnings

BNEF, Sept 2023

How to operate an Energy Asset with a Stable Return of Investment?

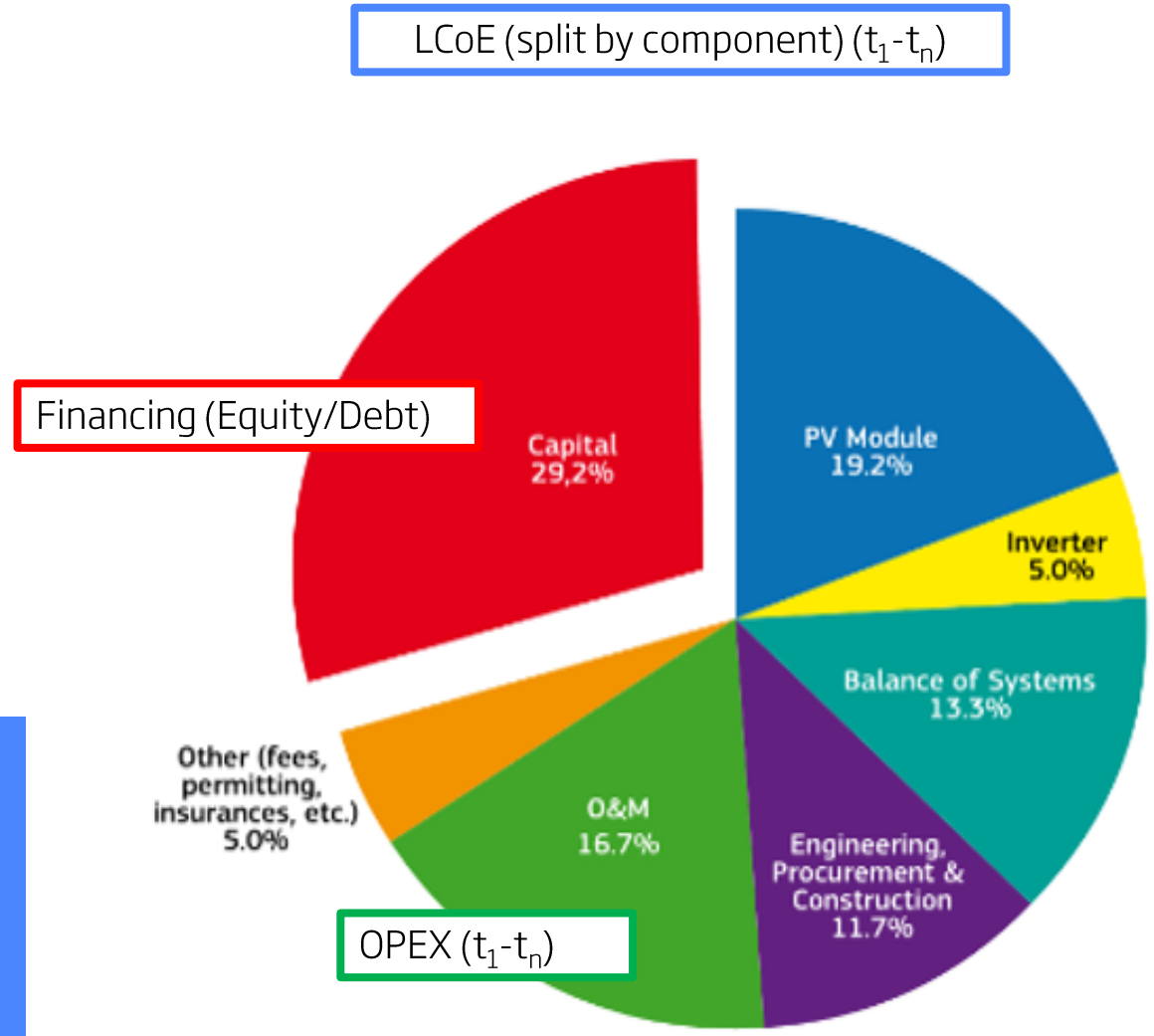
CAPEX (t_0)

OPEX (t_1-t_n)

Energy Production (t_1-t_n)

Financing (Equity / Debt)

LCoE



Effective O&M maximizes Energy production, reduces downtime:

- Measured data needs to be combined with MetaData and converted into helpful Information of the O&M team and owner
- Automated Loss assignment where possible and automated workflows trigger

LCoE for Utility Scale, 5% ROI (Source: JRC); System cost Scenario: 1000 Vdc, Medium, IND/USA/EU; Gantner Instruments System cost model.

PROJECT

Monitoring, Control, and Analytics of a 650 MW PV Power Plant

CUSTOMER
MOVE ON Energy

COUNTRY
Germany, Witznitz, near Leipzig, former open-cast lignite mine

APPLICATION
PV Monitoring, Control, Analytics

MARKET
Energy

SHORT DESCRIPTION

- 1.1 million bifacial PV modules, East-West orientation
- Complies with Germany's Federal Office for Information Security, known as 'BSI'
- Control of 2 transformer station and grid connection points
- Gantner Power Plant Controller with certification VDE-AR-N 4130 for 380 KV
- 3600 PV Inverters with 125 kW nomial power
- 1000 RS-485 interfaces in 22 monitoring containers
- Raw data volume: 17 GB/day, 180 TB/30 years

Source: Gantner Instruments Environment Solutions

Performance Evaluation

Performance Evaluation

Reliable Information for Optimum Energy Output

Atlas Energy Park

La Paz County, Arizona

PV ~1 GW, 18 km^2

ESS ~ 1 GWh

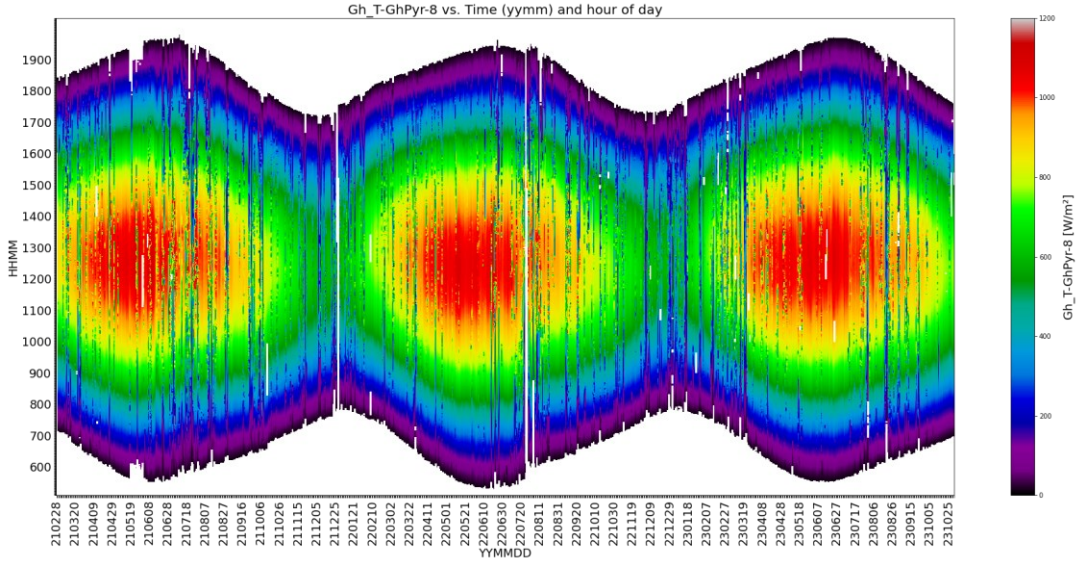
Hydrogen enabled by PV

Connected to Ten West Link 500 kV transmission line with two substations

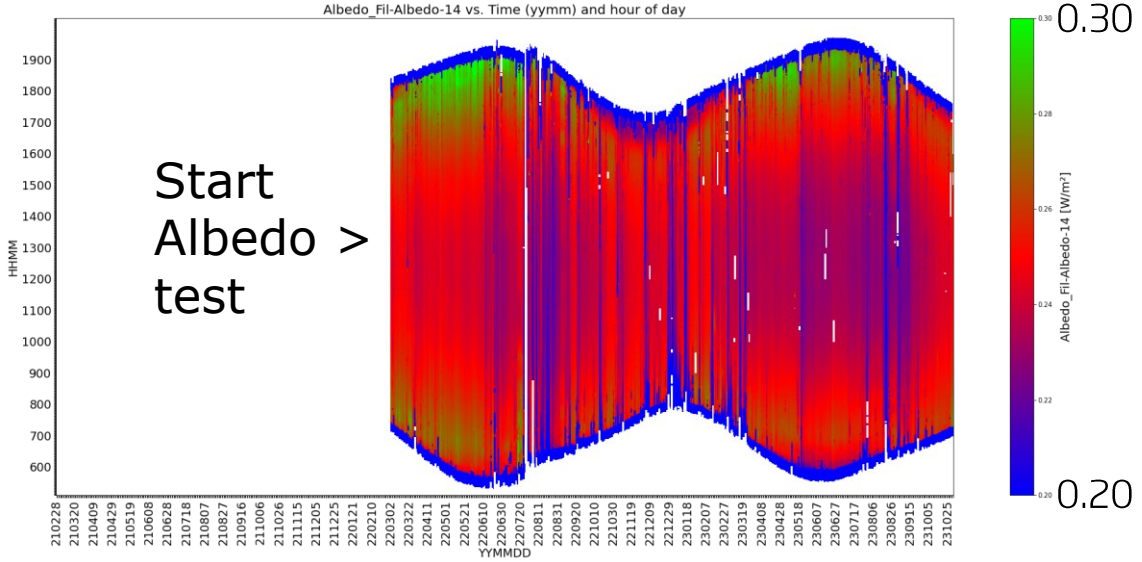
Questions to answer for optimum Energy output:

- How erratic is the weather? → Better simulation and prediction
- Impact of soiling → Cleaning strategy
- Ramp rates (actual and potential lessening) & cloud impact
- Thermal losses

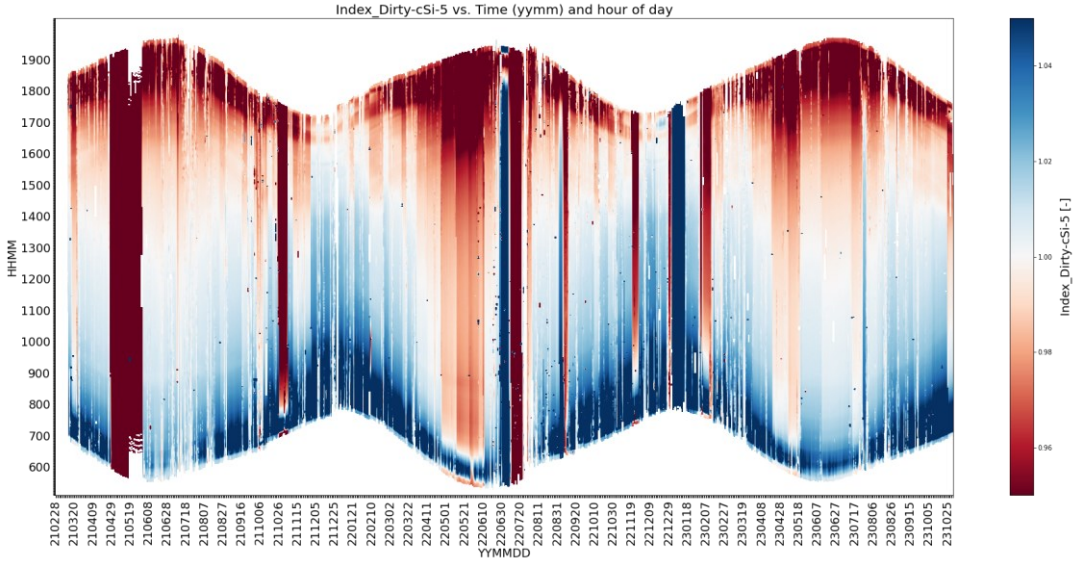
Global Irradiation



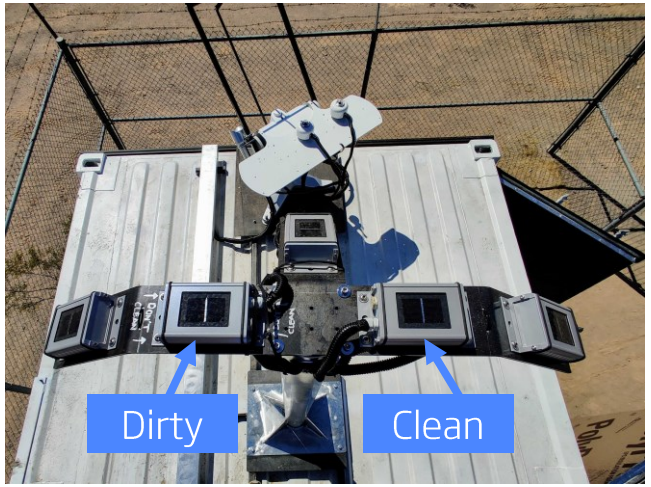
Albedo



Soiling: Index of dirt



c-Si cells with cleaning



Parameters: Wind, Irradiation (direct, diffuse, horizontal, tilted w/ different azimuth; Temperature, and more, 1 Hz resolution; Off-grid system: Cloud-based control and automatic analytics.

Innovation in Alpine Solar: Overcoming Winter Energy Challenges

Project: Sedrun Solar, energie alpina, 8 MW, Start of installation 2024

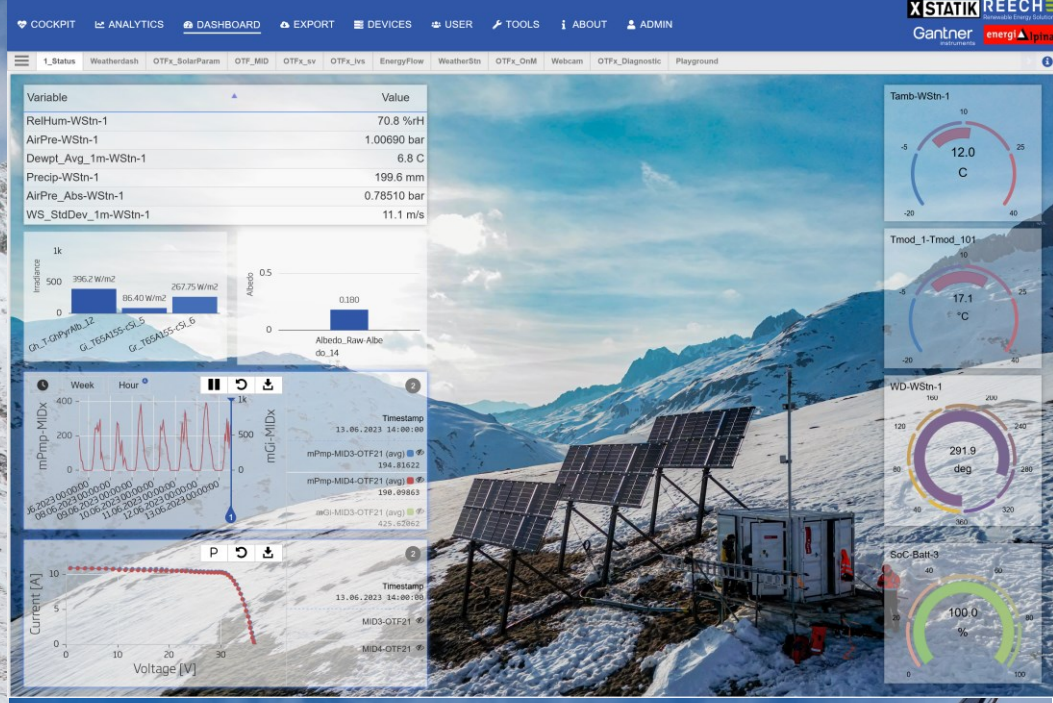
Partners: XSTATIK REECH Renewable Energy Solutions, Gantner instruments, energi Alpina

Autonomous off-grid Test facility at 2100 m height

Weatherstation, IVscan, LossFactorsModel, Albedo measurement

Live internet streaming

Read more



Evaluation of PV Resources and Performance in Alpine Areas

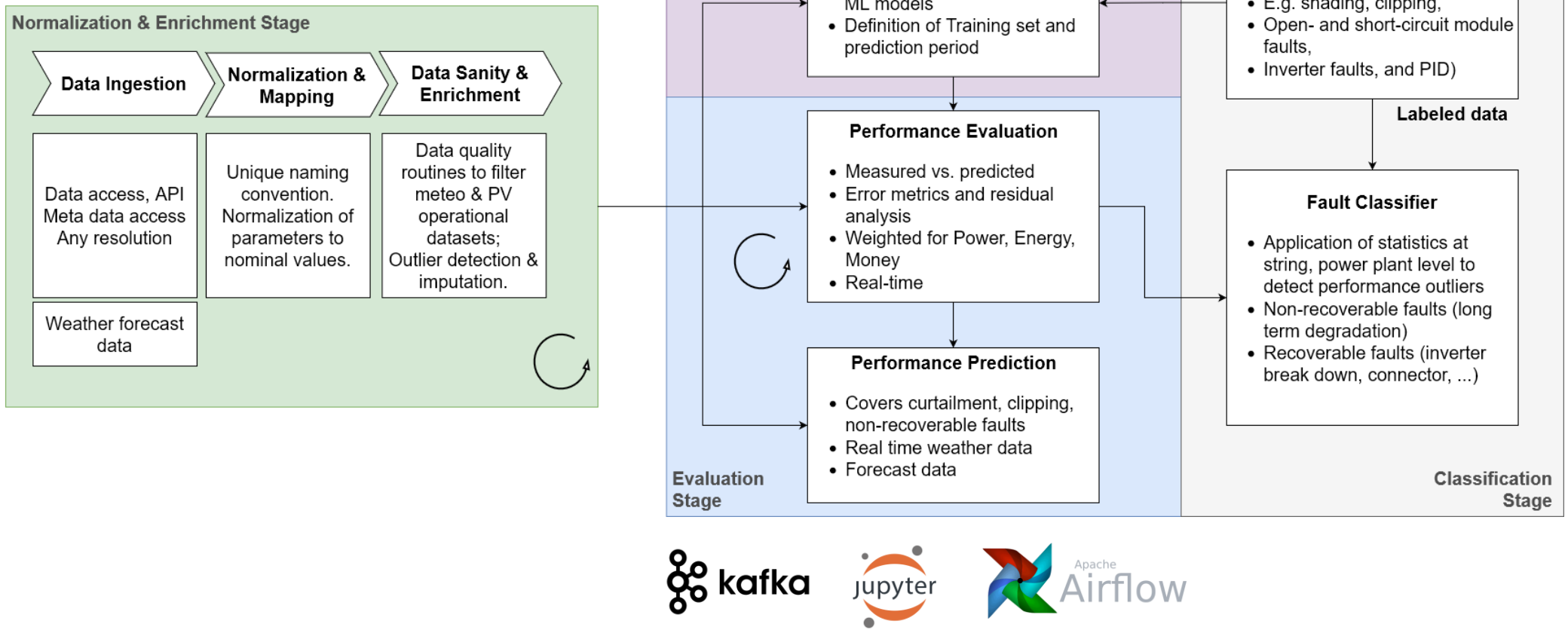
Source: energia alpina, reech, capisci.ch

Predictive Analytics & Streamlined Data Processing

Predictive Analytics & Streamlined Data Processing

Define your Scope

- Performance Model definition
- Inline validation
- Fault detection
- Performance Prediction
- Data from PV, ESS, Hydrogen, Smart Grid



kafka jupyter Apache Airflow

Mechanistic Performance Model (MPM) for Large PV Arrays

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 — Voc and Rshunt — R_{SERIES} — Wind

MPM Advanced

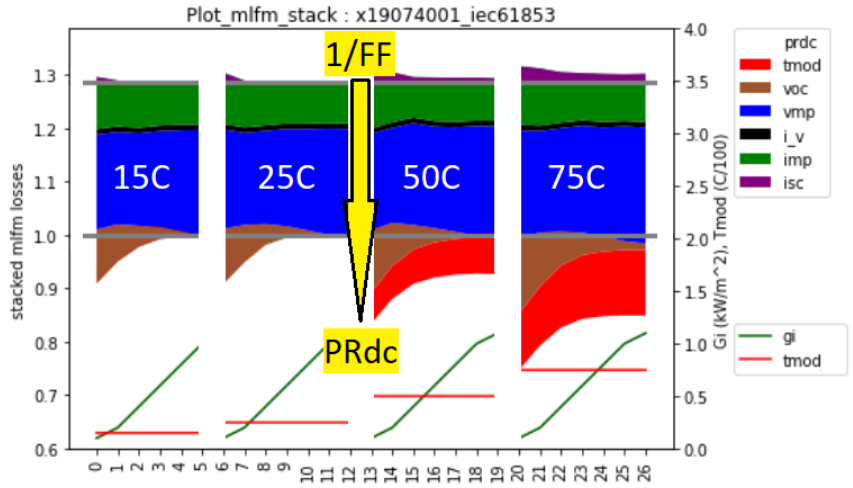
5 Coeff. for typical sites

MPM Professional

Covers also Clipping, Asymmetric behavior

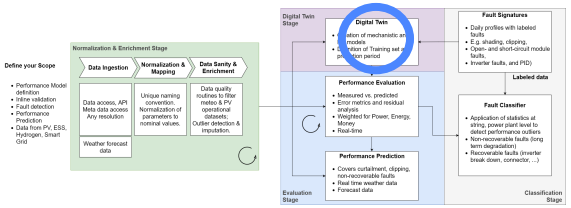
MPM is best to:

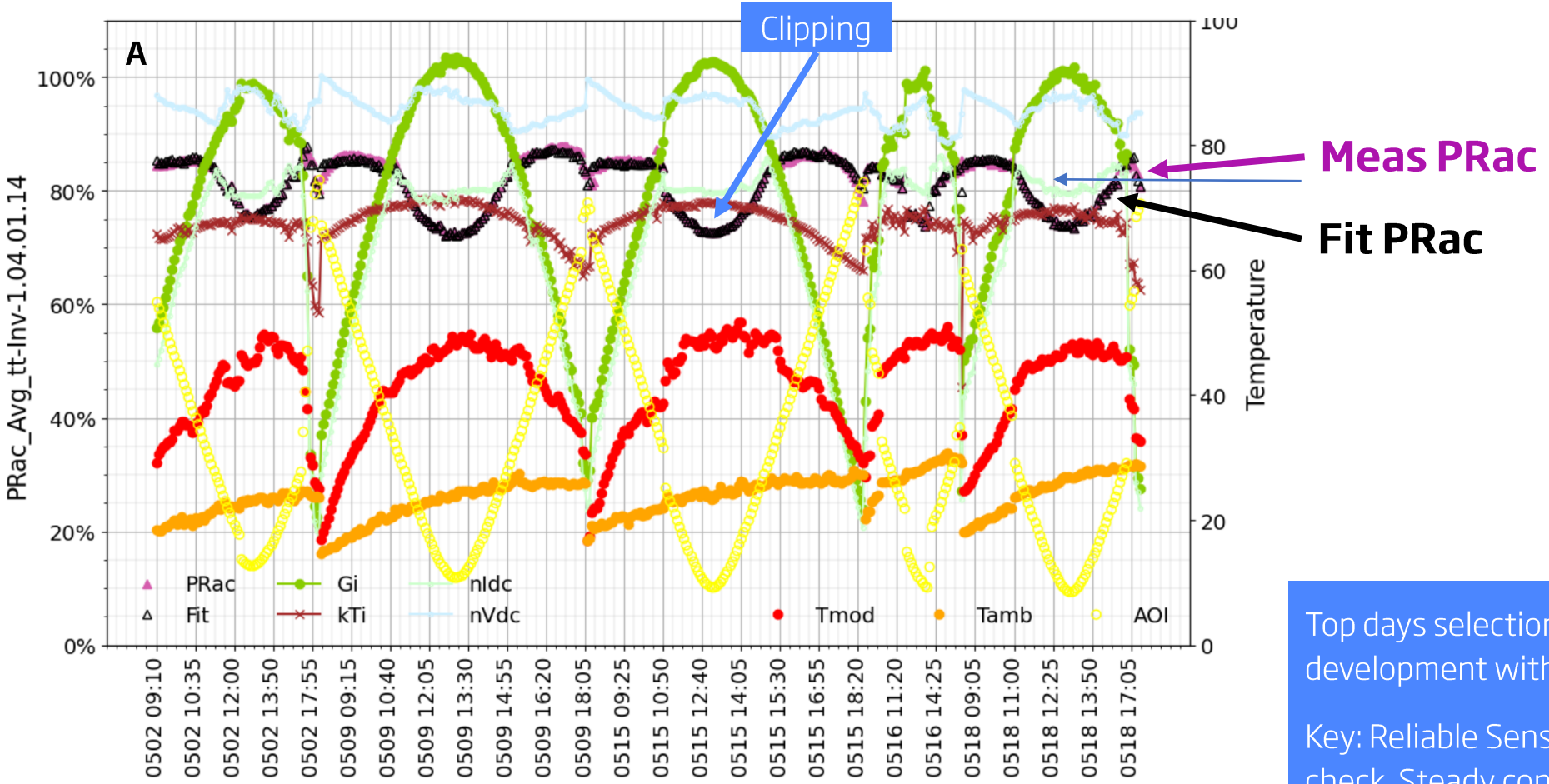
- Fit measured PR vs. Irradiance and Tmodule
- Look for discrepancies or poor-fit coefficients
- Predict performance



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.

Training: Measured and Predicted PRac vs. Time with Clipping

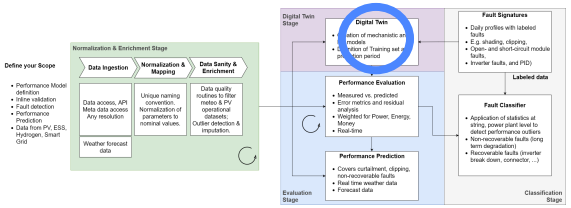




Top days selection for Model development with clipping

Key: Reliable Sensors, Sanity check, Steady conditions

Training
Selected Days



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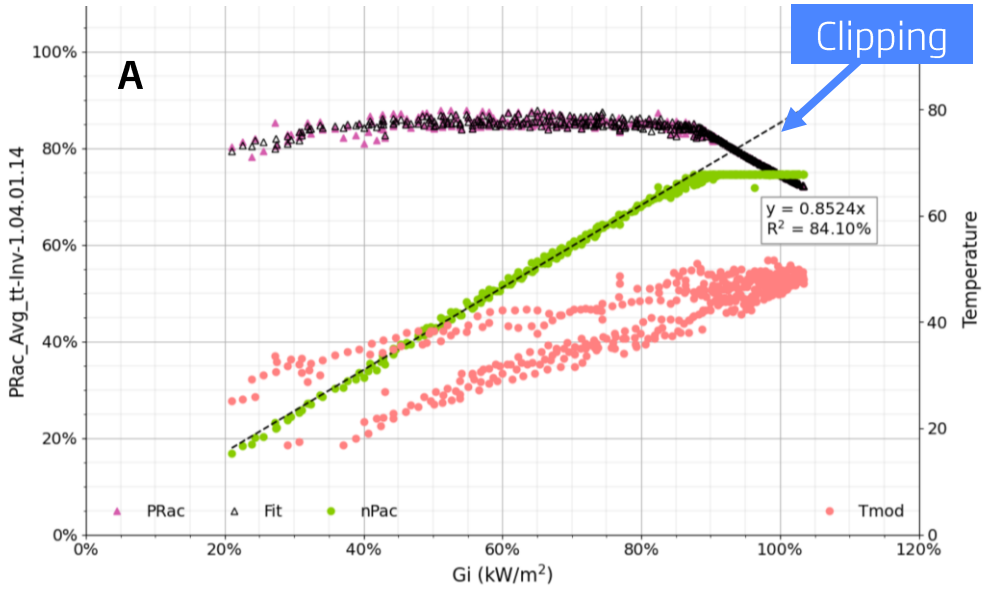
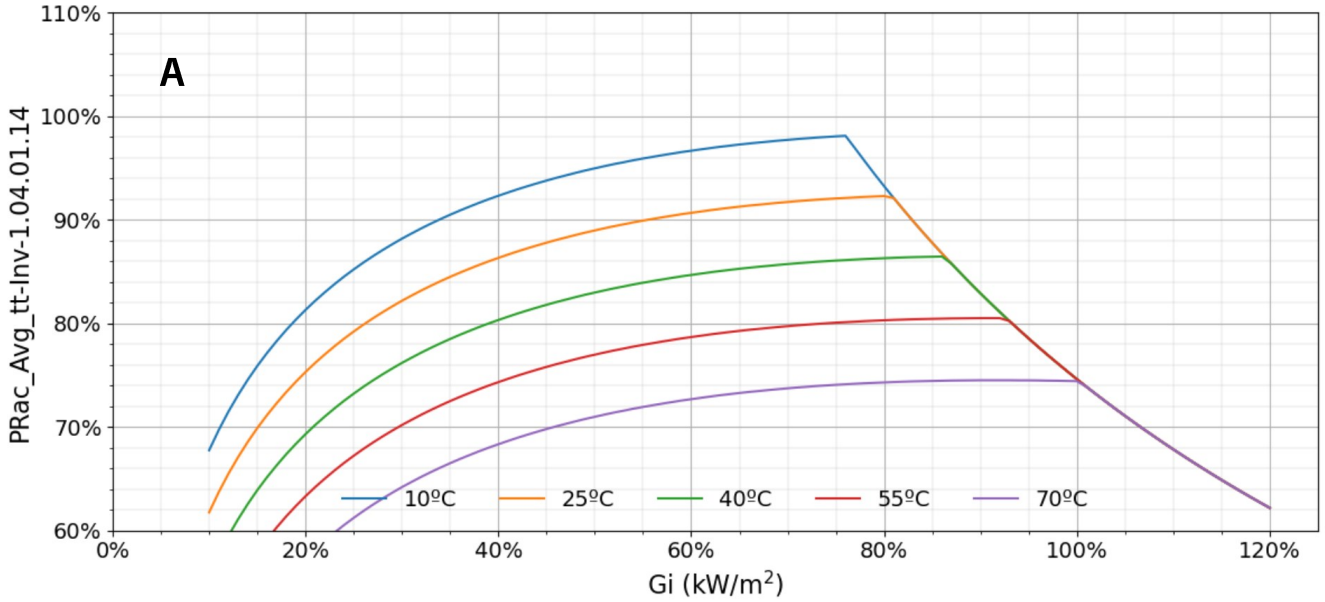
Measured and Predicted vs. Irradiance-Temperature

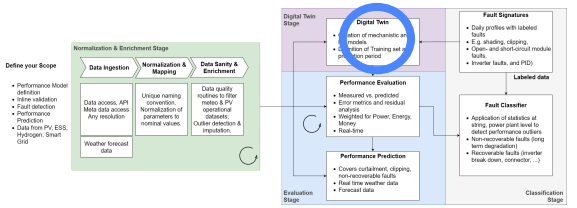


Model vs. Irradiance different Temperature bins

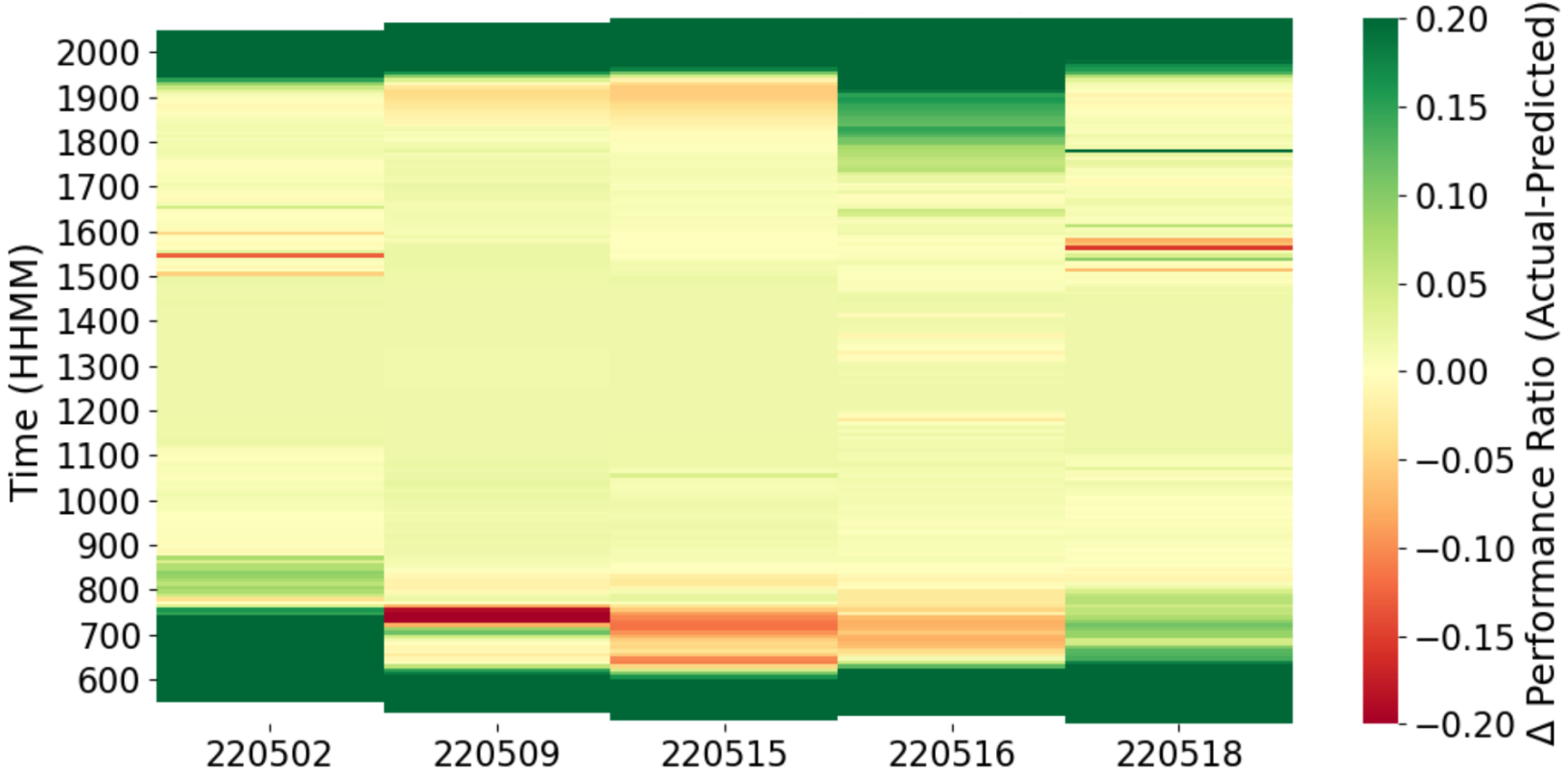


Fits clipping very well

Training: Delta (Actual – Predicted) Selected Days

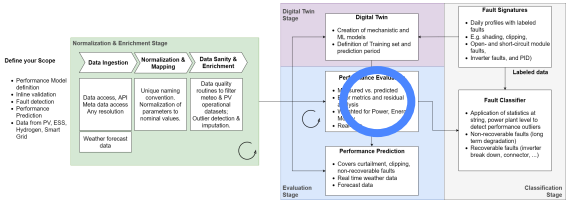


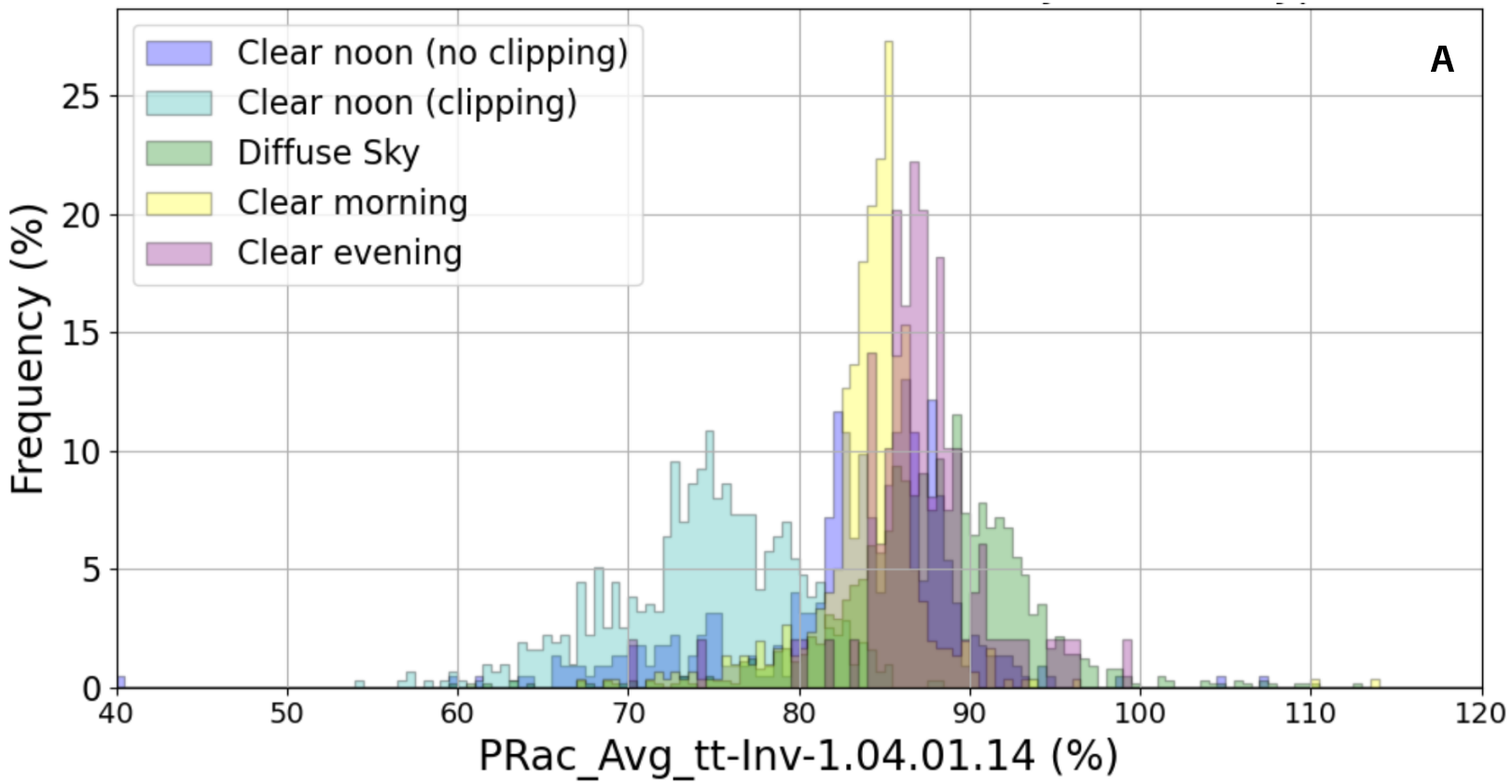
Delta (Actual – Predicted), Inverter



Fits well, Transients visible

Performance Ratio (PRac) by Weather Type Monthly

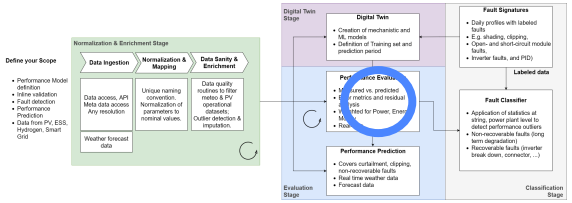


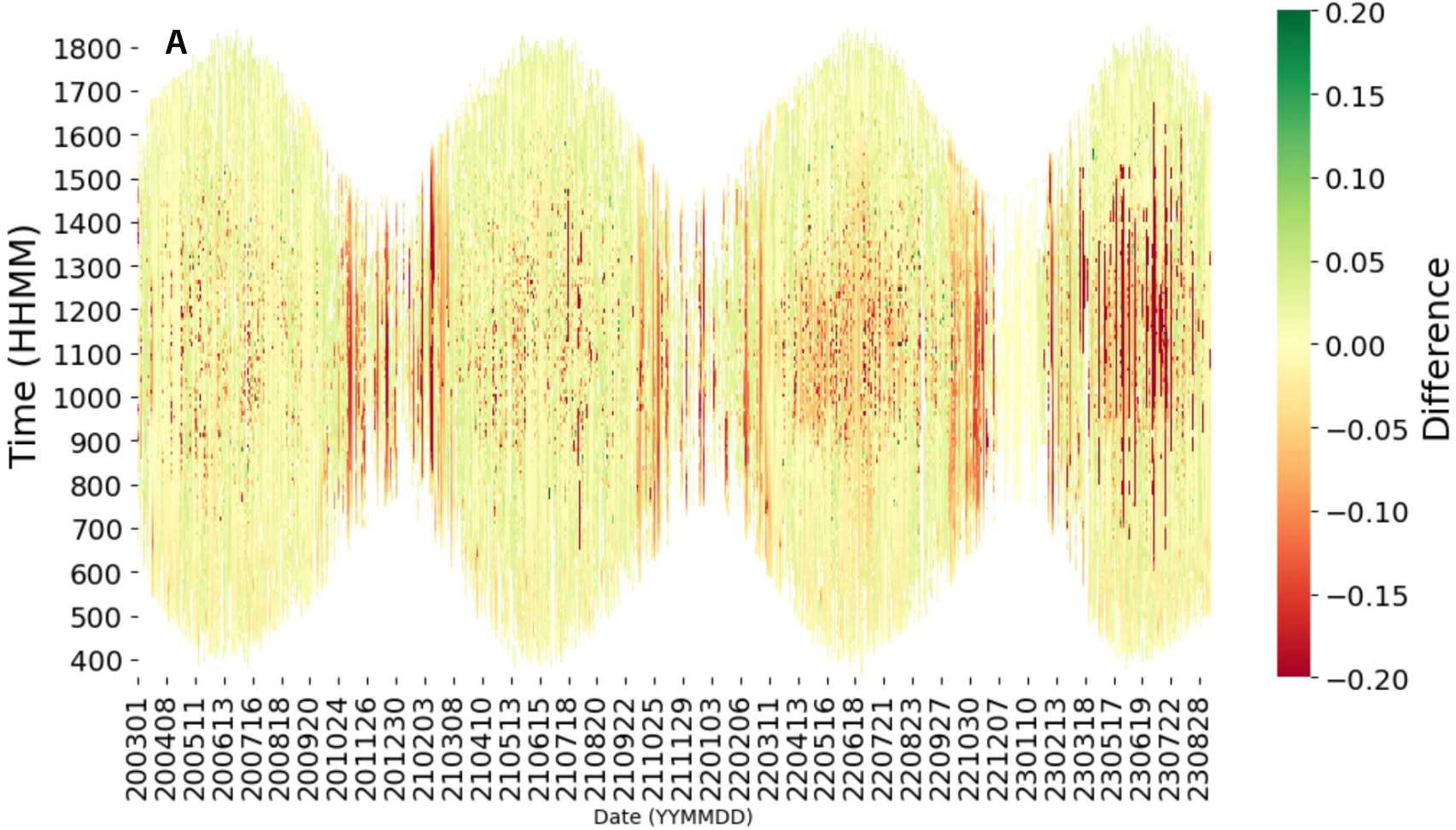


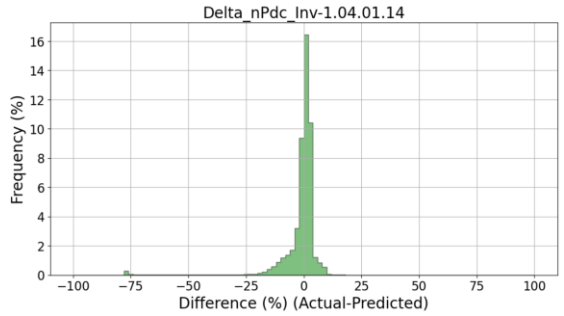
Separation of Clear noon for clipping and no clipping

Difference in Clear morning vs. Clear evening

Prediction: Delta (Actual – Predicted), nPdc, Raw resolution, 4 years



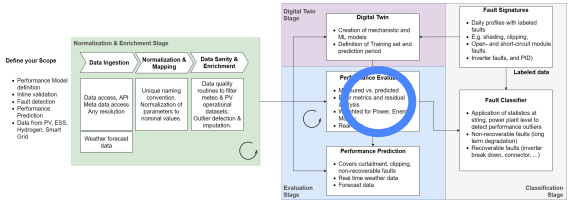




Degradation (Rs?) visible, easy detectable with simple statistical processing

Stacked Losses vs. Time > 12 years

ThinFilm: Hourly resolution, Self-referenced, Tempe, AZ



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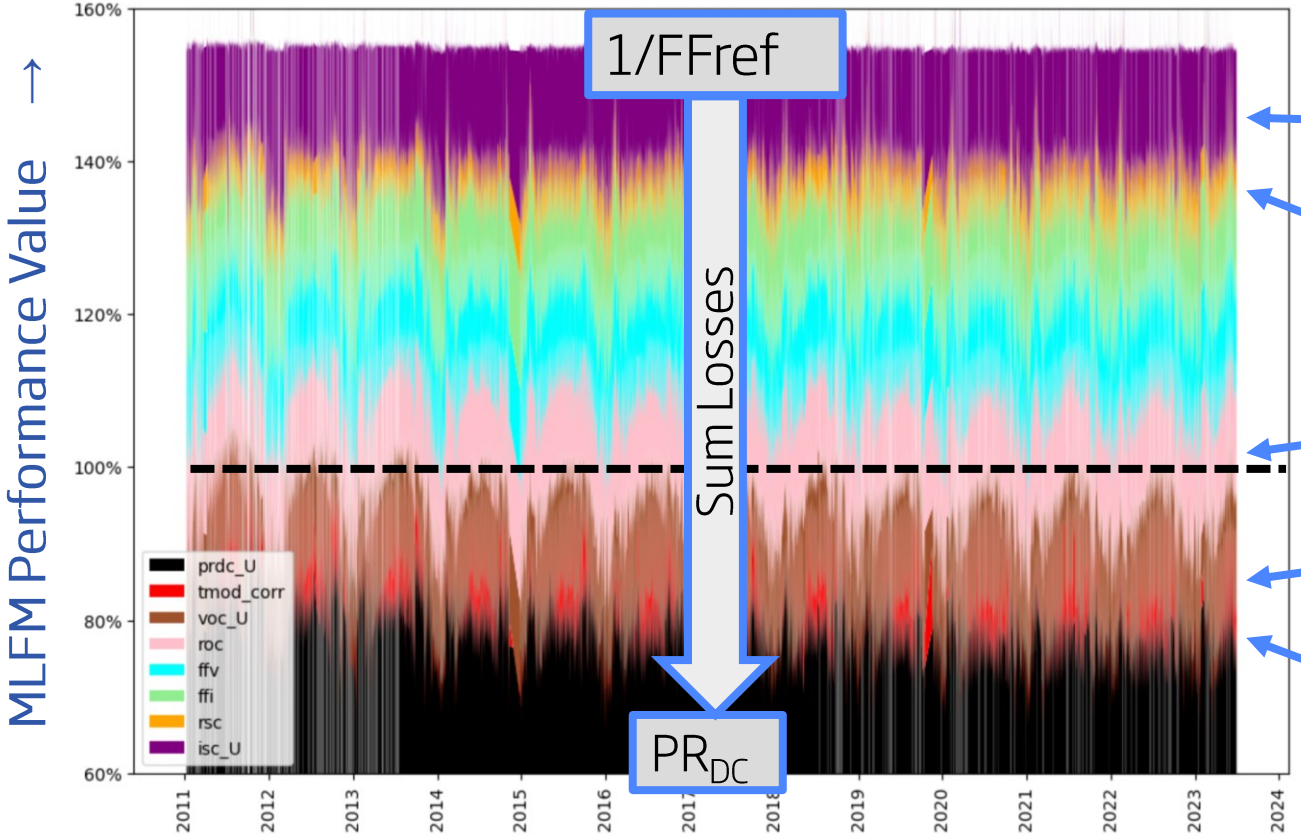
PRdc = 1/FFref – stacked_loss[(isc + rsc + ffi) + (ffv + roc + voc_Tcorr + t_mod)]



When are losses greatest?

(1) Isc loss (aoi/reflectivity, spectrum)→ morning, evening

(2) ~Rshunt loss (low irradiance) → morning, evening

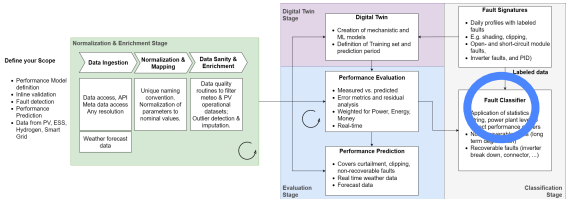
(3) ~Rseries loss (high I^2.Rseries) → noon

(4) Voc_tcorr (temp_corrected) (Voc~log(Gi)) → low irradiance

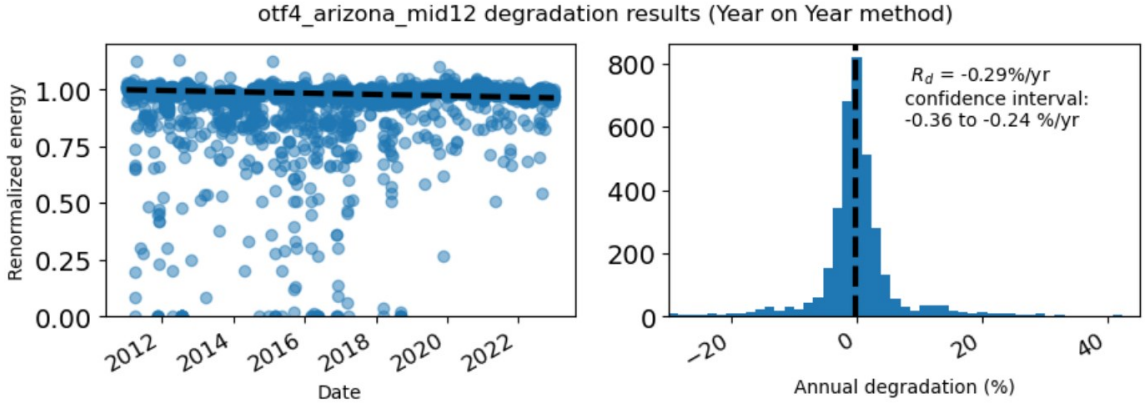
(5) Temperature loss → noon - afternoon (high temperature)

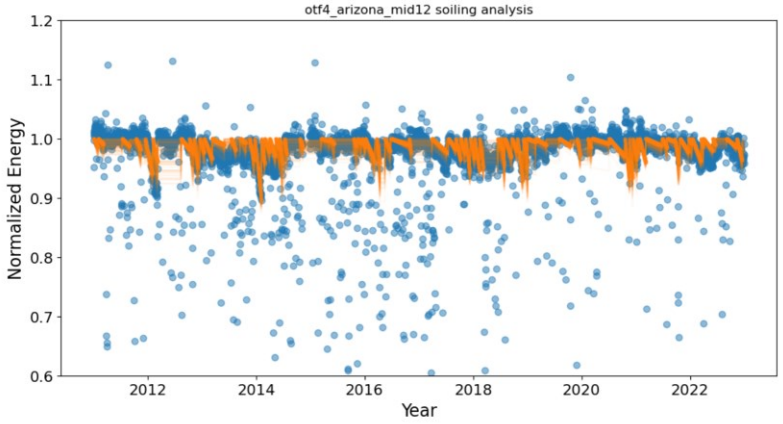
6 Parameter version, Method: self-referenced Isc for clarity; Temp correction subtracted from Voc for simplicity; unstable device
Method: S. Ransome, J.Sutterlueti: How to use the Loss Factors and Mechanistic Performance Models effectively with PVPMC/PVLIB, PVSC 2020

Fault Detection & Classification Accuracy



- Shading
- Clipping/curtailment
- Potential induced degradation (PID)
- Open- and short-circuit module faults
- Module cell cracks
- Inverter faults (thermal, component, tracking)
- Soiling
- Degradation (short-, long-term, LID)





With meaningful Performance Model coefficients reliable separation of faults is possible.

What tools and processes make the difference in Predictive Analytics?

- Good, synchronized data quality
- Effective data processing
- Resilient Digital Twin with Meaningful coefficients
- Real time Evaluation and prediction
- Statistical analysis and Classification

… enables Predictable Energy Output and maximize PV earnings on GW scale.

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

Thank you very much!

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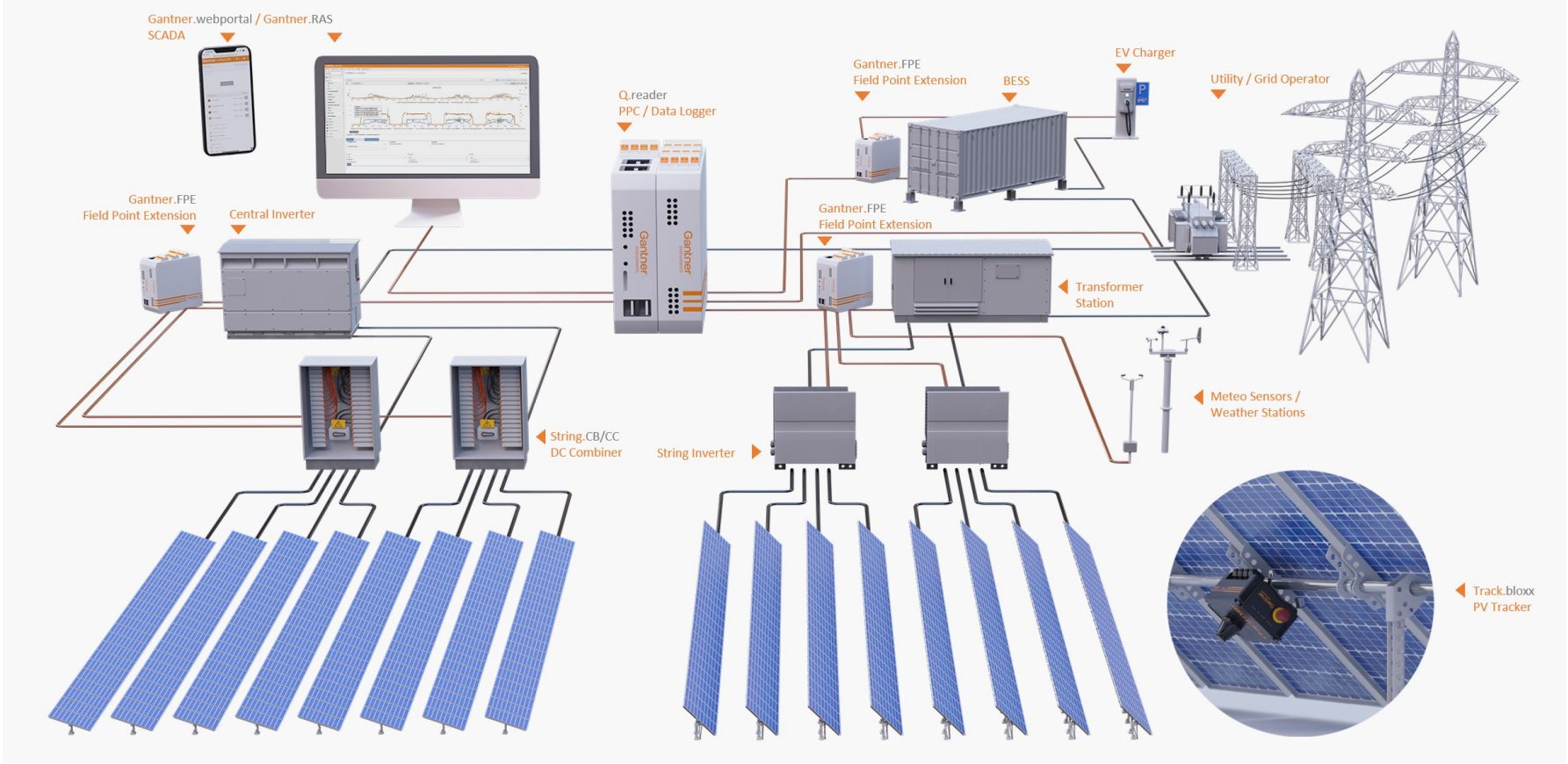
Appendix

Gantner Instruments PV Business Unit:
Global leader in Utility-Scale PV/ESS Monitoring & Control

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



Enable effective energy generation in > 42 countries → gantner-environment.com

Source: Gantner Instruments Environment Solutions

The Analytics project

Analytics
real time edge control and ai
for tomorrows smart grid services

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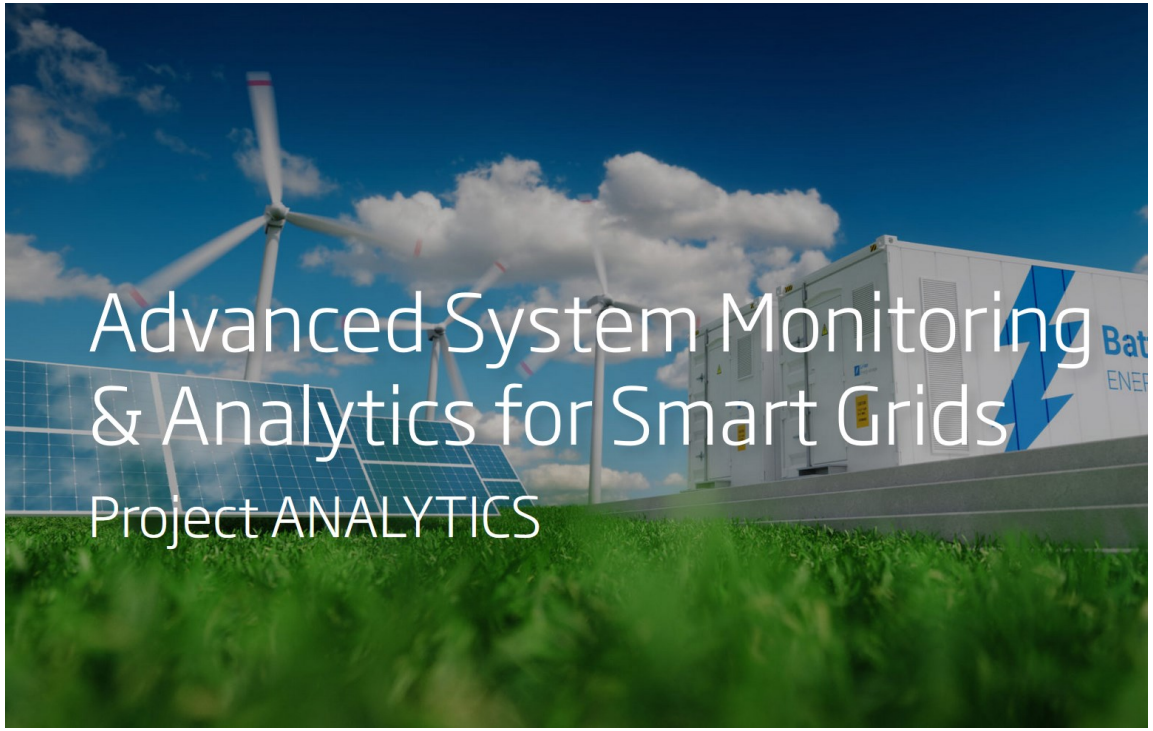

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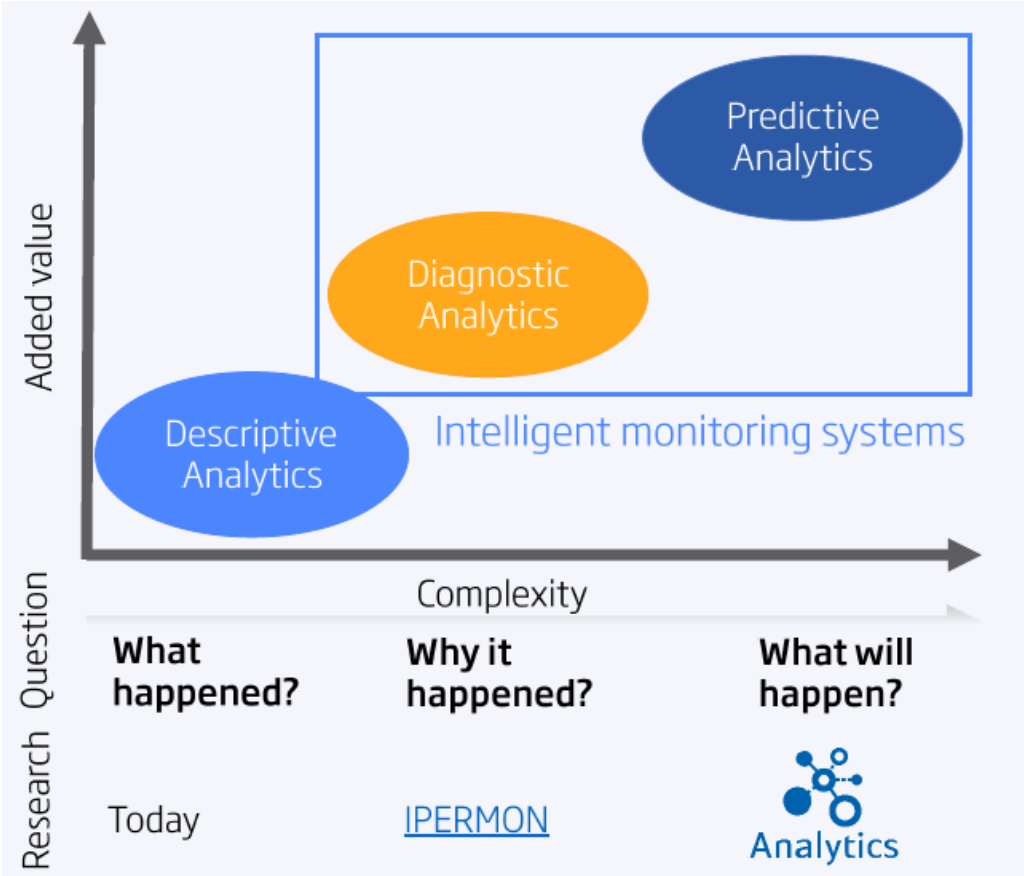
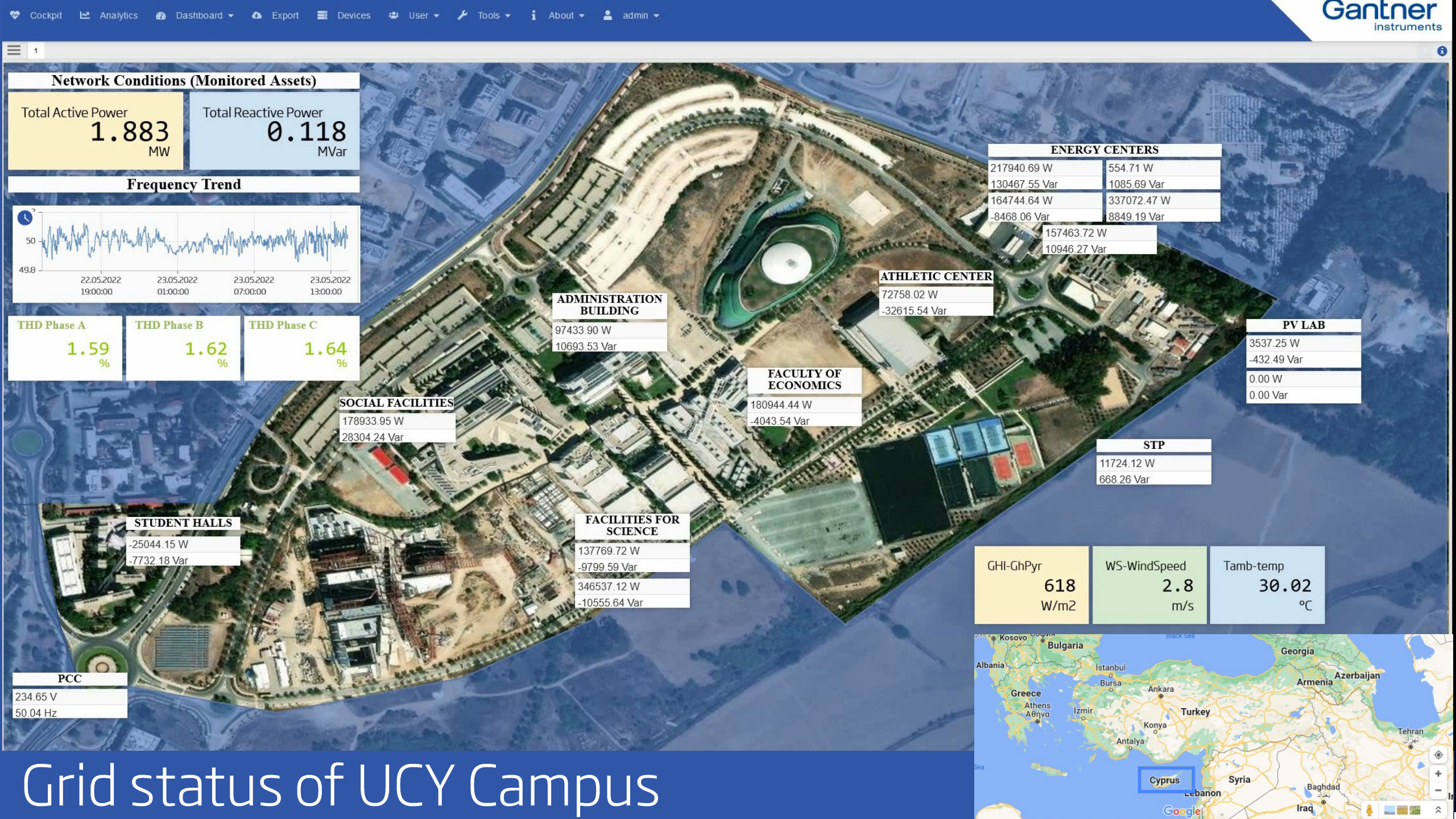
University of Cyprus
PV Technology



More info at:

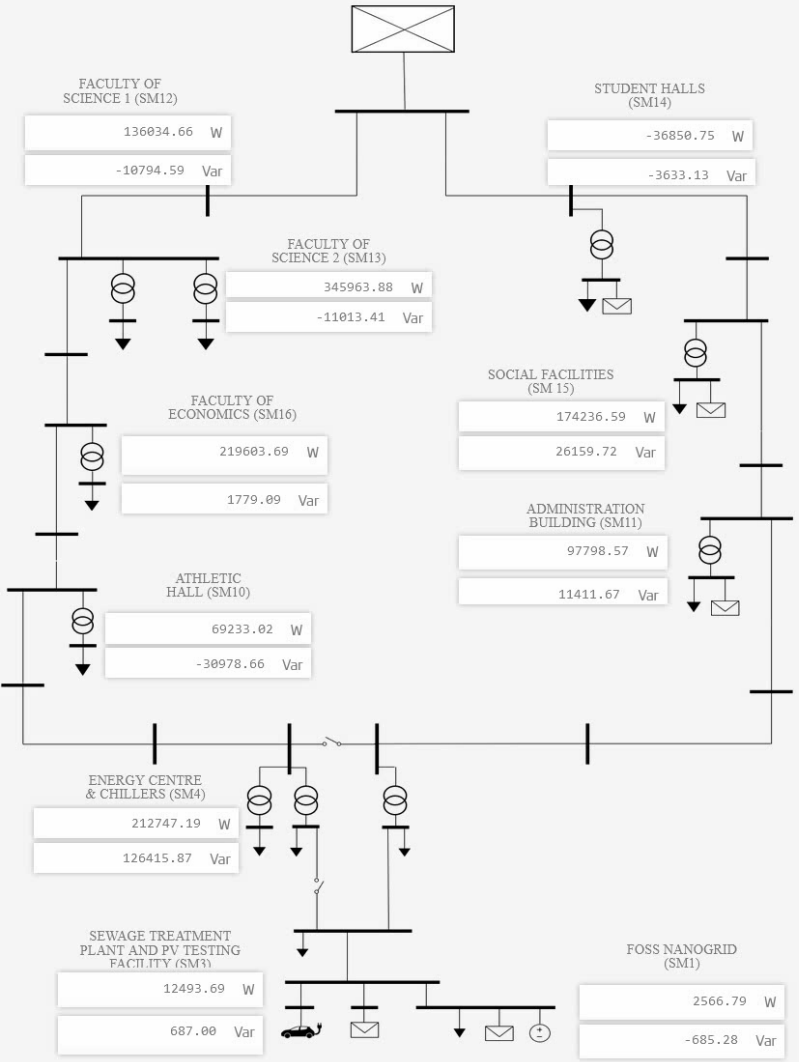
https://www.gantner-instruments.com/research/advanced-system-monitoring-analytics-smart-grid/

Microgrid Real-time Interaction

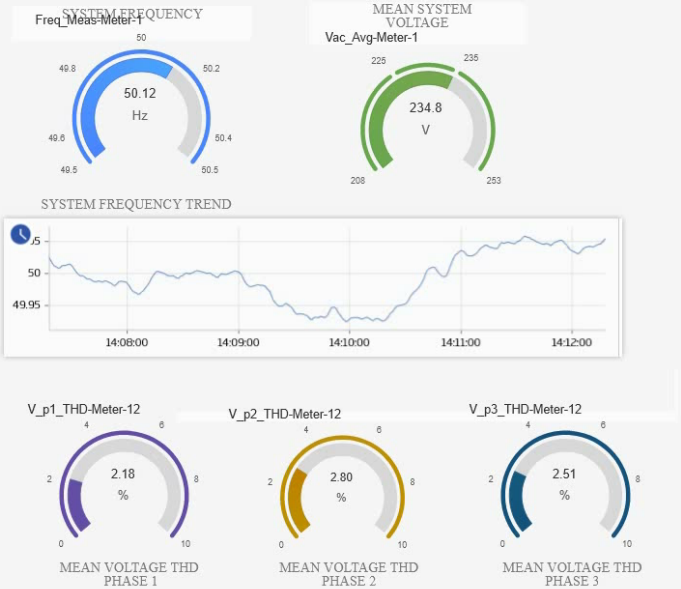


Grid status of UCY Campus

UCY MICROGRID SCHEMATIC



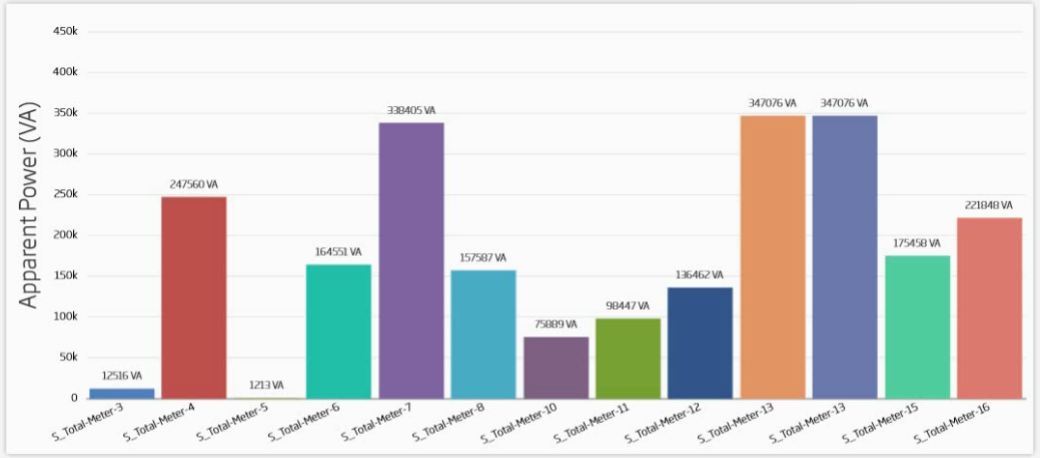
GENERAL MICROGRID DATA



WEATHER CONDITIONS

GHI	655 W/m2
AIR TEMPERATURE	30.5 °C
WIND SPEED	12.0 m/s
WIND DIRECTION	265 deg

POWER CONSUMPTION TRENDS



Smart Grid SCADA Dashboard of UCY campus

Microgrid setup at University Campus in Cyprus

Gantner instruments

PV

BESS

EV Charging

Grid / Load

PROFINET

EtherCAT

Modbus

OPC UA

WAN

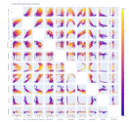
GI.cloud UI

Visualize
Operate
Analyze
Setup

jupyter

python

Analytics
Digital Twin
ML



Distributed, scalable, clustered, API

GI.data

kafka

Event Sourcing
Persistent log
Real-time Enrichment

Indexing
Aggregation
Fast data access

Digitalization and interoperability open communication standards

Real-time data stream

Centralized supervision and control

Read/write data streams
Real-time control

Real-time energy grid control with advanced data processing and qualified models for digital twins

Data acquisition system (DAQ)
Real-world data or Test-bench

→

Data quality routines (DQRs)
- Identify missing/erroneous data
- Correction of data

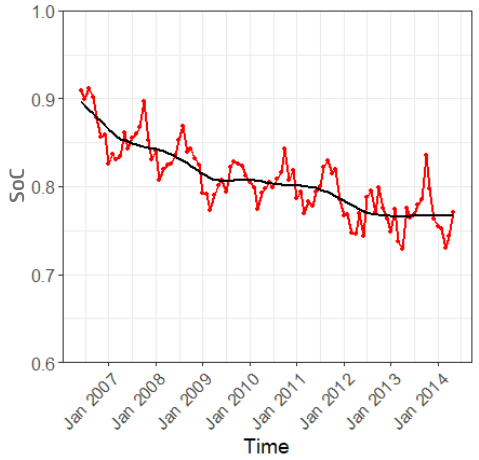
→

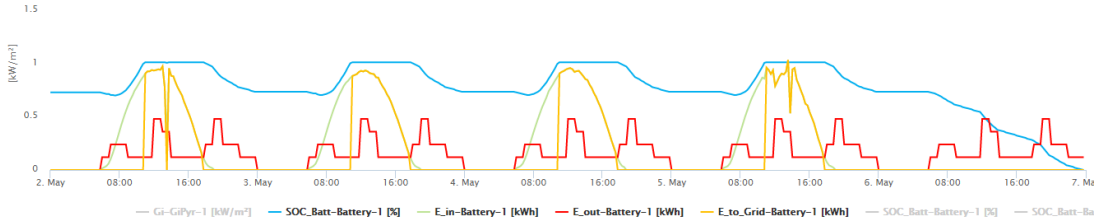
System model prediction
Predict characteristics of the system, residuals

↓ Degradation rate

↓ Health-state detector

↓ Failure diagnosis routines





PROJECT

Outdoor Facility for PV Module Performance Testing

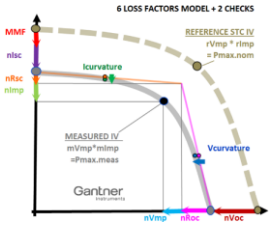
CUSTOMER
Sunpower

COUNTRY
Abu Dhabi, France, USA (California, Arizona), China, ...

APPLICATION
Photovoltaic Testing

MARKET
Energy

SHORT DESCRIPTION
PV Module Performance Characterization System: Based on 4 Wire IV Curve Measurements with Automated KPI Calculations, Max. Power Point Tracking, and Advanced Analytics



Gantner instruments

Scuola universitaria professionale della Svizzera italiana
SUPSI

SUNPOWER

TURKU AMK
TURKU UNIVERSITY OF APPLIED SCIENCES

ines
INSTITUT NATIONAL DE L'ENERGIE SOLAIRE
cea

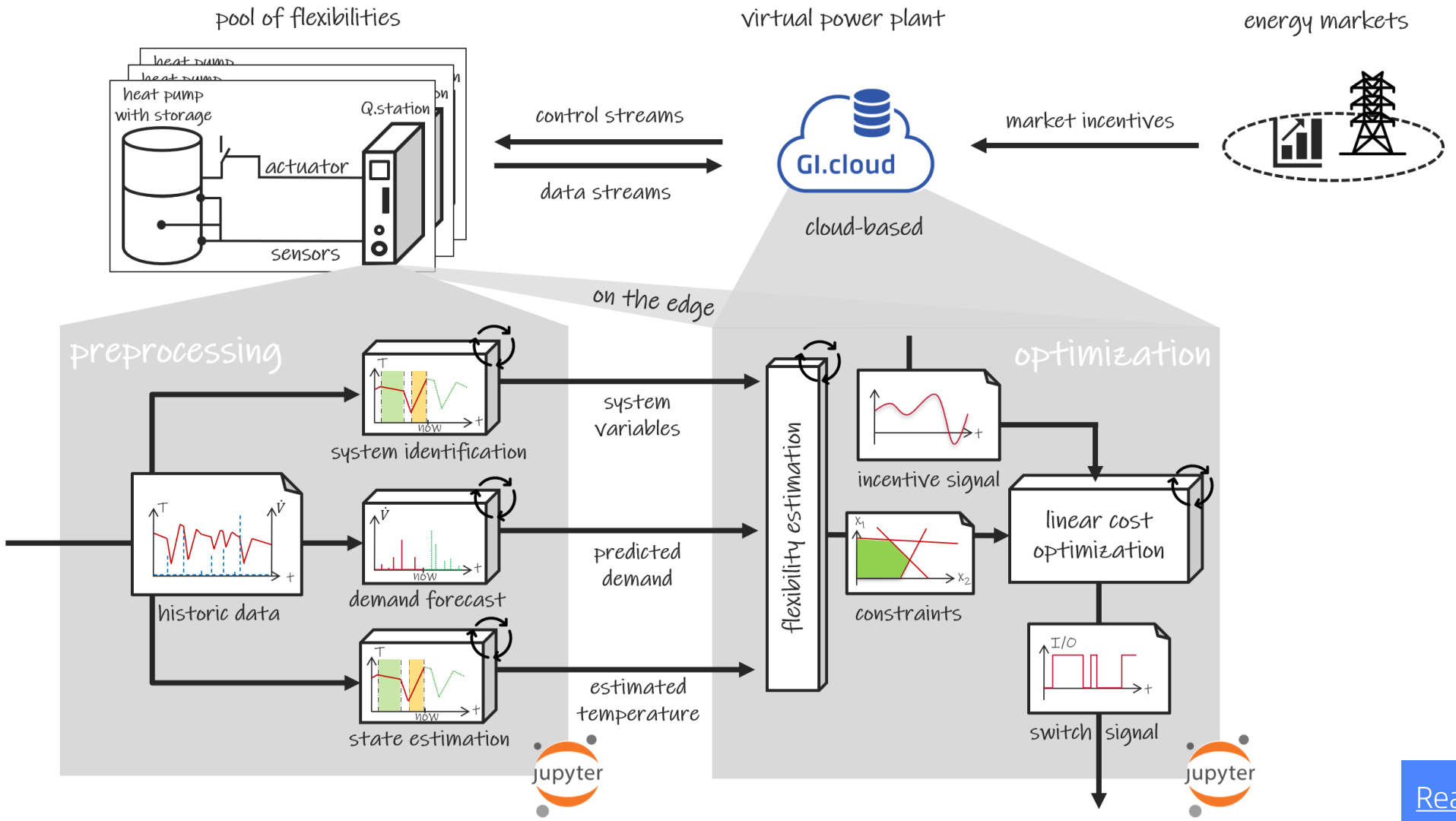
MEYER BURGER

EKZ

TEL
TOKYO ELECTRON

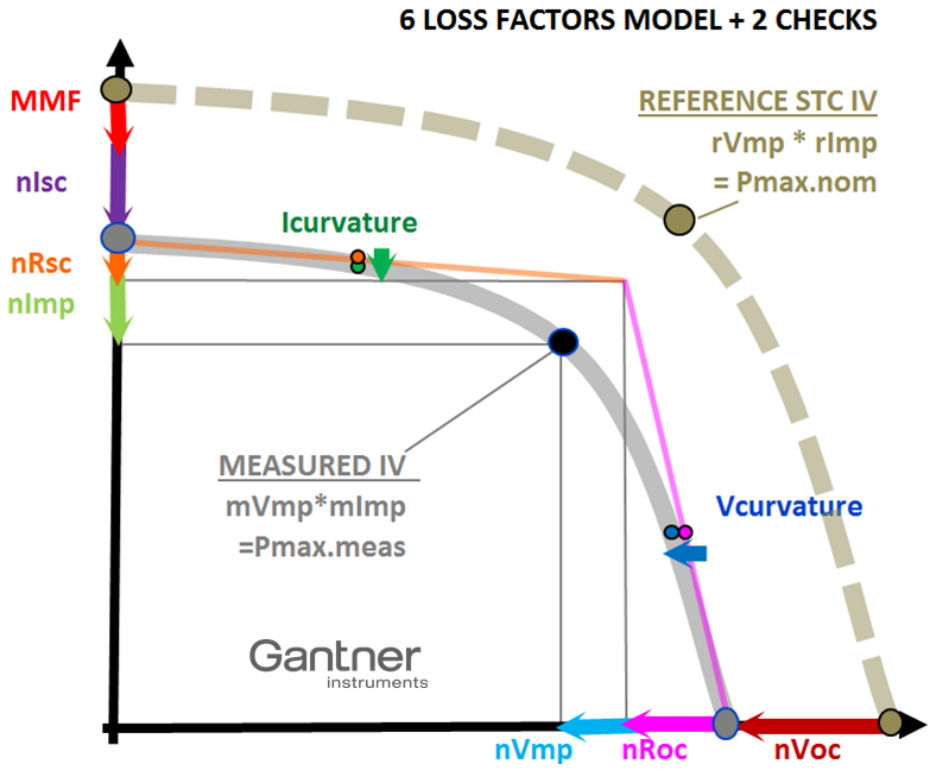
Project on Thermal assets with FH Vorarlberg

Josef Ressel Center for intelligent Thermal Energy Systems



Read more

IVscans – The DNA of PV modules



Loss Factors Model (LFM)
The LFM determines a module's performance from its I-V curve as the product of six physically significant and independent normalized "loss factors" and spectral and temperature corrections. All normalized LFM parameters multiplied together show PRdc.

Turnkey Outdoor Test Facility Solution, 8,16, 32 Channels

Outdoor Test Facility Solution 30 Channels, Gantner Instruments Research site, Arizona

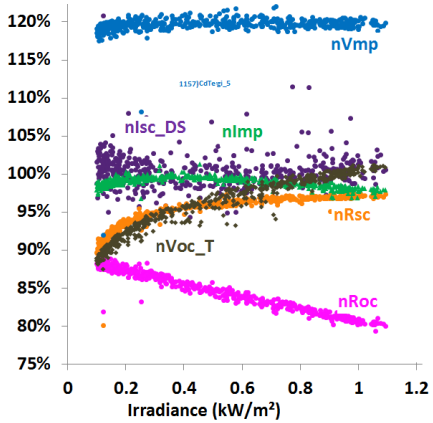
Robust extraction of key values with the Loss Factors Model (LFM)

The **Loss Factors Model (LFM)** provides a powerful analysis of indoor or outdoor IV curves.

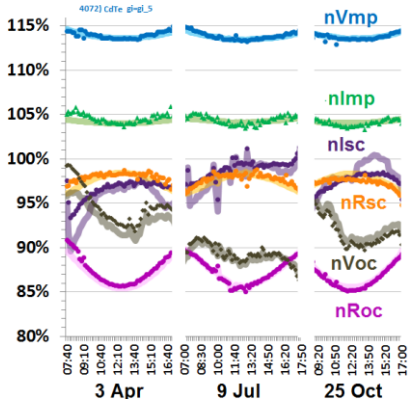
$$PR_{DC} = nI_{SC} * nR_{SC} * nI_{MP} * nV_{MP} * nR_{OC} * nV_{OC}$$

LFM parameters are:
technology agnostic, area independent, normalized, meaningful,
e.g., "% power loss due to R_{SERIES}"

Characterize a module vs. G_I, Tmod, etc.



Predict performance vs. time and weather



LFM can easily find any discrepancies, degradation, poor measurements, etc.