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Using Advanced PV and BoS Modelling and Algorithms to Optimize the Performance of Large Scale Utility Applications

4th PV Performance Modelling and Monitoring Workshop
Cologne; October 23rd, 2015

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Juergen Sutterlueti et al

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"Typical" questions about PV Monitoring for Utility scale PV Plants

- **Why is it needed?**
- **Who needs it?**
- **Who pays for it?**
- **Is it beneficial?**

Product and services

reaching from

String current monitoring,

Plant control,

Data collection

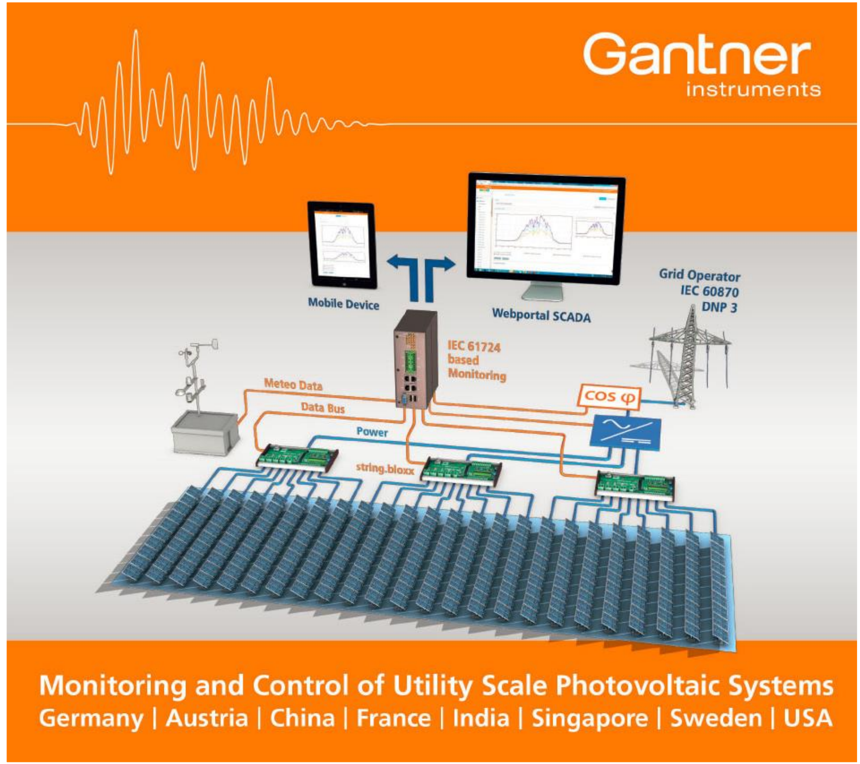
to

O&M optimization and

automated Investor feedback.

Solutions on 3 levels

- STRING level
- DATA level
- Portal/SCADA level



Outline

1 Introduction: Do we need PV Power Plant Monitoring on a MW scale ?

2 PV **Performance understanding**

3 Data **Acquisition** & **handling**

4 Data **Analysis**

5 **Performance prediction** & **Optimization**

6 **Investment** vs. **Benefit** of Monitoring:
Impact on System cost (CAPEX), O&M (OPEX) and LCoE

PV Performance understanding

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Characterise modules outdoor where possible to develop performance algorithms

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2 D Tracker:
6 channels w/
spectrometer

Weather sensors:
Irradiance, Temperature,
Wind, Spectrum, RH, ..

24 Channels fixed: c-Si (ABC, HIT, n-type, ..), CdTe, CI(G)S, a-Si, a-Si:uc-Si; 6 tracked

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Performance understanding

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Benefits

- **Unique PV Module performance track** record since 2010
- Baseline for **next generation of PV** Modeling and **prediction of PV Plant performance** and monitoring
- Technology benchmark
- **Bankability** support for **EPCs, Investors, Insurance**
- Key for **improved Utility PV Monitoring concepts**

USP:
High performance data acquisition, 3rd party technology benchmark, advanced characterization and Analysis methods

Tested PV Module references :
First Solar, Trina, Yingli, Sunpower, Manz, SolarWorld, Solar Frontier, Kaneka, Hanergy, MiaSole, Q-Cells, Bosch Solar, Panasonic

Cooperations with leading Institutions, experts, EPCs and IPPs.

Name	Description	Units
G_H	Global Horizontal Irradiance	kW/m²
D_H	Diffuse Horizontal Irradiance	kW/m²
B_N	Beam Normal Irradiance	kW/m²
G_I	Global Inclined Irradiance (Pyranometers and c-Si ref cells)	kW/m²
T_{AMB}	Ambient Temperature	C
T_{MOD}	Back of Module Temperatures	C
WS	Wind Speed	ms^{-1}
WD	Wind Direction	°
RH	Relative Humidity	%
$G(\lambda)$	Spectral Irradiance G(350– 1050nm)	W/m²/nm

IV curves and weather data are measured every minute for 24 fixed modules and 6 on a 2D tracker
Running since July 2010 with a 98.9.% uptime.

Loss Factor Model (LFM) – SRCL / Gantner Instr.

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Use to characterise PV Modules based on IV measurements

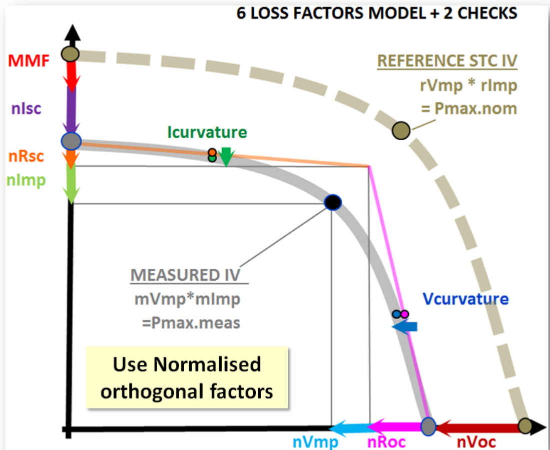
LFM

- 6 normalised orthogonal parameters associated with
  I_{SC}, R_{SC}, I_{MP}, V_{MP}, R_{OC} and V_{OC}
- Multiply all 6 together to give the PR_{DC} or MPR

- Easy **sanity check** for bad data if not ~1
- Easy to see good from bad values e.g. 98% or 90%

- **Differentiates** PV technologies –
  e.g. Thin Film usually has a higher loss due to R_{OC}
  (from TCO resistivity)

Plot LFM values vs	To show
Time	Degradation or annealing
Irradiance	Low light performance
Module Temperature	Thermal coefficients



MMF	Module Mismatch factor – Spectral	
nI_{SC} (U)(T)(S)(D)	Loss to $I_{SC.MEASURED}/I_{SC.EXPECTED}$	Corrections: (U)ncorrected (T)emperature (S)pectral correction (D)irt
nR_{SC}	Loss due to R_{SC} (~R_{SHUNT})	
nI_{MP}	Loss near P_{MAX} to I_{MP}	
nV_{MP}	Loss near P_{MAX} to V_{MP}	
nR_{OC}	Loss to R_{OC} (~R_{SERIES})	
nV_{OC} (U)(T)	Loss to $V_{OC.MEASURED}/V_{OC.EXPECTED}$	

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Performance understanding

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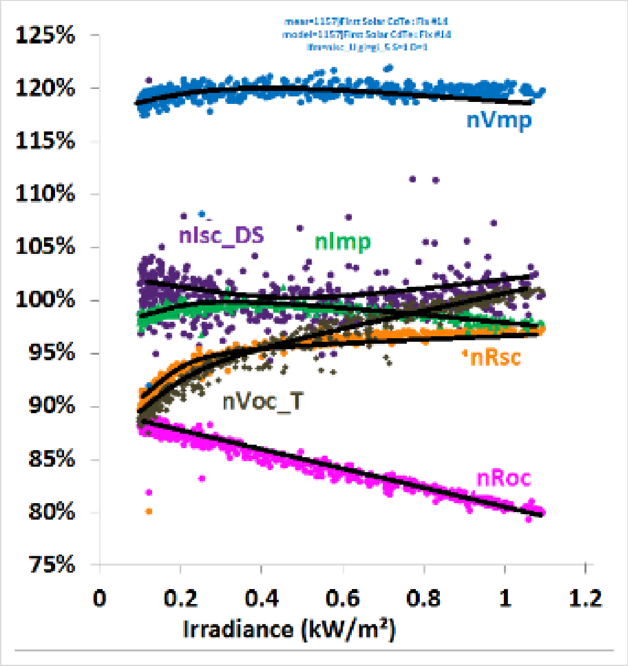
Curve fit vs. Irradiance

- Easy to do sanity check (raw data shown)
- Typical pattern per technology
- Shows low light and I^2.Rs loss
- nVoc_T: temp corrected for clarity
- nIsc_DS diffuse, spectral corrected for clarity

- **nImp**
- **nVmp**
- **nRoc**
- **nRsc**
- **nVoc**
- **nIsc**



D=Diffues, S=Spectrum

LFM measurements II

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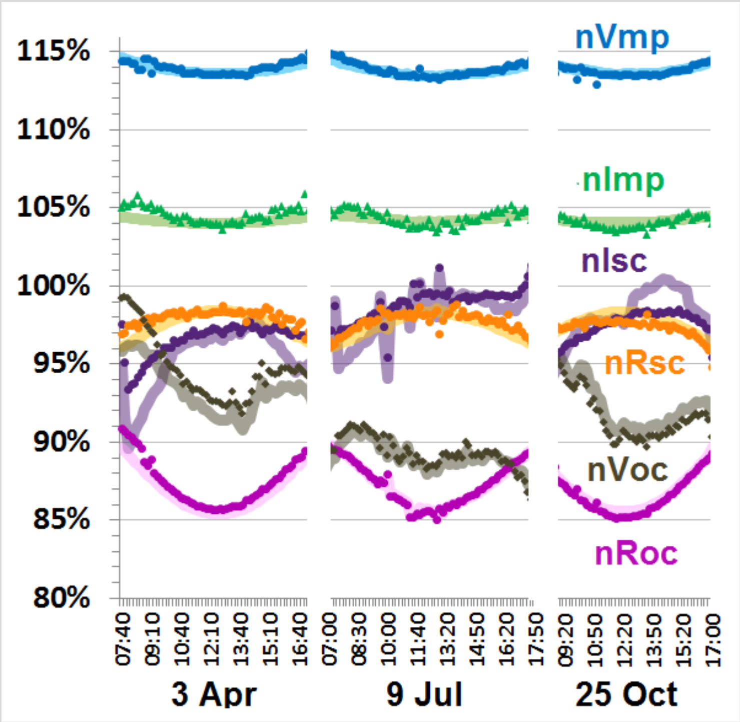
Compare Measured vs. Predicted

- Prediction over time
- Data every quarter to show degradation or seasonal
- Residual analysis

- nImp
- nVmp
- nRoc
- nRsc
- nVoc
- nIsc



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Performance understanding

Data Acquisition & handling

Monitoring of large arrays

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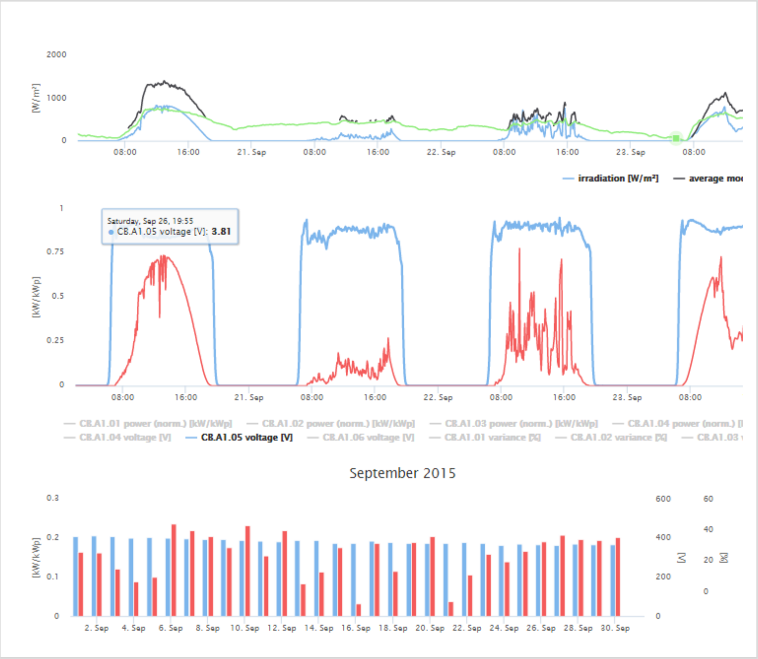
Market expectations:
Monitoring and control concept for cost effective PV Energy generation and risk reduction

- Transparency of PV Plant production (fast & reliable)
- Vendor-independent PV Plant monitoring
- Unified platform for all PV assets (information, data)
- Combines all available information (Inverter, DC & AC side, grid, DSO)
- Effective and automated PV plant management, Inventory information
- Reporting, Alarms
- O&M logging
- Access form anywhere (HTML5, W3C)
- Provide baseline for O&M activities, Performance Guarantees, energy prediction (day ahead), energy trading, etc.

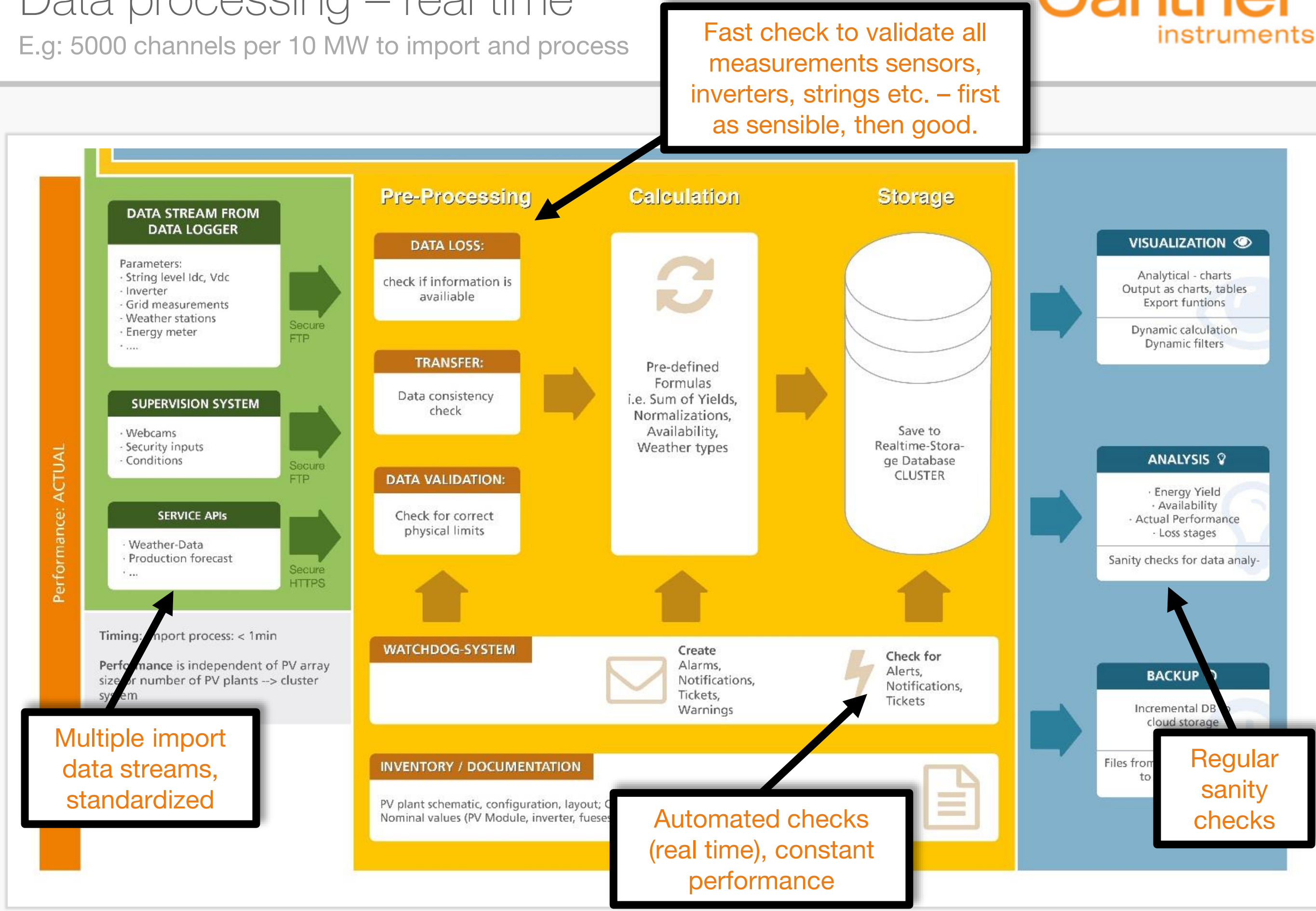


Data Acquisition & handling

Samples pictures from latest UK installations; out of >2.8GW installed

Data processing – real time

E.g: 5000 channels per 10 MW to import and process



PV Plant Structure

PV Plant structure incl. warnings and linked information

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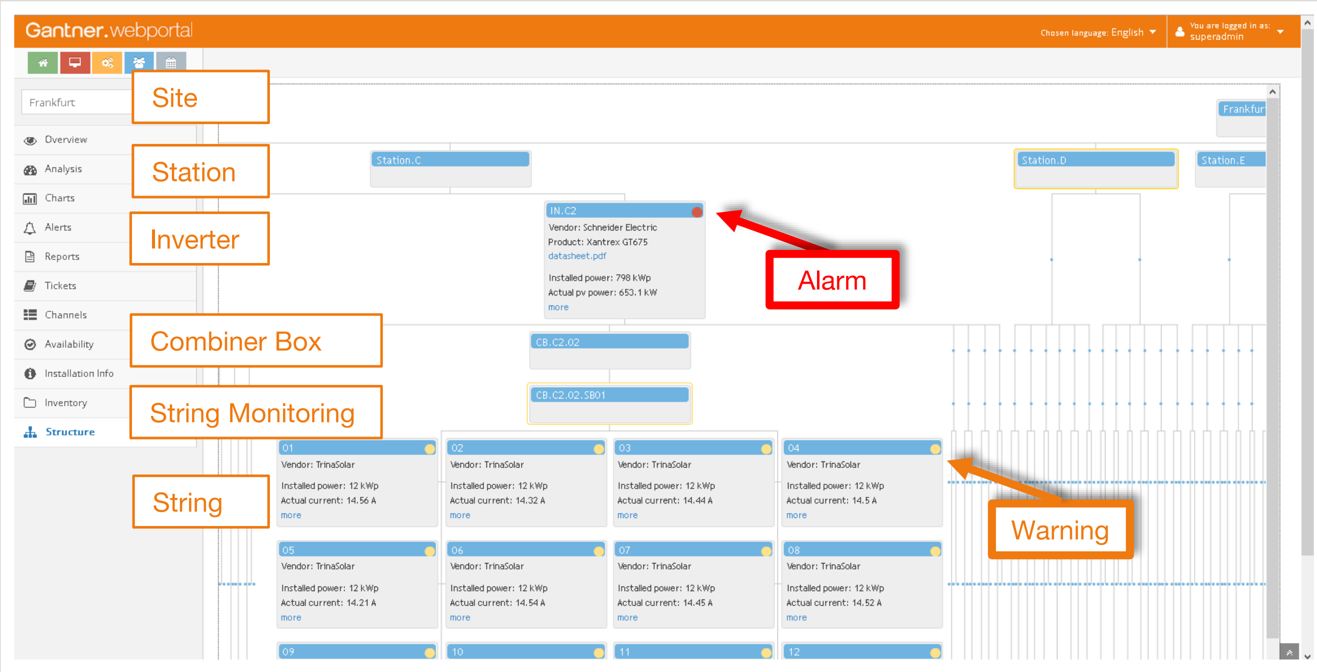

- Plant structure (generated during **data import**) allows **design & sanity checks**
- **Fast validation check of all measurements** (sensors, inverters, strings)
- **Compare performance** of peers , **localize issues.**

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Data Acquisition & handling

Normalization / Deviation of Strings, SCB, Inv.

Absolute Values: I MEASURED differs for larger and smaller arrays

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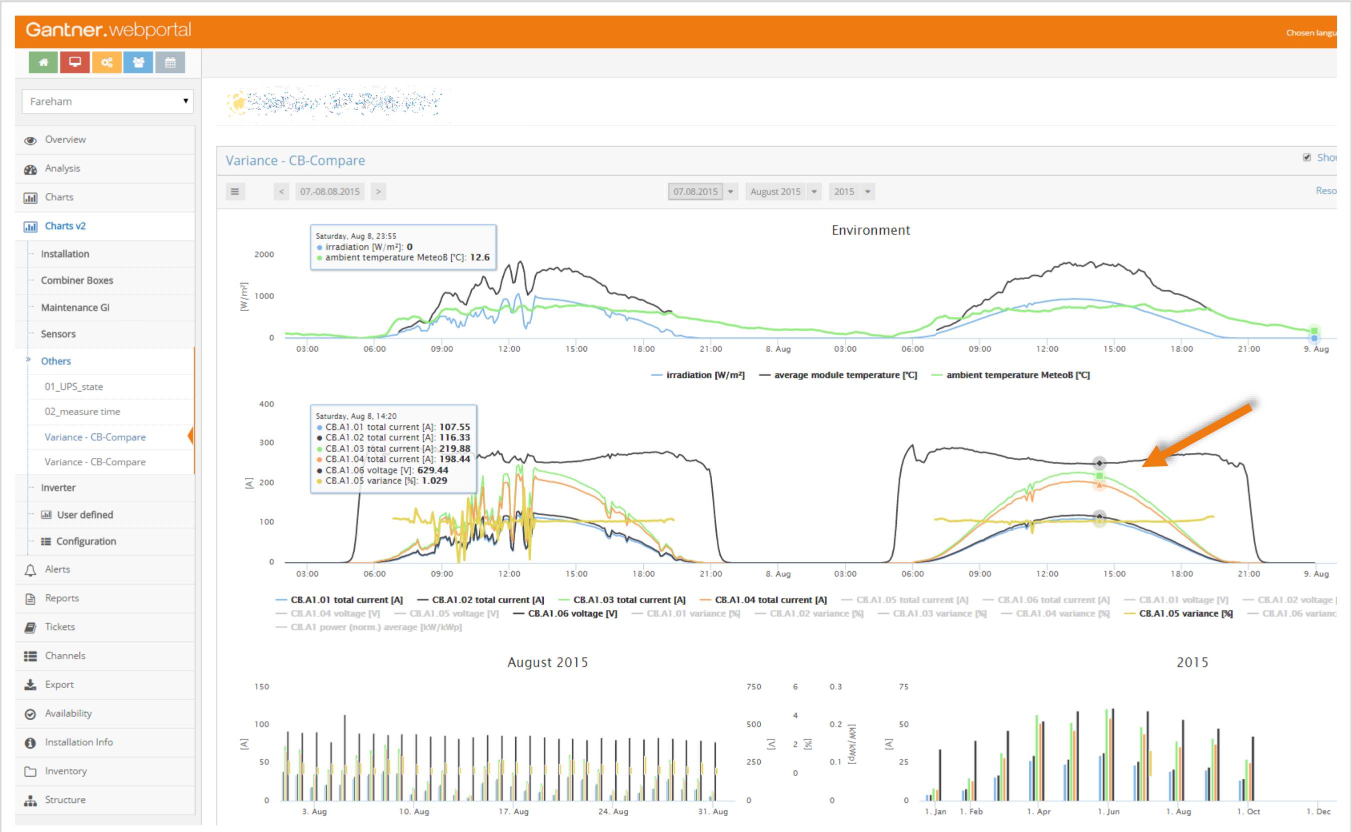

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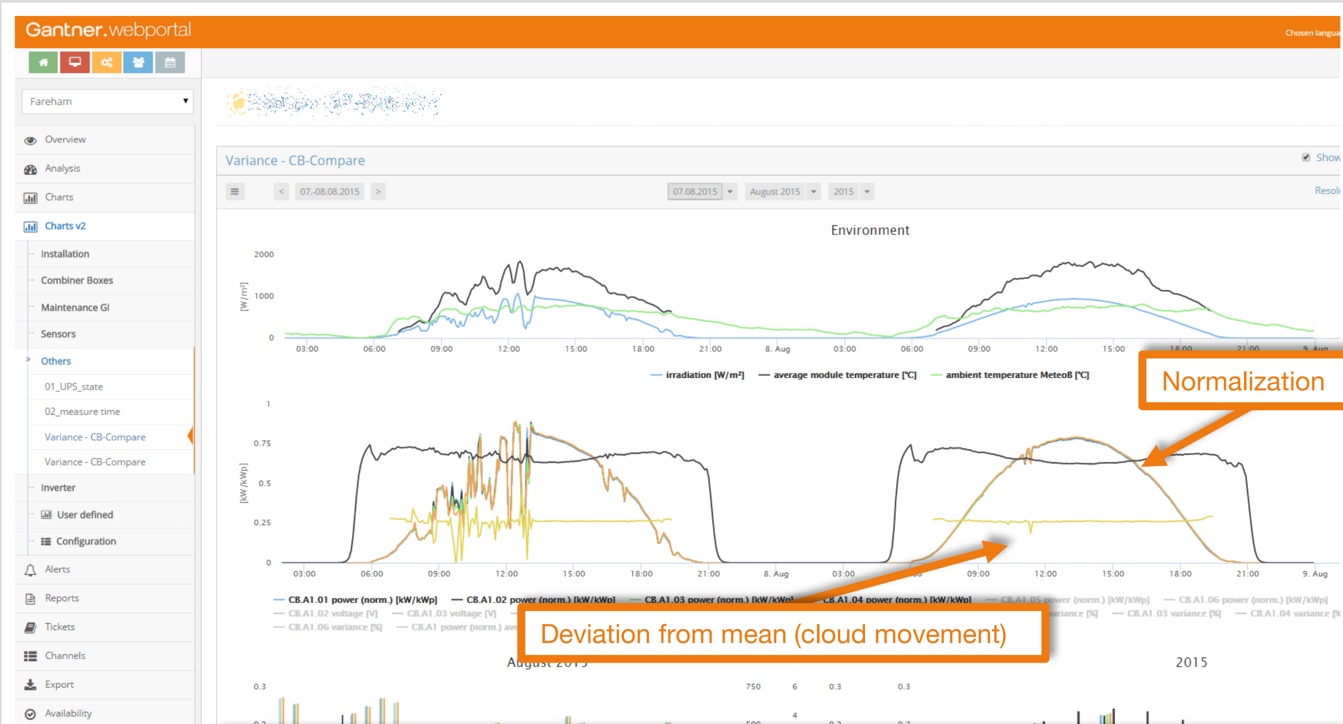
Data Acquisition & handling

Normalization / Deviation of Strings, SCB, Inv.

Normalized values: $I_{MEASURED}/P_{NOMINAL}$ show <u>similar</u> values



Good **sanity check of all components** (easier with normalised data, redundancy e.g. with NOCT, weather (kT, BF, ..), DC, AC, solar position, AOI, ..

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Data Acquisition & handling

Availability Monitoring

Availability calculation for PPA / IPP contracts

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Availability

Layout per 12 month, custom start date

Site	Period	H_PER [h]	SYS_AIV [%]	IN count []	AMA [h/IN]	SYS_AIV_AMA [%]
Oxford	2013/01-2013/12	2932	98.91	7	10	99.25
Oxford	2014/01-2014/12	2987	99.47	7	10	99.8
Oxford	2015/01-2015/12	817	100	7	10	100

- Resolution: h, day, month, year, 12month floating
- For each component (Inverter, System, Sub-System, Production batch, ..)

→ Supports preventive maintenance strategies

Layout per 12 month, custom start date detailed

Site	Period	H_PER [h]	WR.1_AIV [%]	WR.2_AIV [%]	WR.3_AIV [%]	WR.4_AIV [%]	WR.5_AIV [%]	WR.6_AIV [%]	WR.7_AIV [%]	SYS_AIV [%]	IN count []	AMA [h/IN]	SYS_AIV_AMA [%]
Oxford	2013/01-2013/12	2932	99.86	96.73	99.73	96.73	99.86	99.66	99.8	98.91	7	10	99.25
Oxford	2014/01-2014/12	2987	99.13	99.2	99.67	99.1	100	100	99.2	99.47	7	10	99.8
Oxford	2015/01-2015/12	817	100	100	100	100	100	100	100	100	7	10	100

Layout per Year

Data Analysis

Data Analysis for Utility Scale Projects

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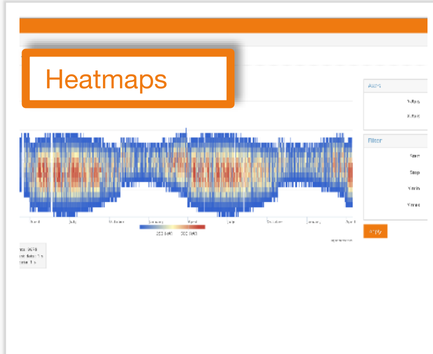
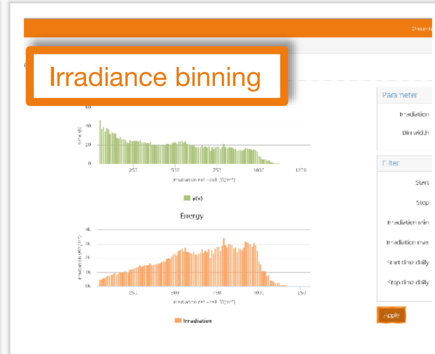
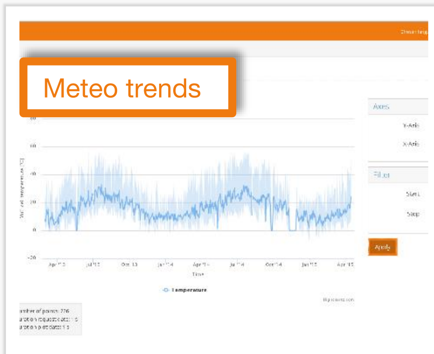
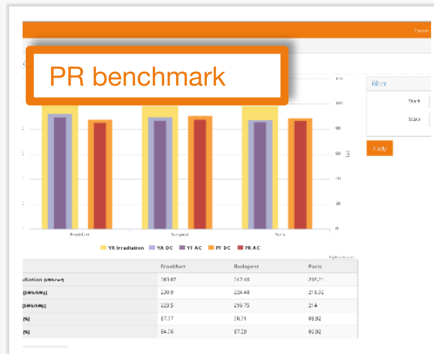
Features (selected):

- Heat maps for quick detection of outages or drifts: should be smooth, sinusoidal, repeatable yearly, ..
- Irradiation binning
- Temperature trends (min, max, avg.)
- Asset – performance: Comparison of different installations, normalized
- Temperature behavior
- Low- & Mid-light behavior
- Maps
- Sensor-cross-checks
- Availability analysis for IPP contracts









Actual Performance I

Loss Stages – Identify the losses real time

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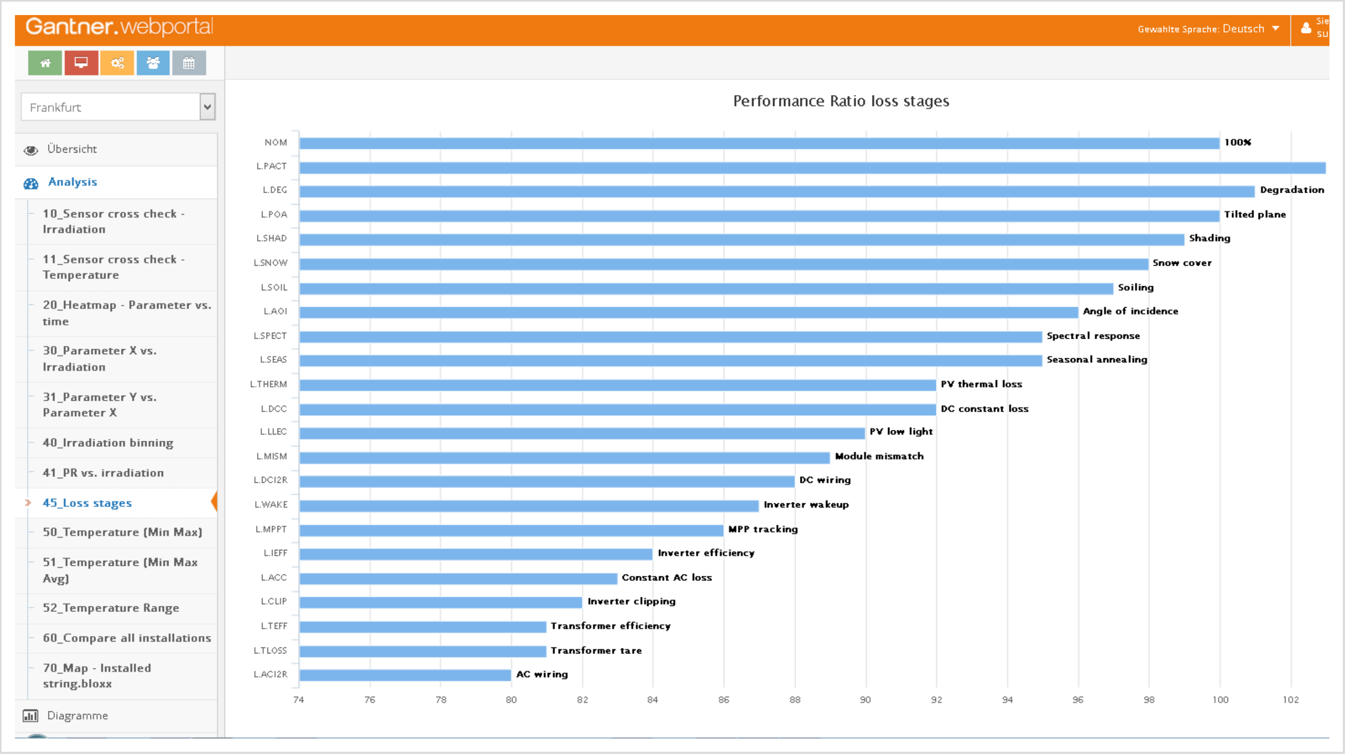
Can check losses at each measurement to show if anything is too large like shading or thermal



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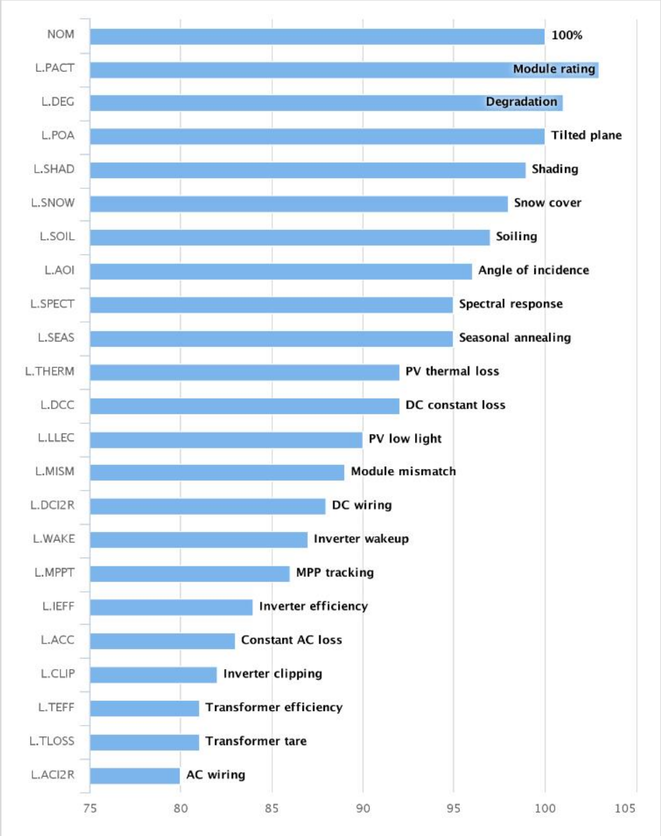
Data Analysis

Actual Performance II - Zoom

Loss Stages – Identify the losses real time



- Start at Nominal P_{MAX} = 100%
- Module Tolerance $P_{ACTUAL}/P_{NOMINAL}$
- Degradation vs. time
- Plane Of Array Insolation
- Shadow (vs. solar position)
- Soiling vs. time and precipitation
- Angle of incidence includes reflectivity
- If possible Spectrum from EQE, multi junction
- Seasonal, anneal for some TF
- Thermal loss T_{MOD} from T_{AMB}, NOCT/NMOT, gamma, wind speed
- DC constant loss if needed
- Low Light efficiency change @ ~0.2 suns
- Mismatch from series strings
- DC I^2.Rs wiring loss
- Inverter wakeup
- MPPT
- Inverter efficiency
- AC constant
- Clipping
- Transformer efficiency
- Transformer loss
- AC wiring

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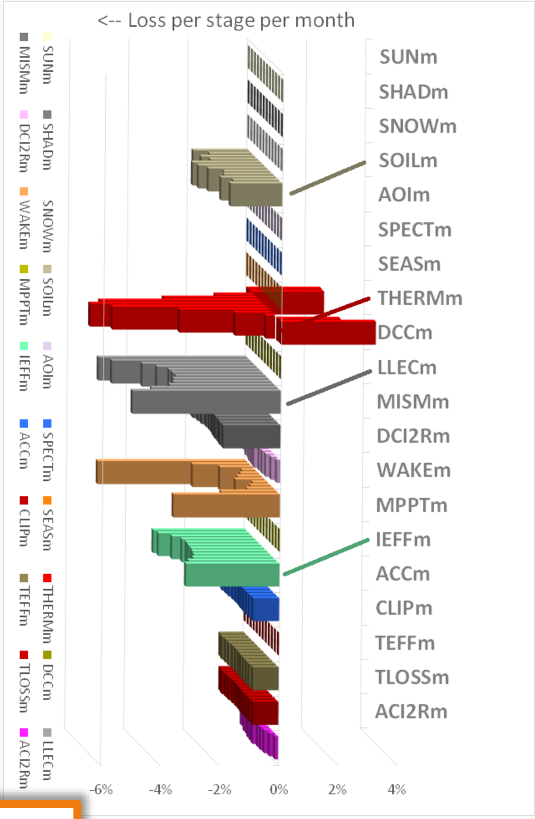
Data Analysis

Performance prediction & Optimization

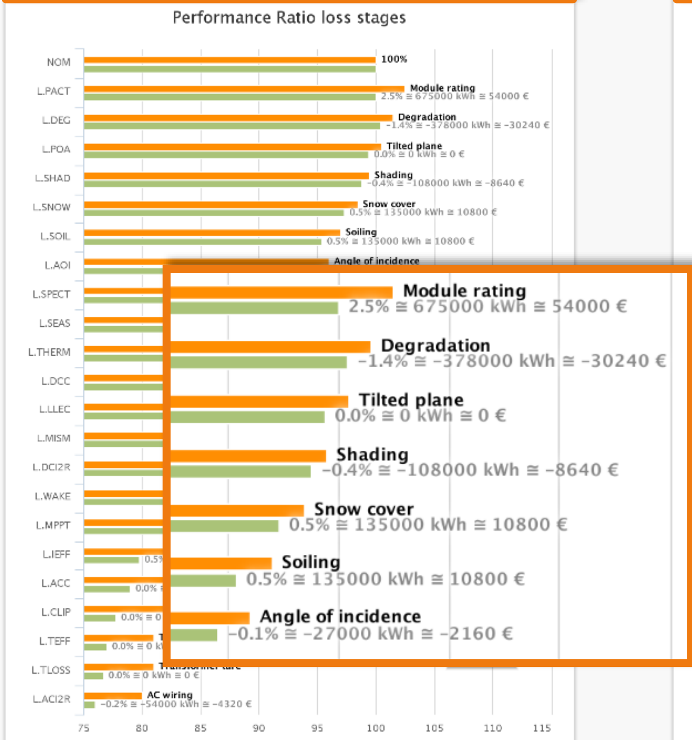


.. by using hourly simulation programs

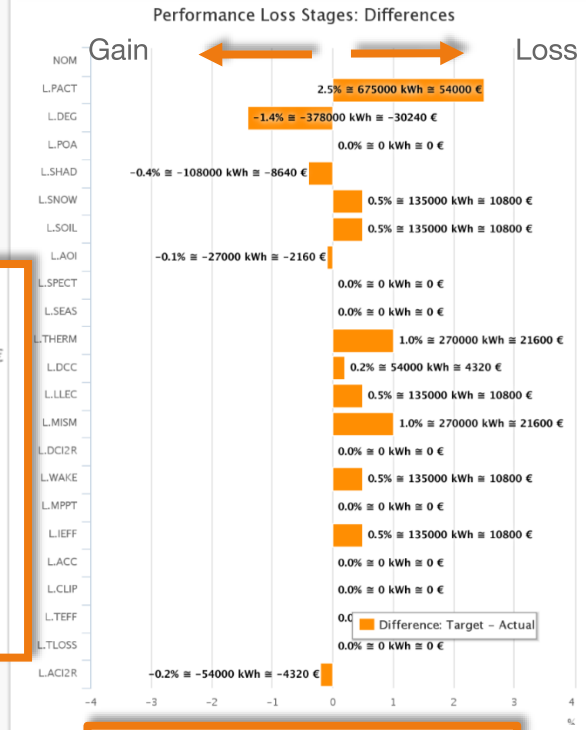
Loss Stages: Actual vs. Target performance

Compare w/ assumptions, use actual weather data and simulations, real time

Run this for Target and Actual performance



→ **Difference** shows your **actual gain/loss**



Total annual loss: **110 160 €**

Assumptions: YF (per year) 1350 kWh/kWp; Pnom_site 20 MWp; Energy value 0.08€/kWh (assumed); LCoE background model possible.

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Prediction & Optimization

Performance Prediction

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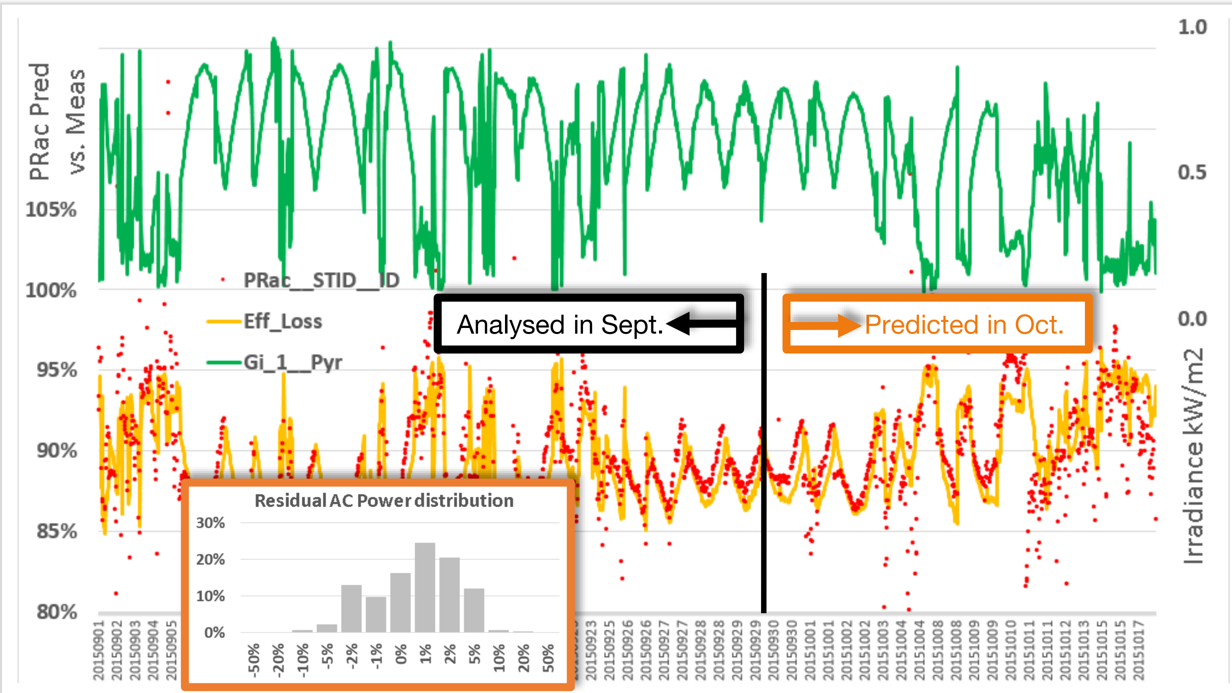
- Setup algorithms to predict instantaneous PV and BoS performance for measurement validity and energy yield predictions
- Basic version (shown) gives already very useful results for system cross-check and trend detection (soiling alerts, shading, ..)



Location: Frankfurt site

Investment vs. **Benefit** of Monitoring: Impact on System cost (CAPEX), O&M (OPEX) and LCoE

CAPEX (t_0)

OPEX (t_1-t_n)

Energy Production (t_1-t_n)

Financing (Equity / Debt)

LCoE

Monitoring Investment & Benefit

Impact of Monitoring on System cost (CAPEX), O&M (OPEX) and LCoE

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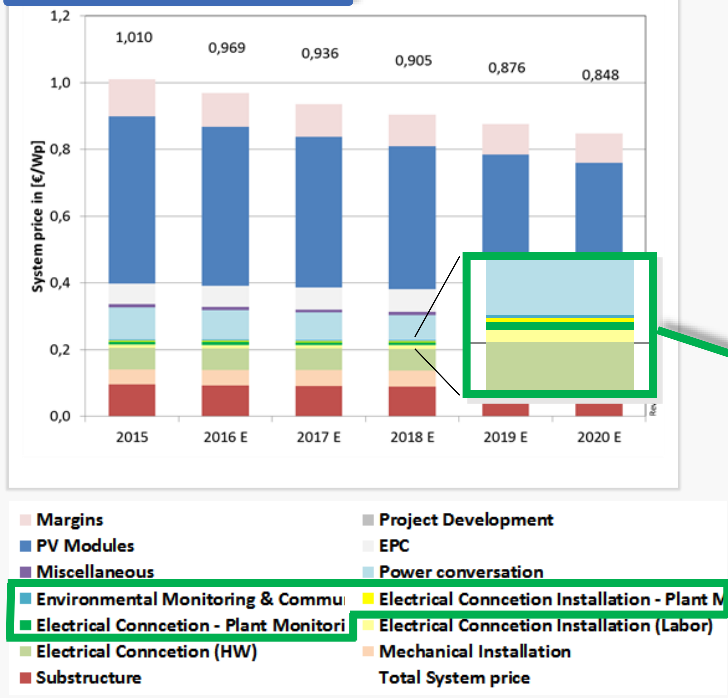
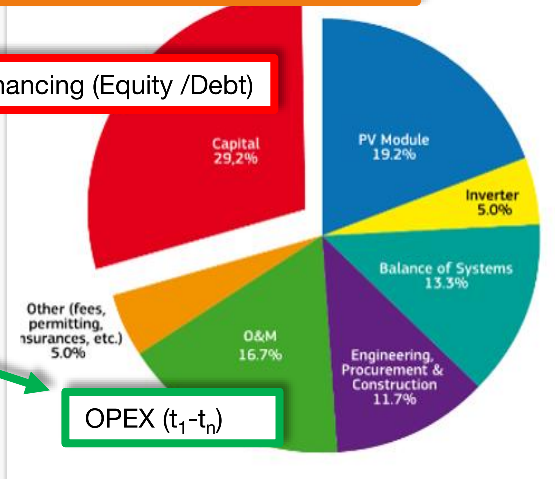
System Cost (CAPEX)



LCoE (split by component) (t_1-t_n)

Financing (Equity /Debt)

OPEX (t_1-t_n)



- **Monitoring cost** share of system price: ~ **1.4%** (0.013€/Wp, EU)
- **Installed Monitoring** gives **direct control of 17% of the LCoE Cost** (O&M cost)
- **Control performance of Inverter**, cables & connections, ..

LCoE for Utility scale, 5% ROI; Source: JRC, 2014; Gantner Instruments System cost model, Europe

Monitoring Investment & Benefit II

Impact of O&M strategy on Yield, LCoE and Profits, 10MWac

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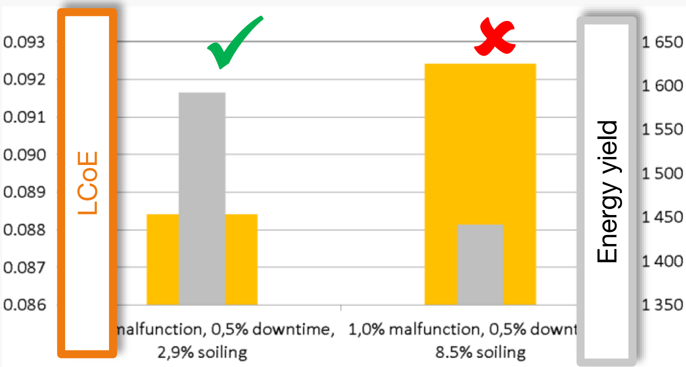
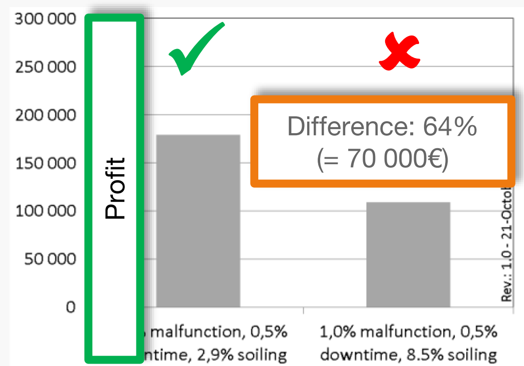
Losses (O&M relat'd)	Example	Monitoring ✓	No Monitoring ✗
Downtime	Maintenance	0.5 %	0.5 %
Malfunction	Modules, combiner boxes, fuses	0.5 %	1 %
Soiling losses	Cleaning events	2.9% (4 x)	8.5% (2 x)
O&M cost (€, per yr)		166 577	154 577
Energy yield (kWh/kWp)		1546	1442

PV power plant area: 138 219m²; GCR: 0.5; 77 Combiner boxes (CB); 24 Strings per CB; Annual numbers: YF=1608 kWh/kWp; Yearly operation costs w/ labor € 45 950; Power plant care cost € 26 790 (18 469); Project lifetime 25 yr; Labor cost 25€/h; Inflation rate 2.5%; Water 0.0025 €/l; Fuel cost: 1.5 €/l; Cost for components exchange and stock





PV power plants **with monitoring** can deliver **7.3% better Energy yield,** results in **4.5% better LCoE**

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Investment vs. Benefit

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Cost effective Monitoring Solutions can :

- Reflect Financial KPIs (Performance guarantees, allowed maintenance, integrate simulations)
- Allow "real time" data processing for availability, alarms, warnings
- Automated Performance Analysis and characterization in terms of kWh and $ (loss separation, sensitivity to irradiation, weather, cleaning, ..)
- Implement preventive maintenance strategies

Advanced Monitoring Algorithms leads to:

- Providing Investors with reliable information about O&M, track record & plant performance, control
- Separating and identifying losses where "actual vs. target" differs
- Optimizing Plant Performance during lifetime
- Reducing LCoE based on advanced Monitoring design (characteristic trends, Loss Factor Model)
- Reducing risk for Investors & Independent Power Producers (IPPs)

Thank you very much for your attention!

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We would like to thank our colleagues Jörg, Andre, Daniel, Stefan, Holger, Stefan, Samuel and Vasu for their indefatigable effort in realizing successful customer projects worldwide.

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