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Analysis of Fault Detection and Defect Categorization in Photovoltaic Inverters for Enhanced Reliability and Efficiency in Large-scale Solar Energy Systems

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Motivation

Experience from operators:
Daily messages / information from the monitoring systems in general

1

Portfolio size: 300 MWp (various system sizes with string and central inverters)

"**1 to 15 error messages per day**, sometimes significantly more, depending on the weather conditions and external influences such as grid fluctuations"

→ This results in **3-5 tickets** per day, which require a service call with an **on-site diagnosis** and, if necessary, a repair.

2

Portfolio size: 130 MWp (distributed over 12 systems, consisting of central inverters)

„**30 to 60 error messages per day**"

⇨ **There is a great need in O&M in large system portfolios to detect a deviating behavior at an early stage.**

⇨ **Objective: Detect faulty inverter behavior, limit the causes of defects and identify similarities in patterns.**

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Outline

observed inverter error
"IGBT switching error"

root cause analysis
→ material characterization

impact analysis
→ data analysis of the monitoring data

automated fault detection

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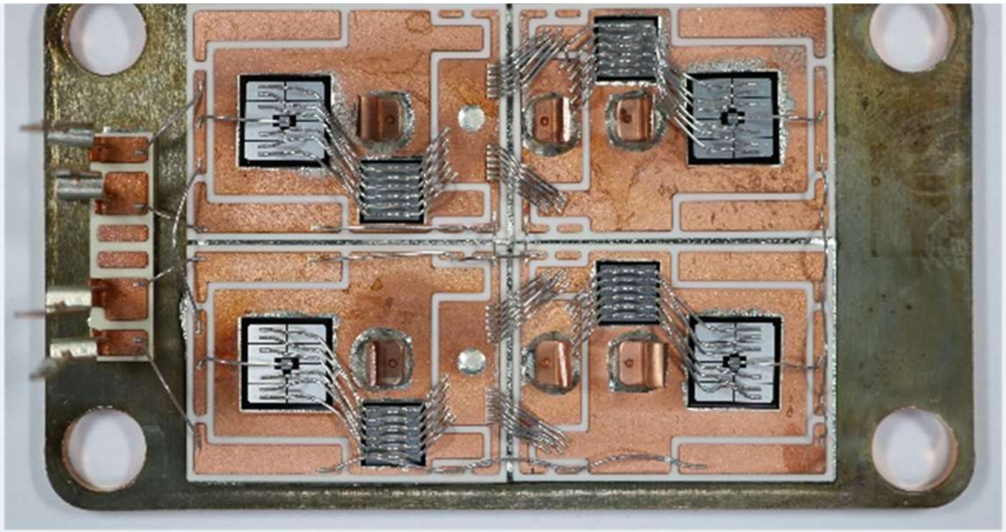
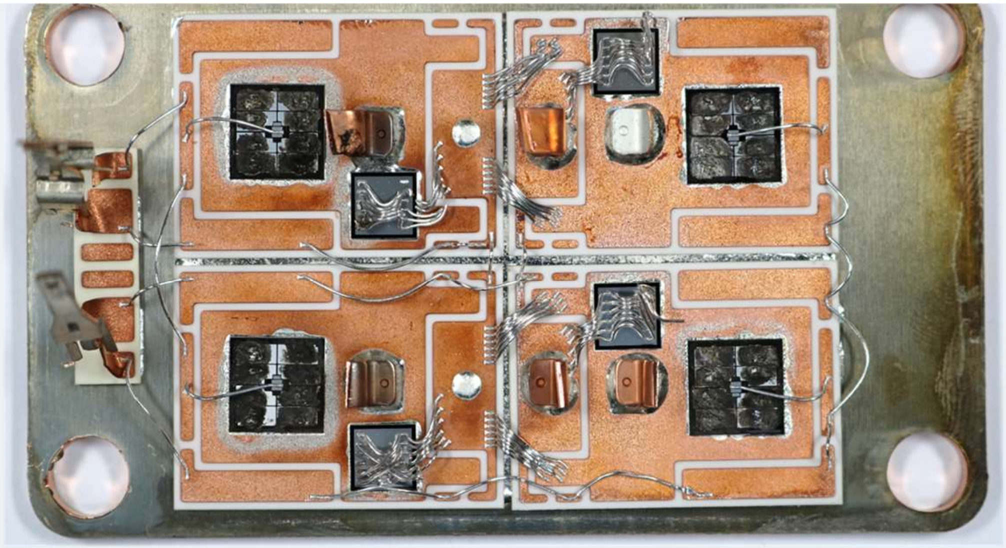
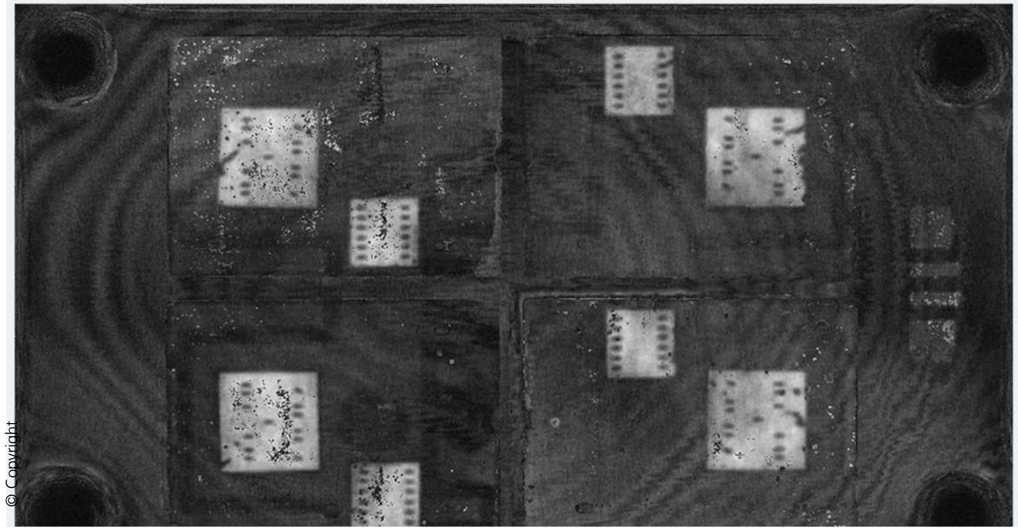




Material characterization



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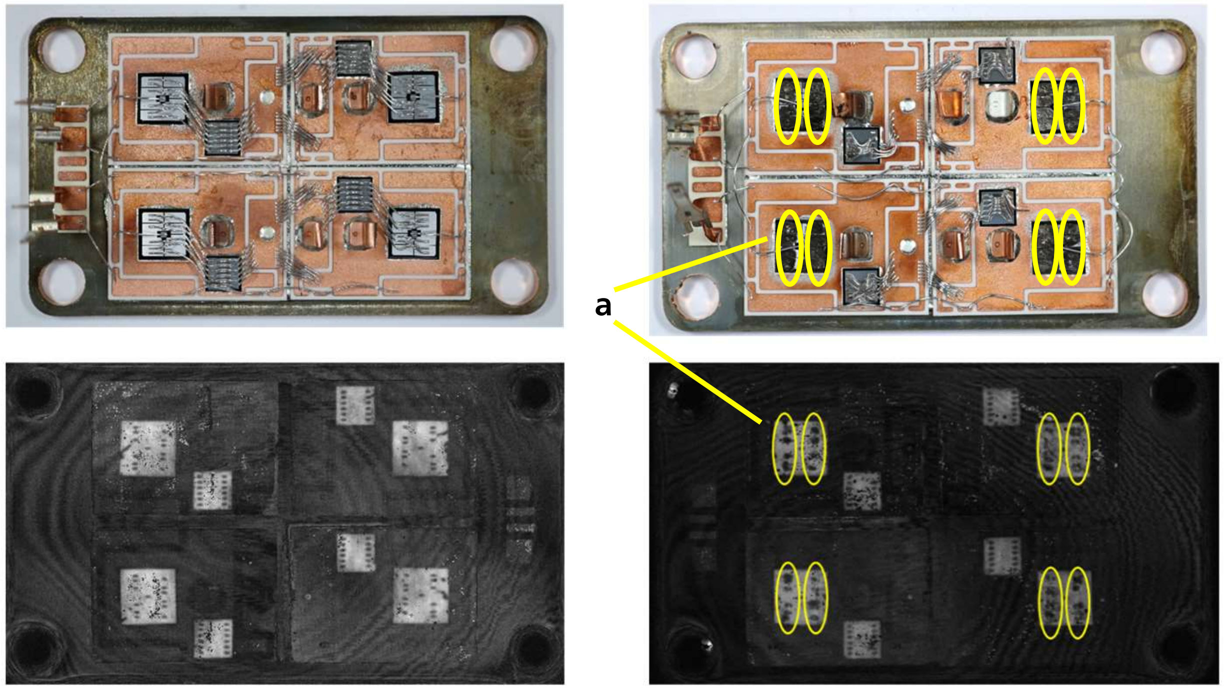
Material characterization

Non-destructive analysis

- a Impairments in plane of the wire bond connections
- b The emitter metallization of the IGBT components is completely degraded and the associated wire bond connections to the DCB substrate are also destroyed.
- c Re-melting of the solder connections of the chips and the pins of the connection terminals is visible.

Power module after field ageing | **Power module after failure**



Characterization of the failure mechanisms in inverter components,
above: Power modules without housing and potting
bottom: non-destructive scanning acoustic microscopy (SAM) analysis (wire bond level) before removal of housing and potting

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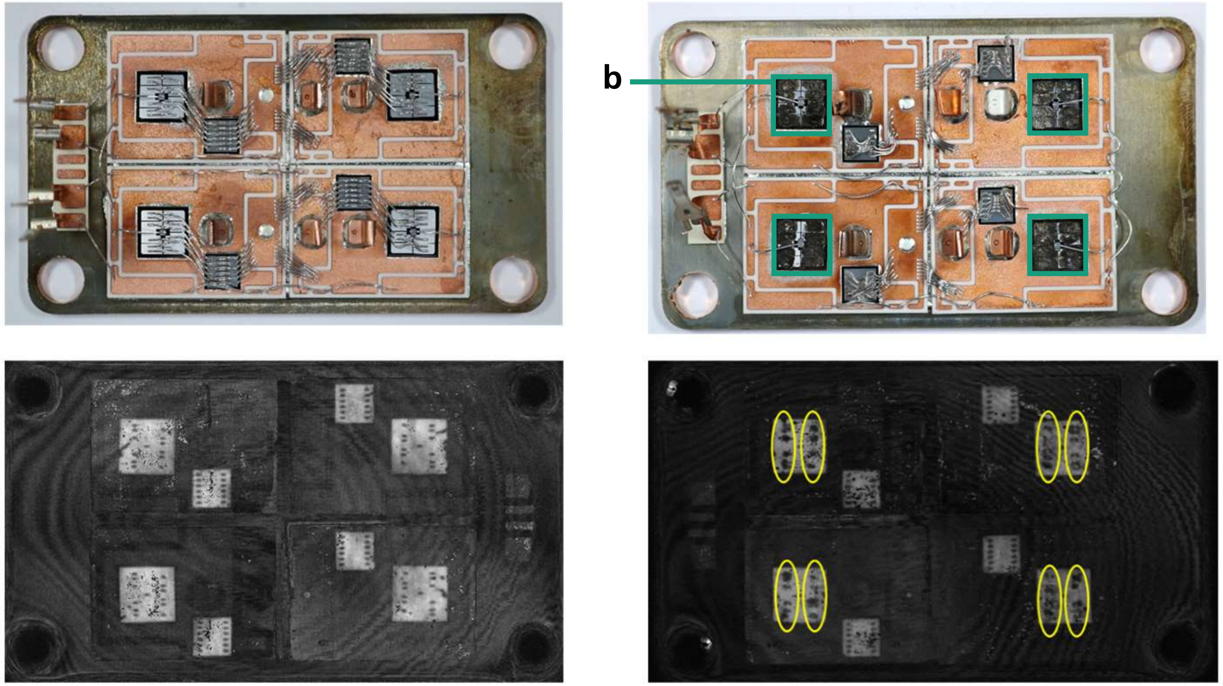
Power module after failure



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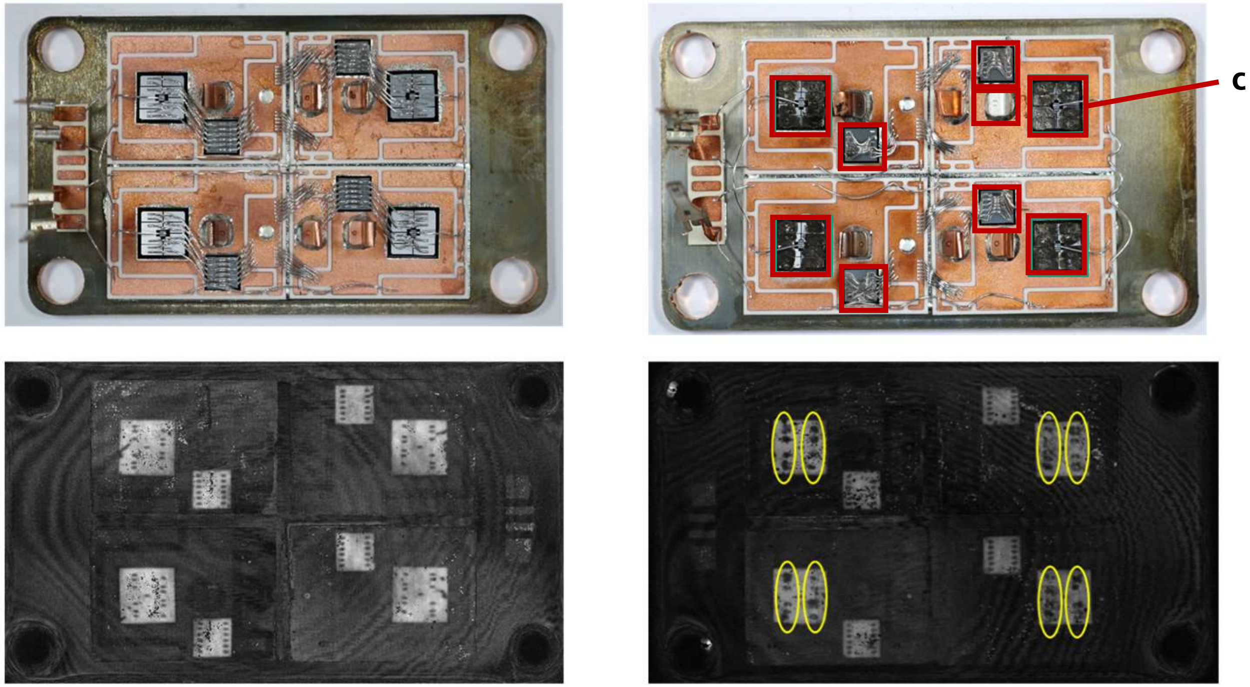

Characterization of the failure mechanisms in inverter components,
above: Power modules without housing and potting
bottom: non-destructive scanning acoustic microscopy (SAM) analysis (wire bond level) before removal of housing and potting

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Material characterization

Cross-sectional view – light microscope

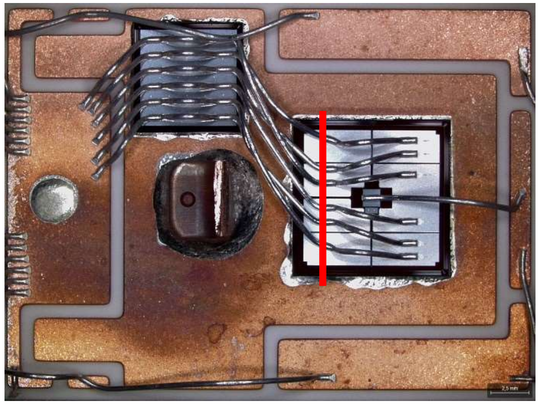
- **wire bond contacts are destroyed and not visible**
- **partially missing chip and solder area up to the DCB substrate**
- **The module was exposed to enormous heat, causing melting the chip and solder materials locally.**

Conclusion

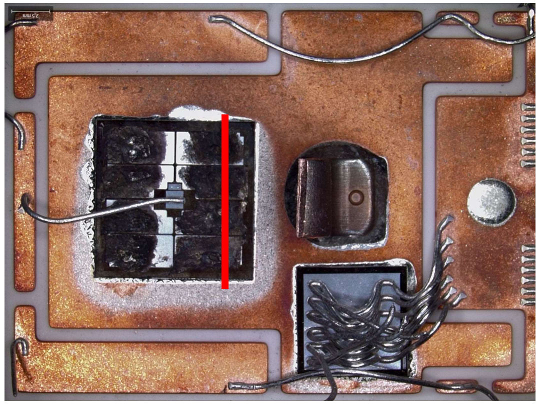
1. **all four IGBT components are equally affected**
2. **the associated diodes show no damage**
3. **the peripheral extent of damage is less drastic overall**

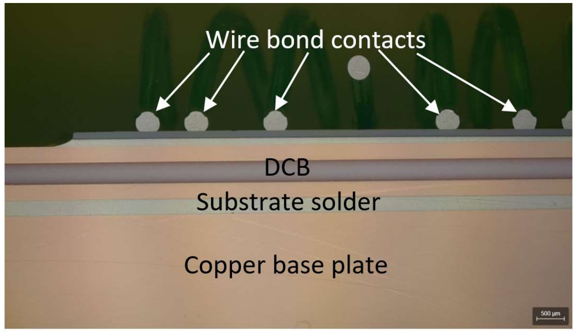
- **a longer lasting overtemperature load has led to degradation of the semiconductors**
- **In the end, a breakthrough occured and the final damage was caused by the short-term release of massive heat.**

Power module after field ageing



Power module after failure





Cross sectional view of the bonding wires and solder contact using light microscope imaging of the IGBTs

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Take away message:

- root cause analysis done
- failure mechanism understood

→ overtemperature load over a longer period → degradation of the semiconductors

→ Final damage: breakthrough happened and a release of massive heat

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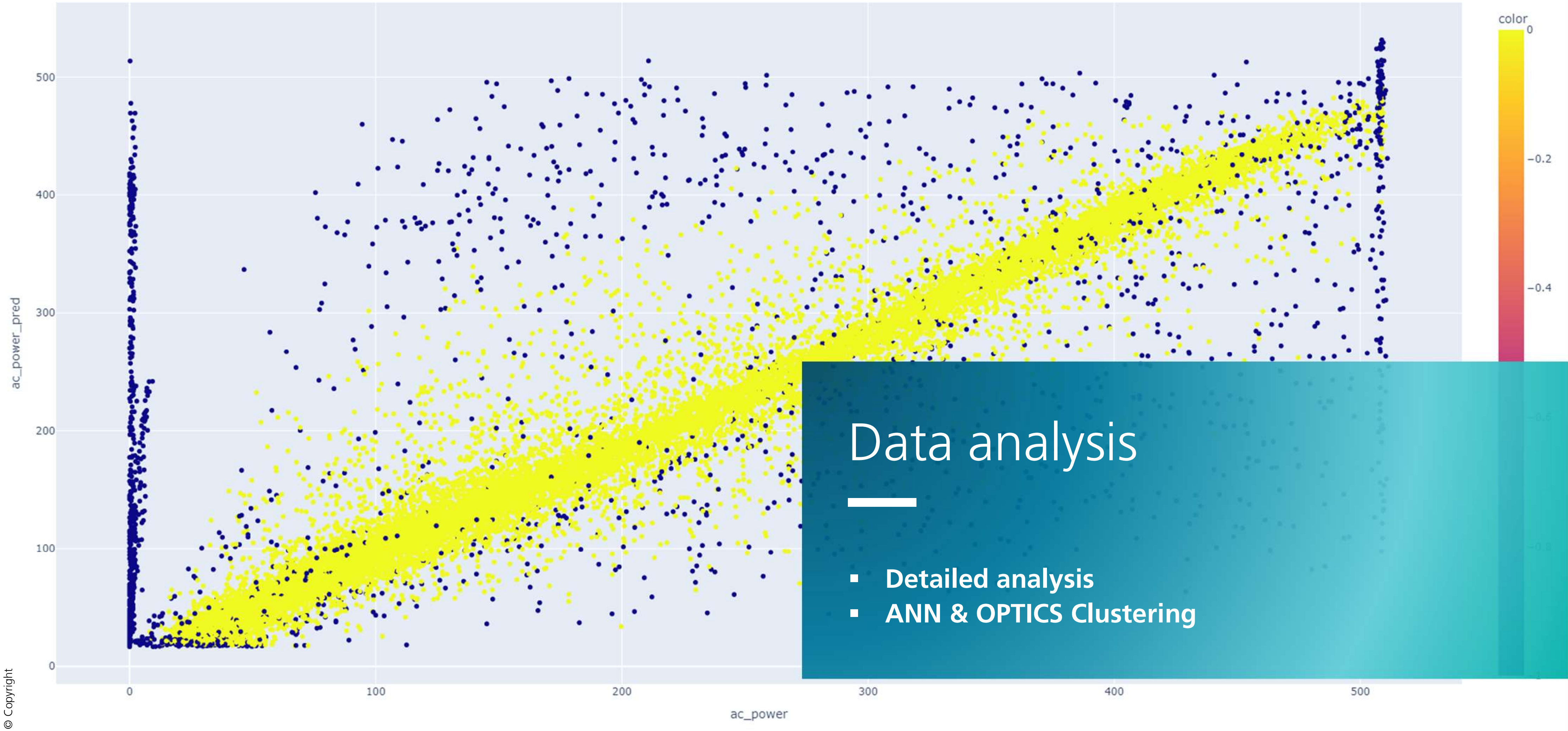

Data analysis

- **Detailed analysis**
- **ANN & OPTICS Clustering**

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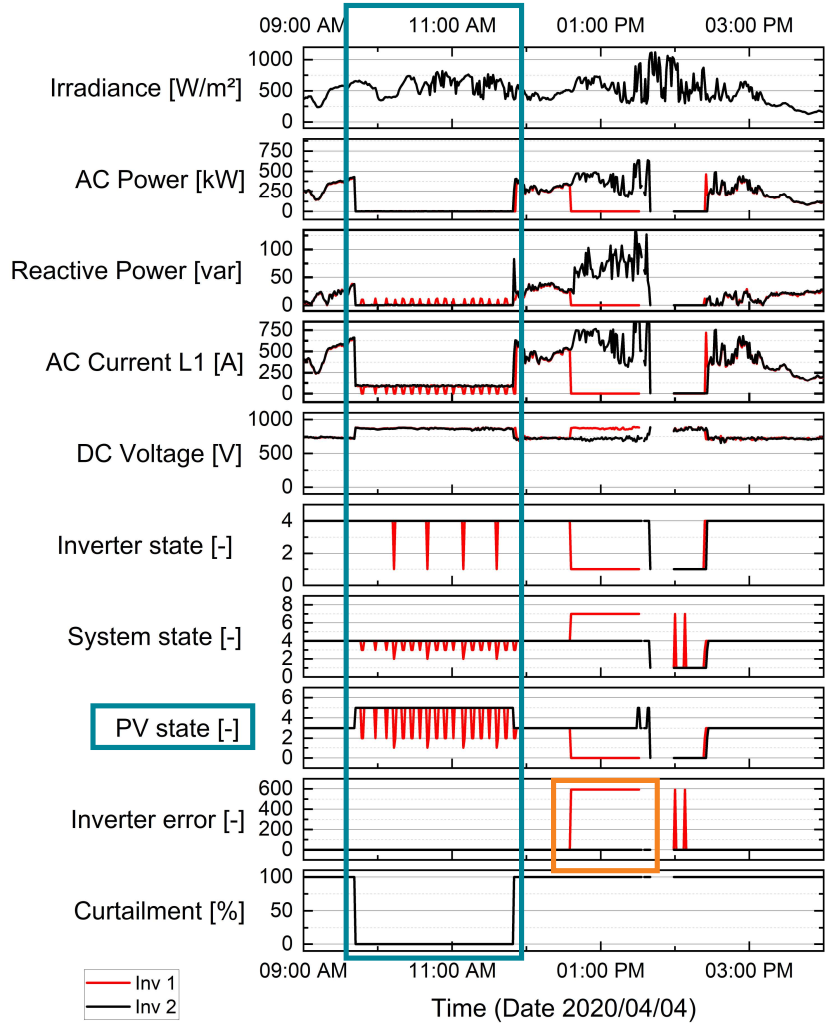
Data analysis

Detailed analysis

Detailed investigation of individual parameters of the inverters

- **Deviating inverter behavior recognizable during a grid-related curtailment of inverter 1**
- **Different states are approached alternately (“underload” - “wake-up” - “underload”, “night”) in contrast to inverter 2**
- **Occurrence of the error message “IGBT switching error” ½ h after curtailment ended → IGBT module defective**



Comparison of measured electrical variables and status information of Inv 1 and a comparable Inv 2 in the same system

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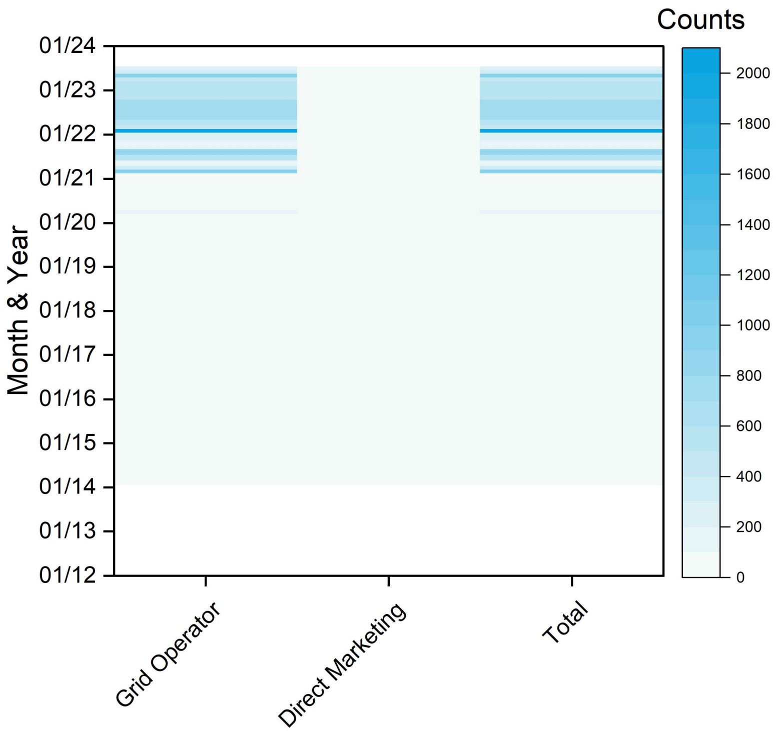
Data analysis

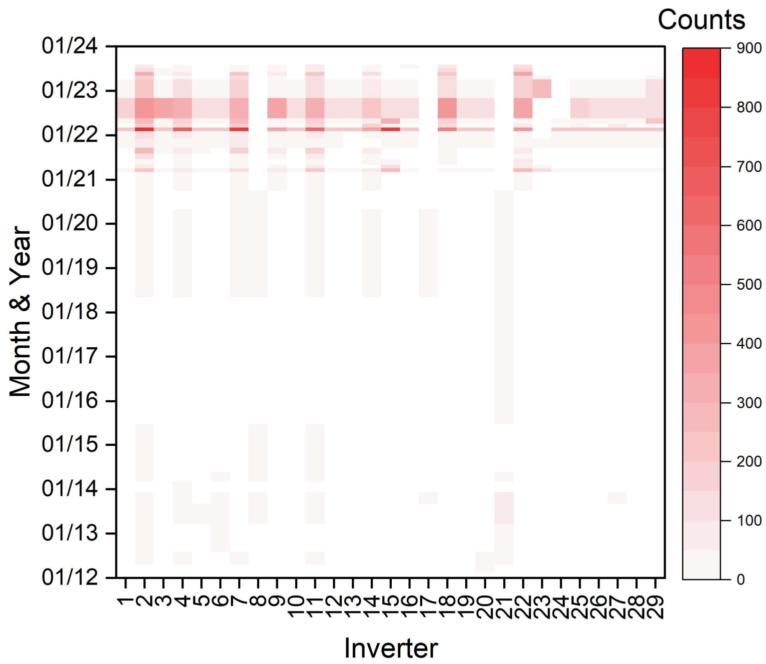
Application of System Portfolio

How often does curtailment occur?

Is the pattern also visible on other inverters?



Amount of minutes of curtailment occurrence, aggregated per month and year, split between grid operator and direct marketing



Amount of faulty inverter behavior during curtailment; determined by the state information and it's change from one minute to the next

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Take away message:

- impact analysis done
- pattern found and possible affected systems identified

→ But is it possible to detect it automatically?

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Data analysis
ANN & OPTICS Clustering – Results

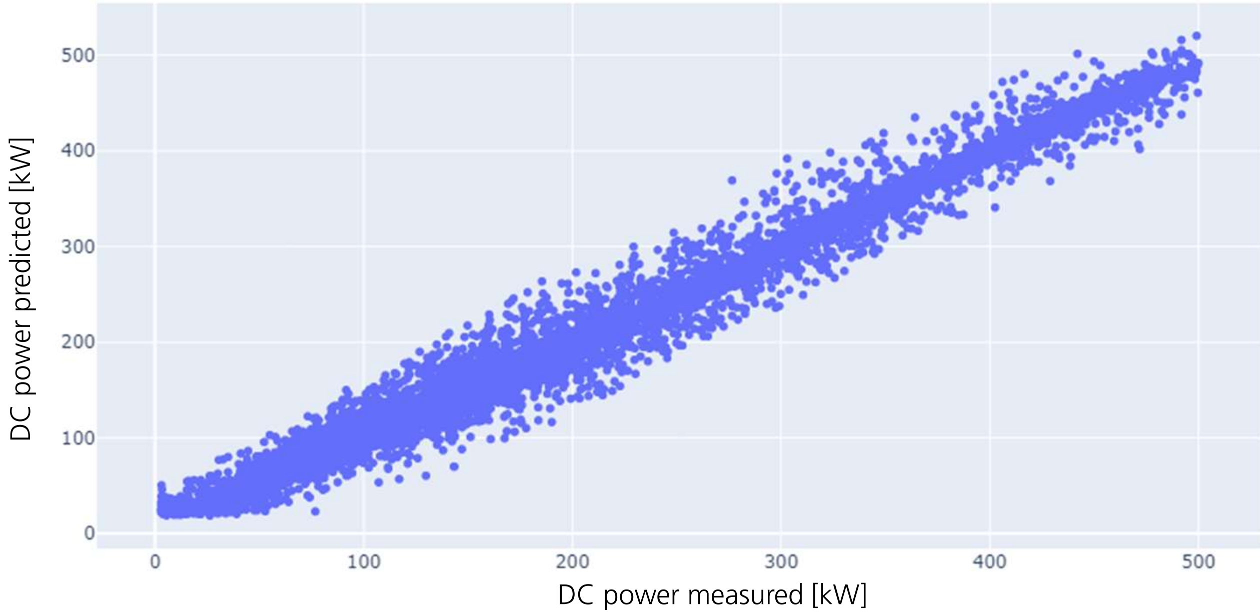
ANN Modelling → First OPTICS Clustering → Second OPTICS Clustering

Determination of reference behavior

- input
  - irradiance, ambient temp
  - sun position
- output
  - DC & AC power

- 1 year (10 min interval) – year 2021

- RMSE
  Training 15.5 kW
  Test 15.8 kW



Data analysis
ANN & OPTICS Clustering – Results

ANN Modelling → **First OPTICS Clustering** → Second OPTICS Clustering

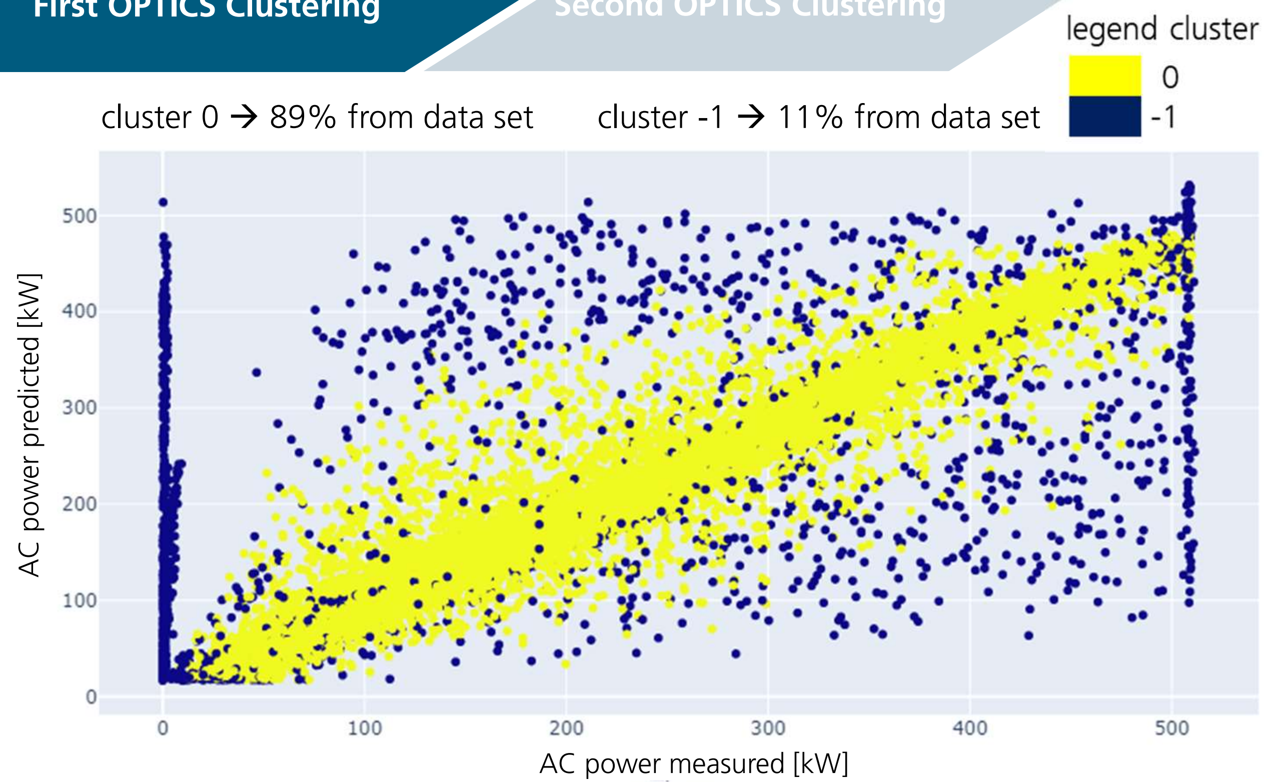
Distinguishing between "normal" and "irregular" behavior

parameters for clustering:

- electrical inverter parameters
- pred. DC & AC power from ANN
- irradiance, ambient temp
- sun position

- 1 year (10 min interval) – year 2022
- exclusion of night-time values

- metric: Mahalanobis
- minPts=3000 ξ=0.001



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Data analysis

ANN & OPTICS Clustering – Results

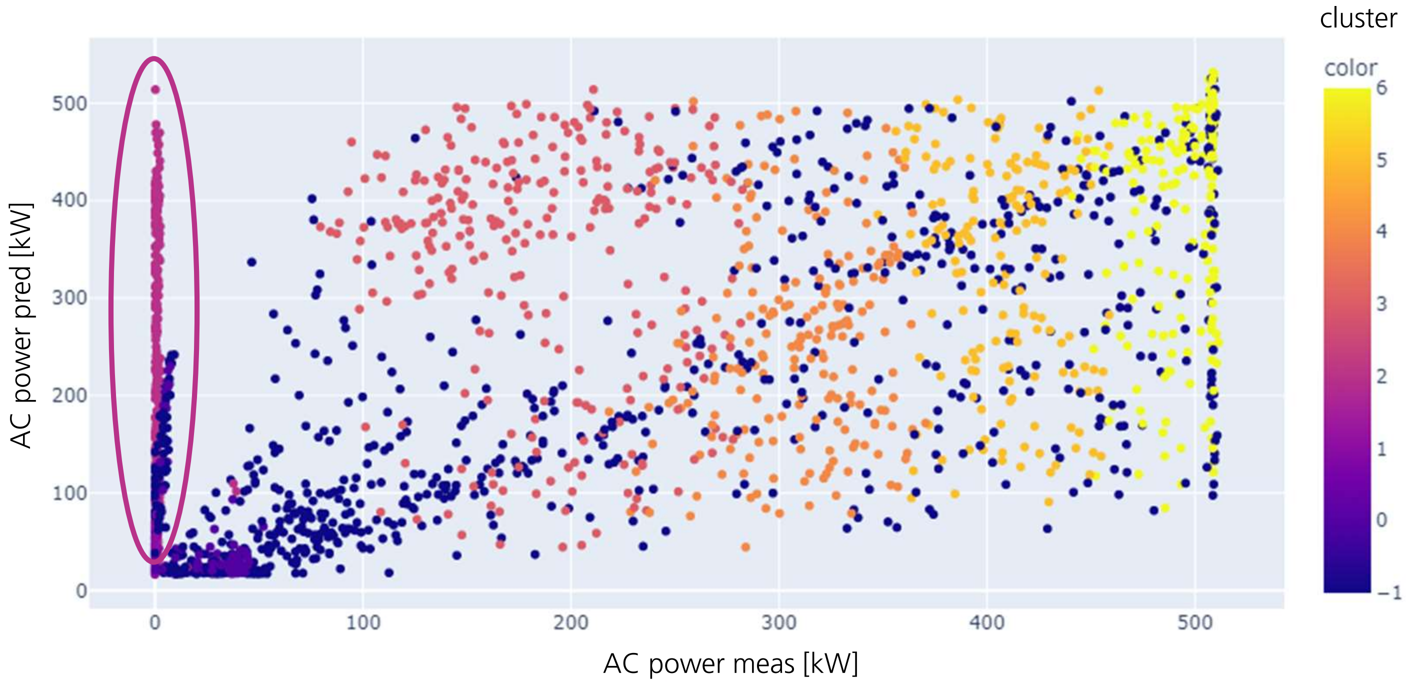
ANN Modelling → First OPTICS Clustering → Second OPTICS Clustering

A closer look at irregular behavior

Parameters for clustering:

- "outliers" of first clustering (year 2022)
- electrical inverter parameters

- metric: euclidean
- minPts=100 ξ=0.001



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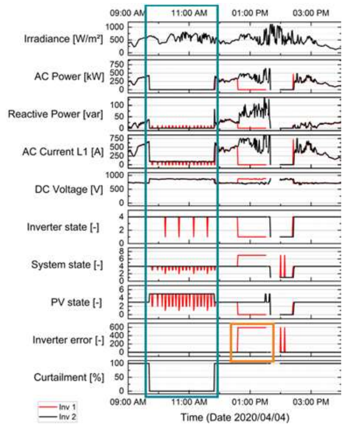
Conclusion

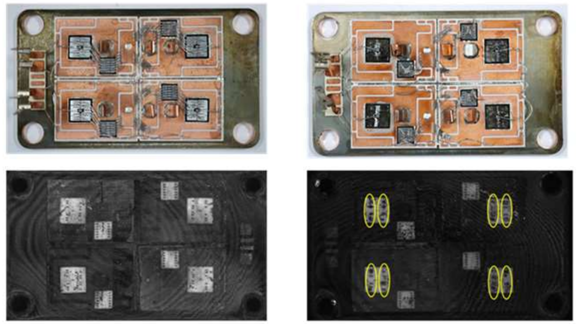
observed inverter error
“IGBT switching error”

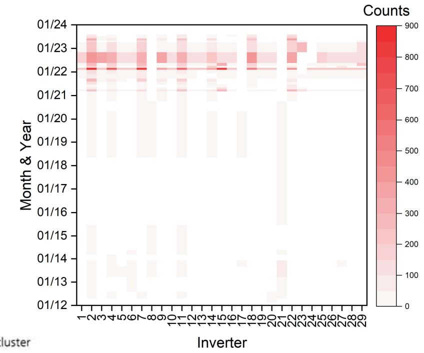
failure mechanism understood

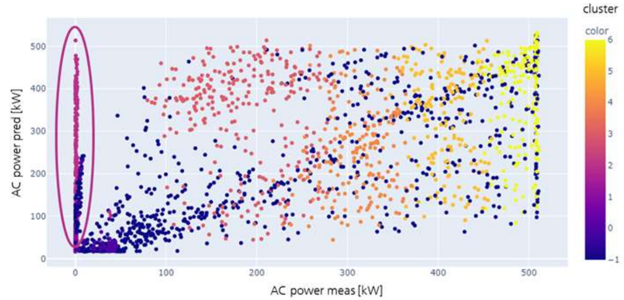
pattern found and impact of the entire system identified

automatically detected in the field









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Thank you for your attention

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