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University of Cyprus
PV Technology

Advanced failure diagnostic approach for grid-connected photovoltaic systems

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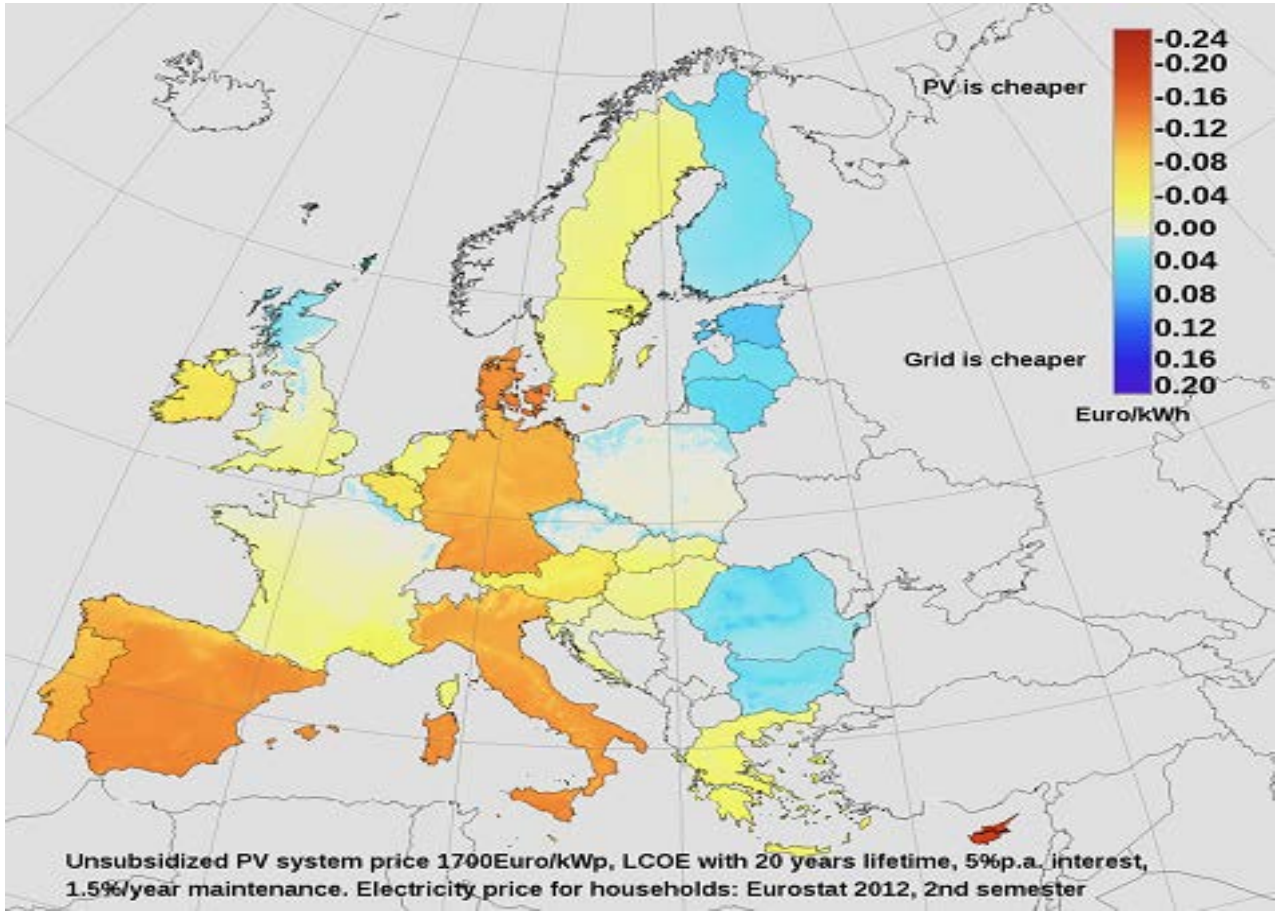
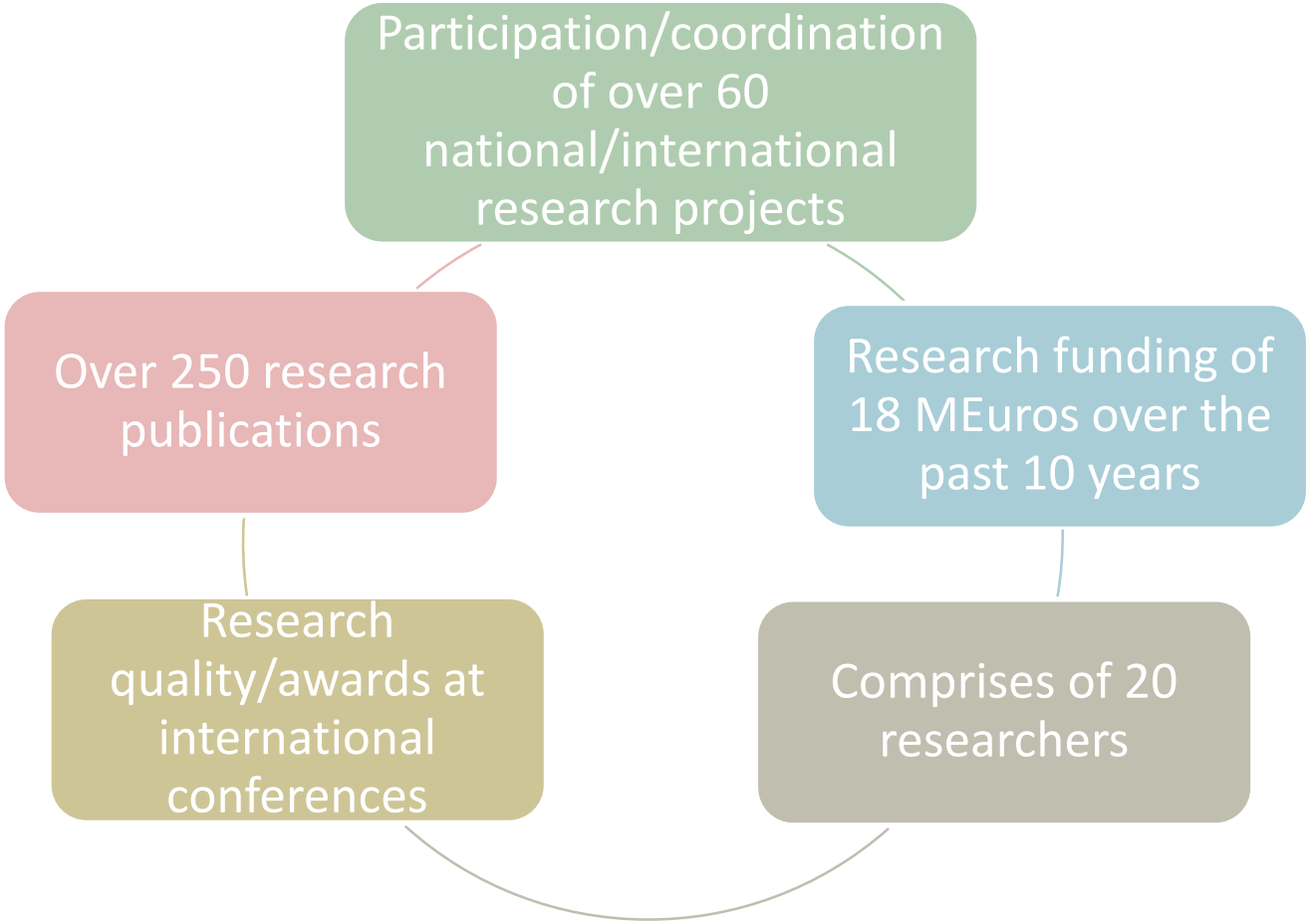
Outline

- Cyprus and the PV Technology Laboratory of the UCY
- Introduction to FDR
- State-of-the-art
- Approach
- Results
- Conclusions

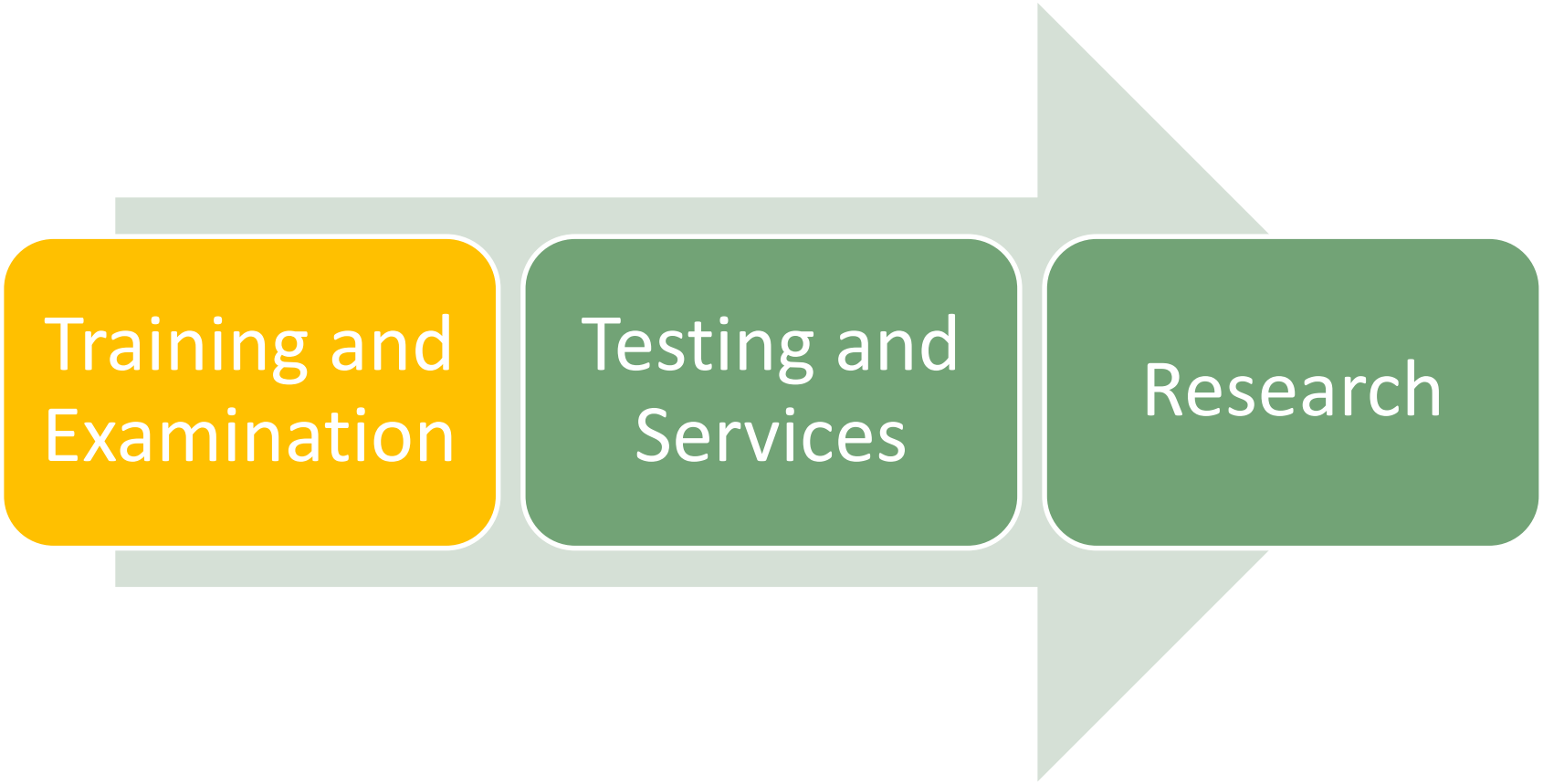
Cyprus


PV is cheaper
Grid is cheaper
-0.24
-0.20
-0.16
-0.12
-0.08
-0.04
0.00
0.04
0.08
0.12
0.16
0.20
Euro/kWh
Unsubsidized PV system price 1700Euro/kWp, LCOE with 20 years lifetime, 5%p.a. interest,
1.5%/year maintenance. Electricity price for households: Eurostat 2012, 2nd semester

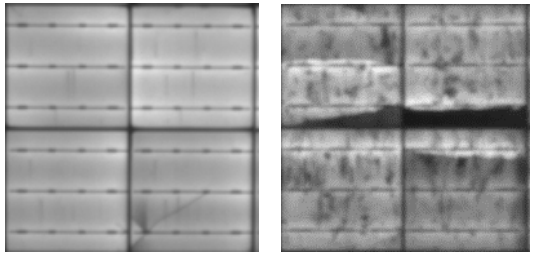
Highlights of the PV Technology Laboratory

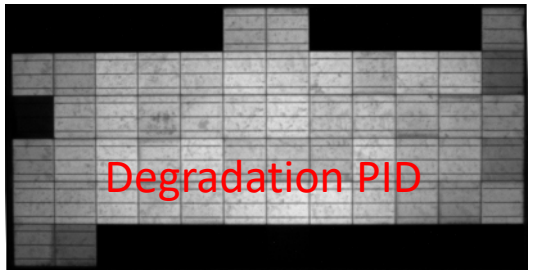


PV Technology Laboratory



Indoor/outdoor testing





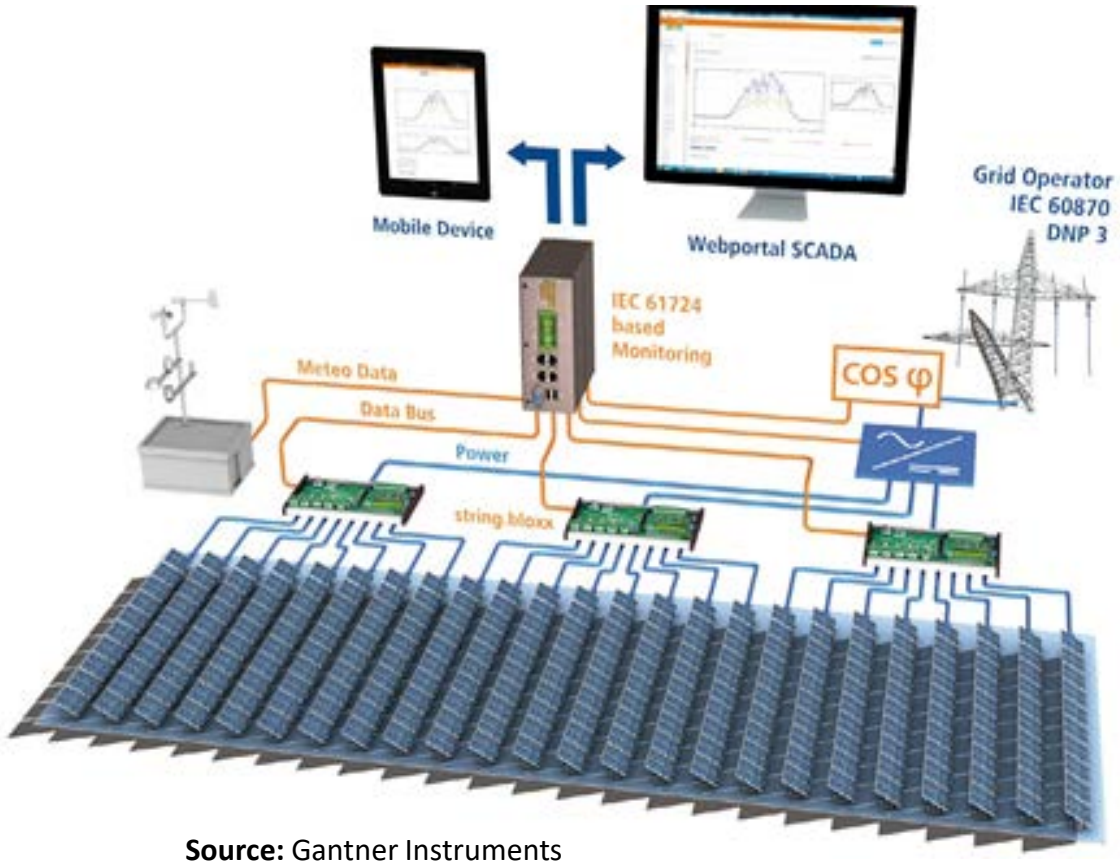
Introduction

- A major requirement for further uptake of PV is the assurance of the lifetime energy yield.
- This requires accurate identification of failures in PV systems.
- Failures can occur during the operational lifetime of PV systems due to different factors.
- Such failures decrease the output power of the PV system.

Motivation

- Need to ensure optimal performance and lifetime output of PV systems.
- Development of advanced condition monitoring algorithms that will significantly improve quality of operation of PV systems.

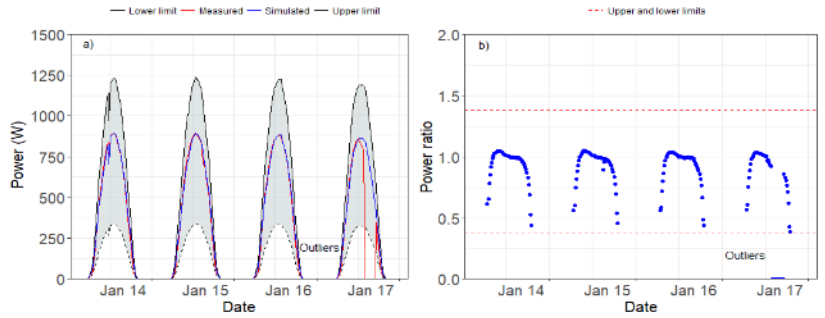
IPERMON



Source: Gantner Instruments

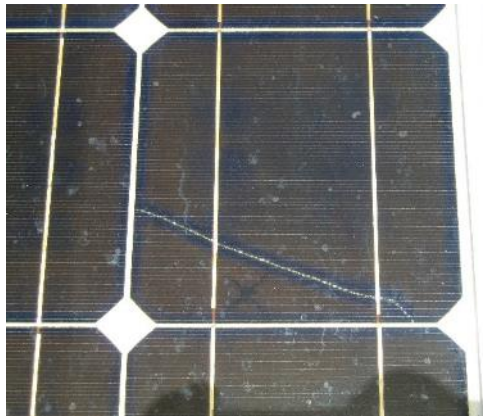
Partners: Gantner Isntruments and University of Cyprus
Project: IPERMON [Solar-ERA.net project]
Budget: €400,000
Duration: 36 Months
Weblink:
http://www.pvtechnology.ucy.ac.cy/projects/ipermon/

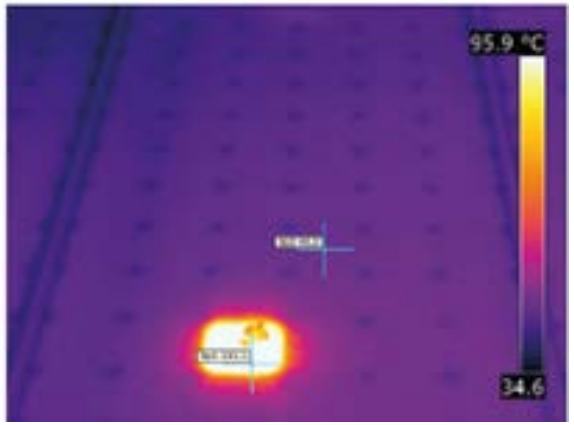
Development of innovative condition monitoring platform (algorithms and devices to quantify performance loss, diagnose faults and estimate degradation from acquired data).

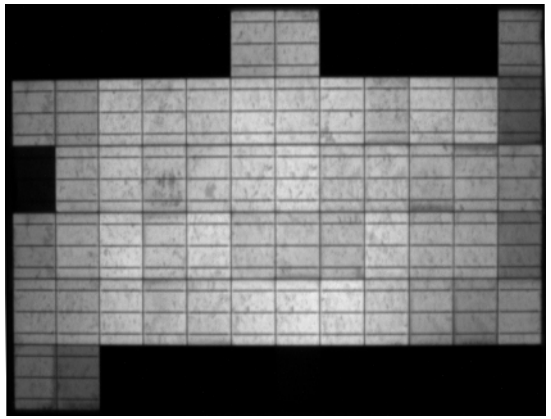


State-of-the-art

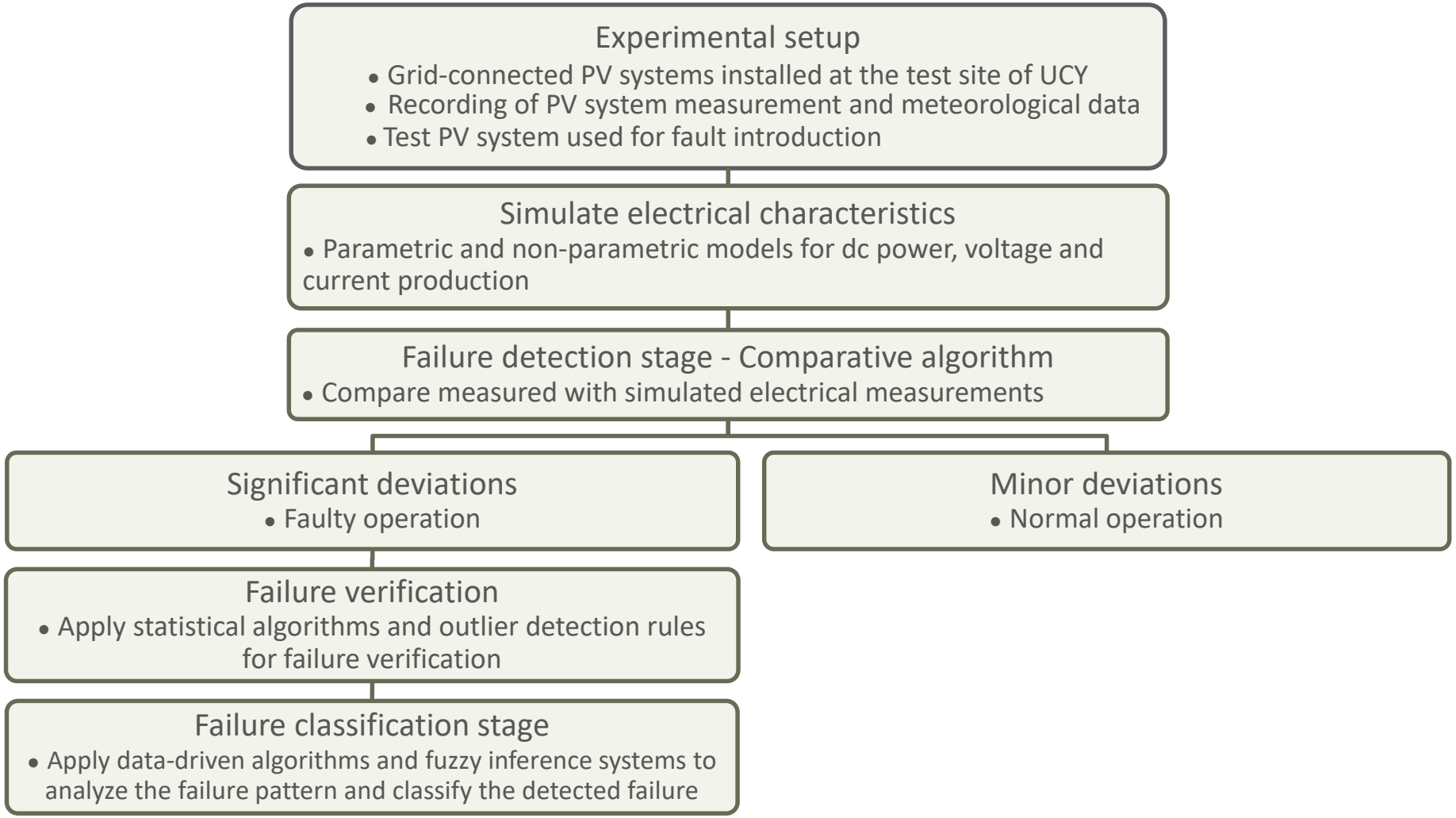
- Visual inspection is the simplest method to detect visible failures.
- The most popular technique for failure diagnosis is image analysis.
- Methods based on advanced data analysis of electrical parameters are becoming increasingly popular.





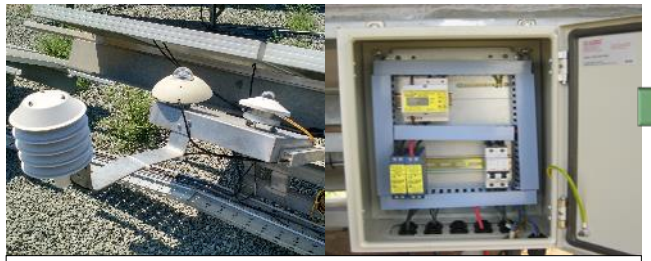


Advanced Failure Diagnosis - Approach



Experimental apparatus

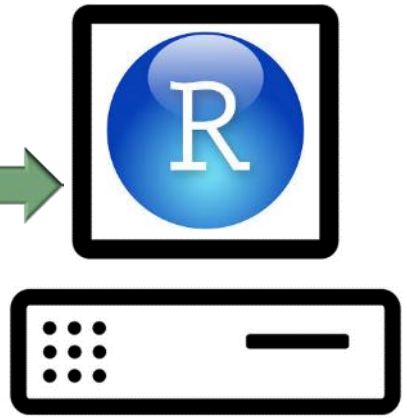
1.3 kWp poly-c Si system



Sensors for recording of operational and meteorological measurements

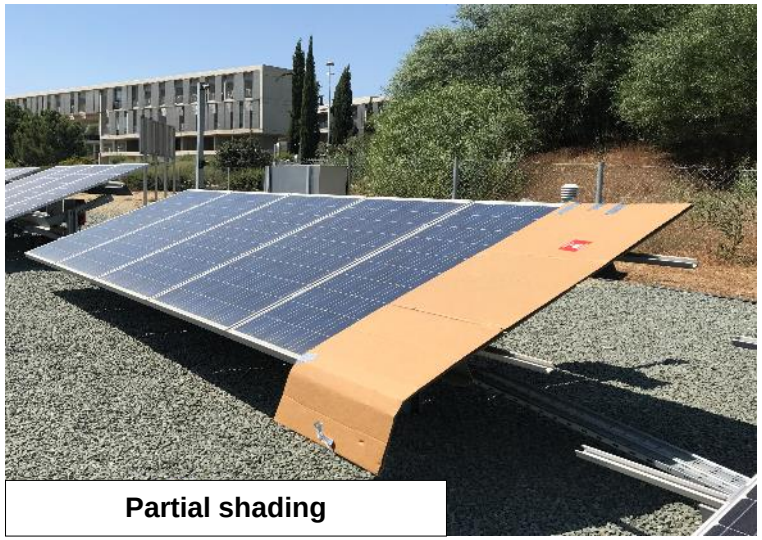
Data-acquisition platform

Measurements are stored in the database



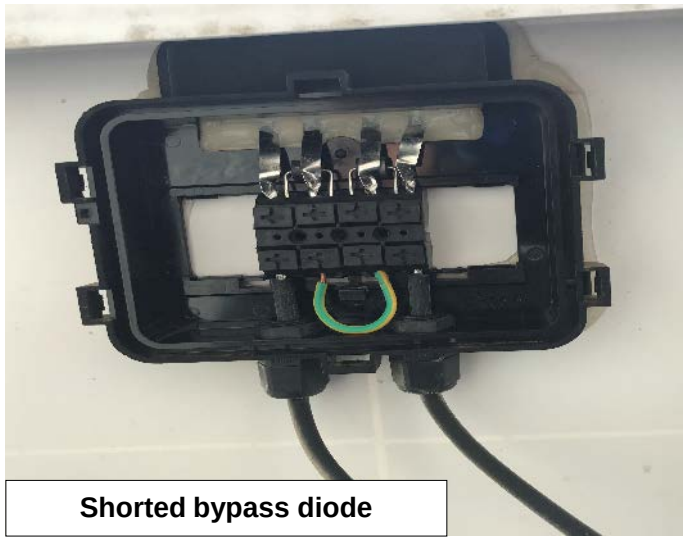
Control – Data analysis using R software program

Emulation of failures

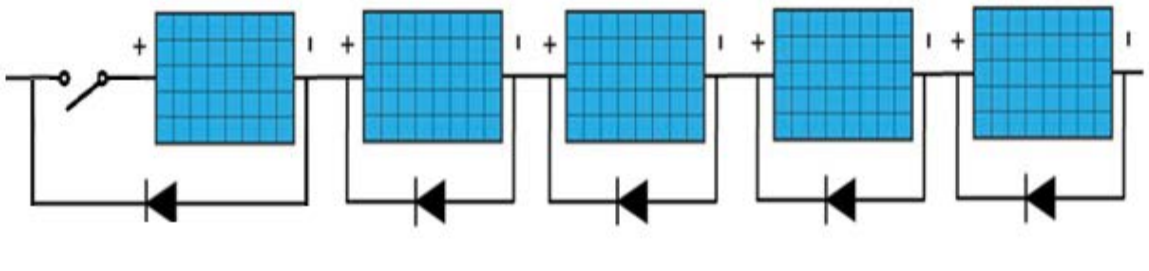


Partial shading

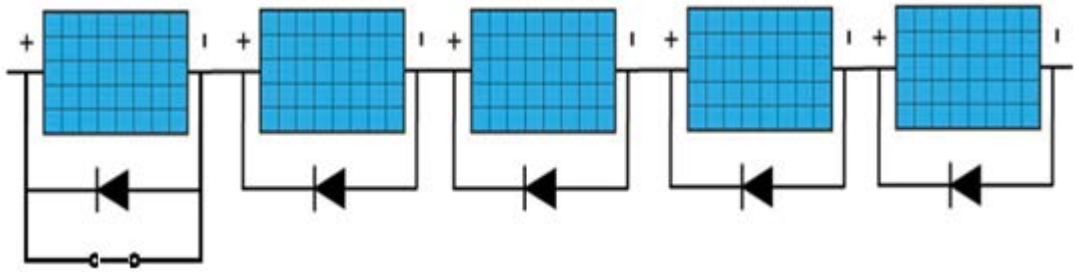
Inverter fault



Shorted bypass diode



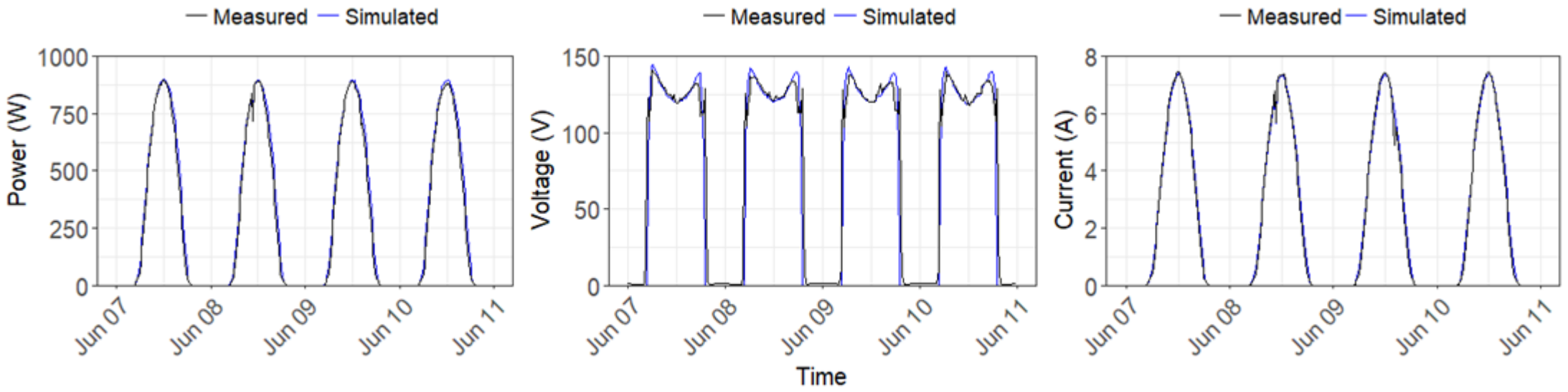
Open-circuited PV module



Short-circuited PV module

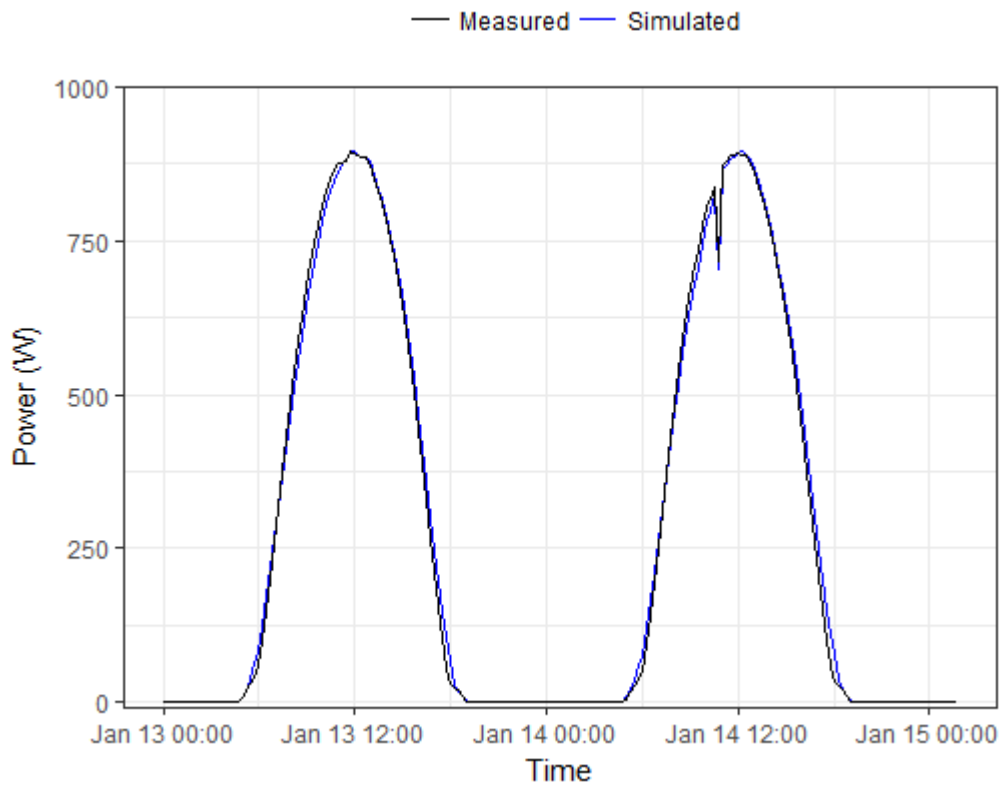
Simulation of electrical characteristics

- Parametric and non-parametric simulation models
  - Empirical models
  - Data-driven models (machine learning)

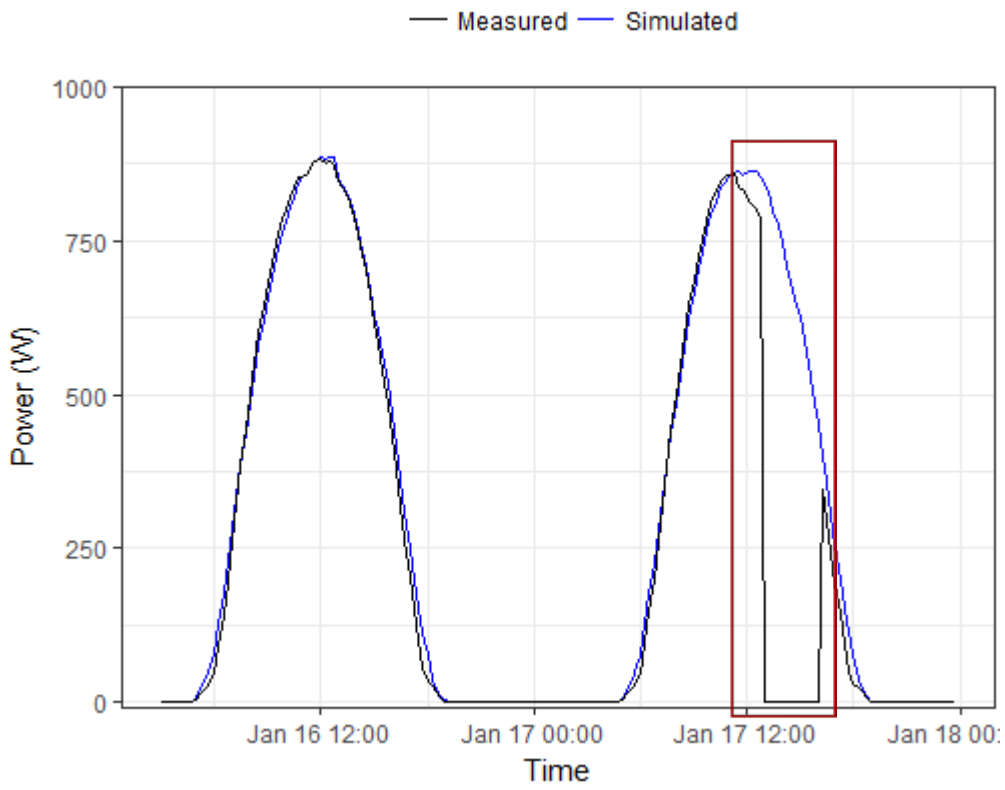


Failure detection stage - Comparative algorithm

Normal operation

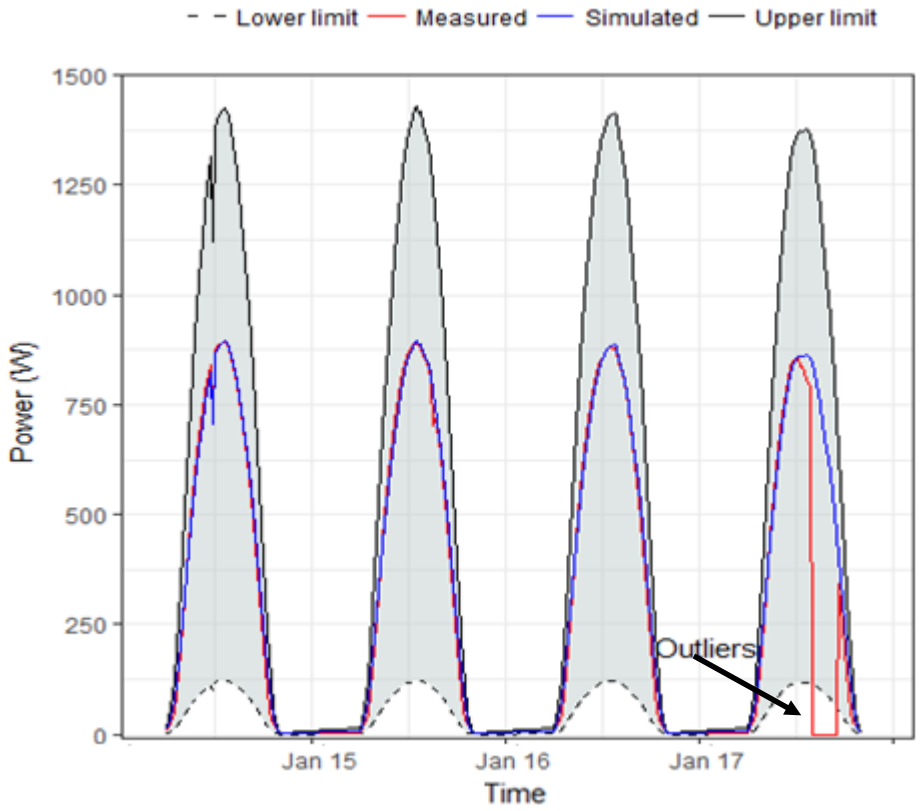


Faulty operation

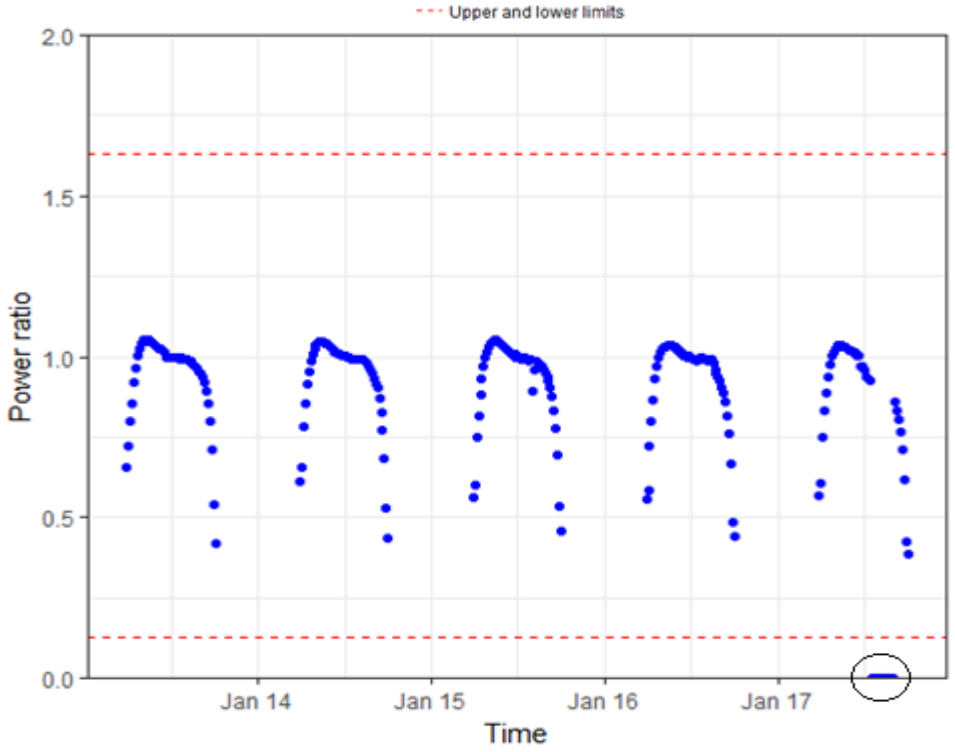


Failure detection stage - Failure verification

- 3σ method

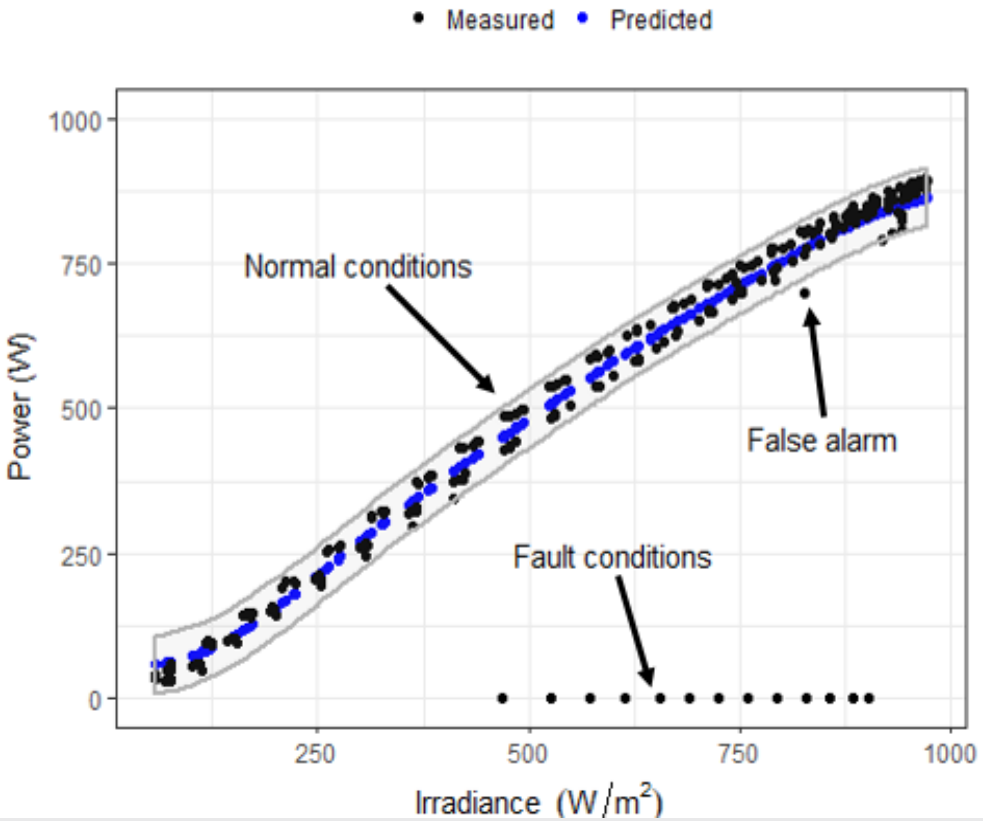


- 3σ control chart

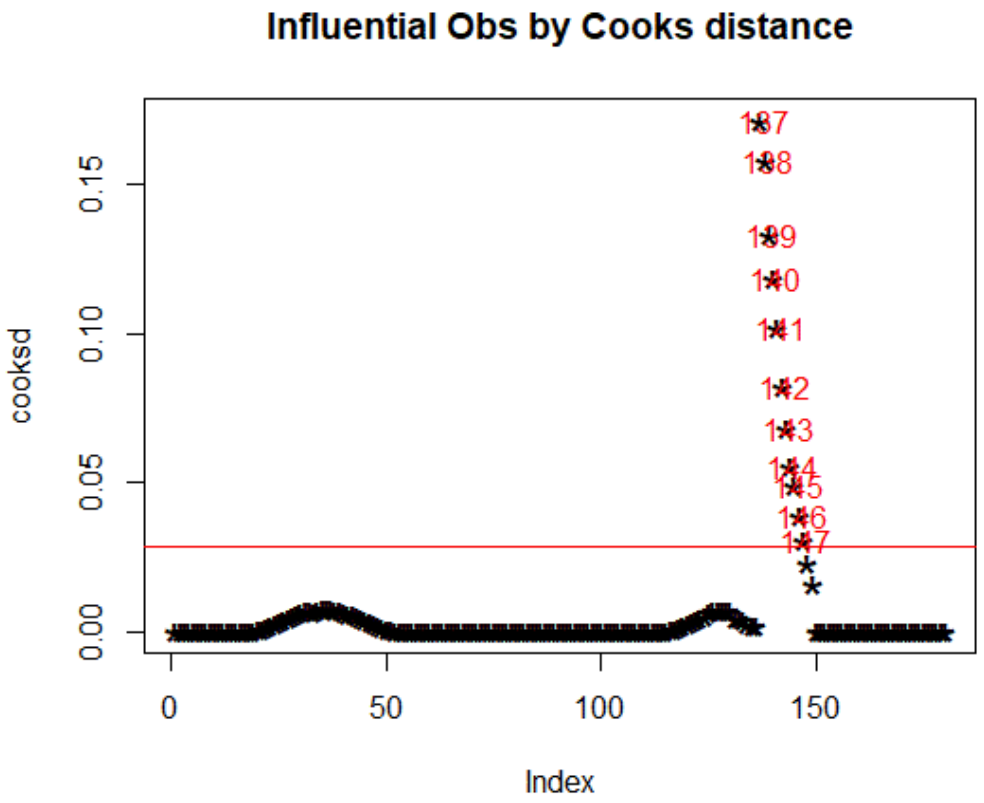


Failure detection stage - Failure verification

- Power-irradiance diagnostic plot

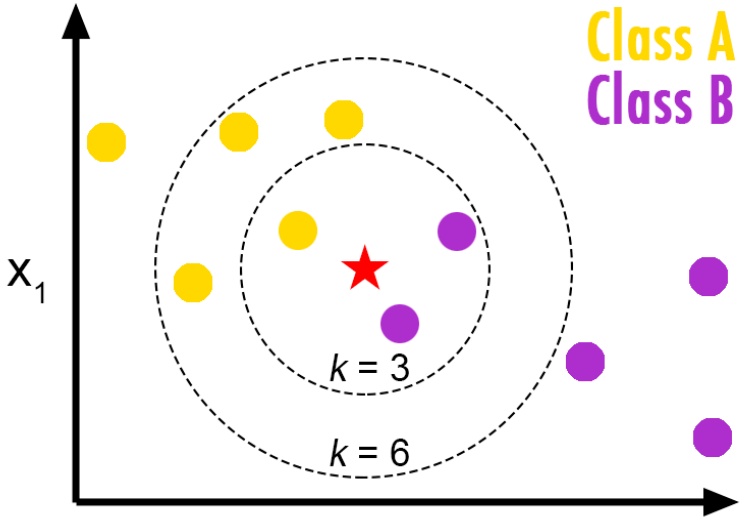


- Cook's Distance

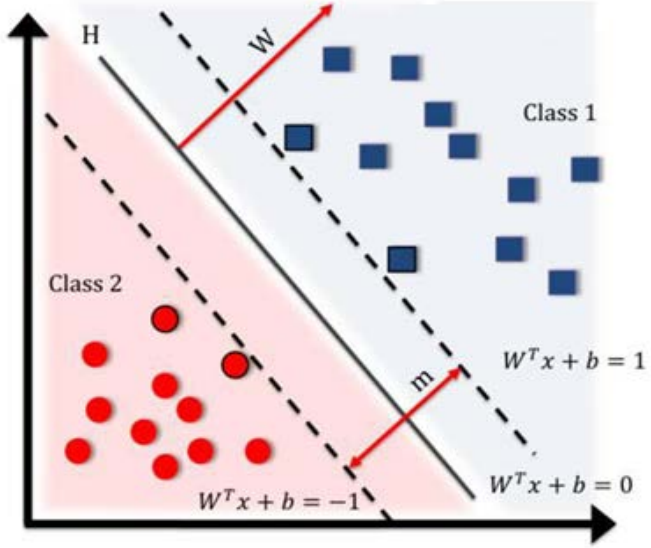


Failure classification stage – Supervised Learning

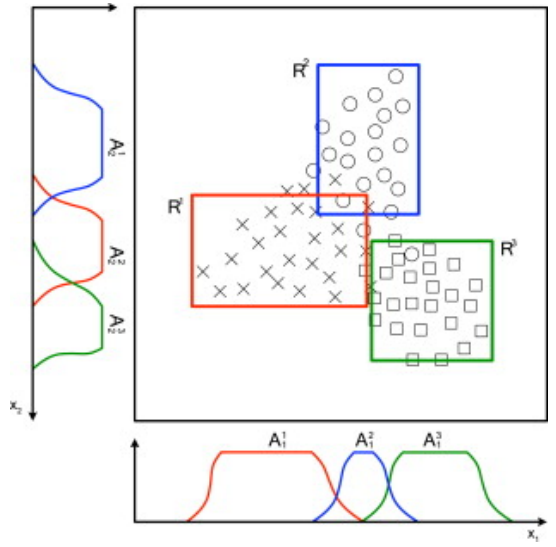
- Supervised learning processes (K-NN, SVM and FIS)
- Accuracy Metric – Binary confusion matrices



k-Nearest Neighbors (k-NN)



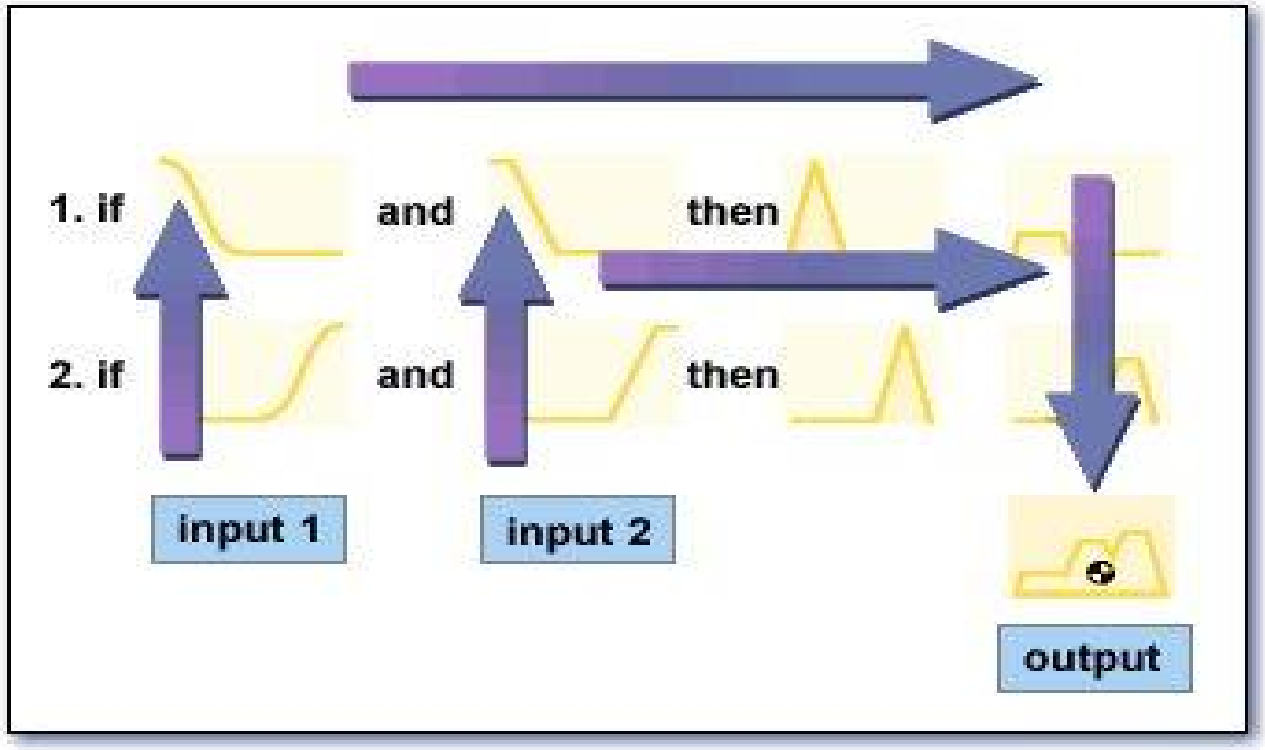
Support Vector machine (SVM)



Fuzzy inference Systems (FIS)

Failure classification stage – Unsupervised Learning

- Unsupervised learning process based on Fuzzy Logic Rules (FLR)

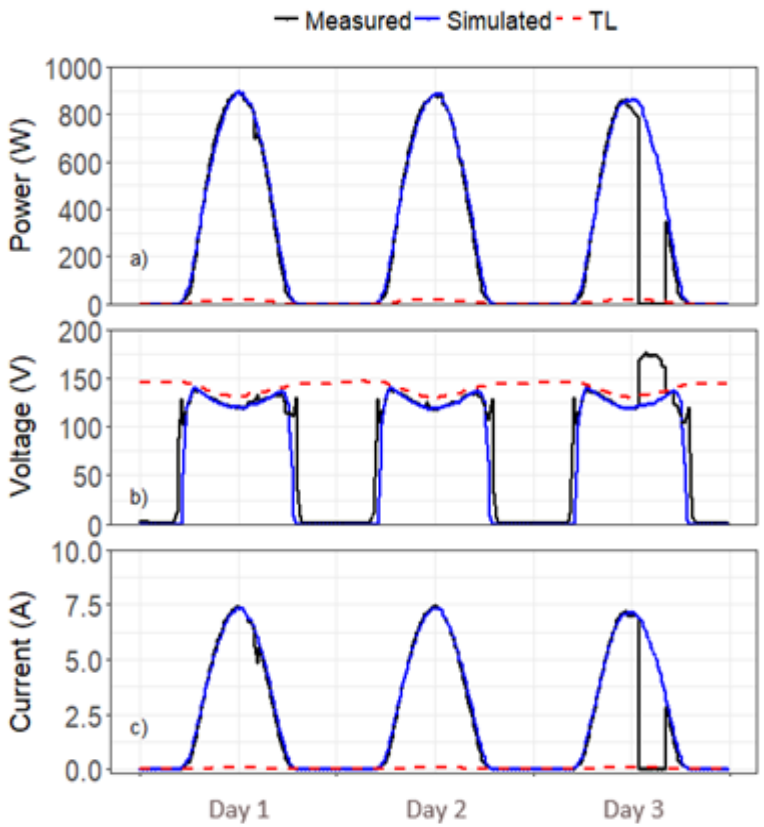


Results - Open-circuit fault

Fuzzy Logic Rules (unsupervised)

- $P_{DC\ measured} \leq TL = 2\% \cdot P_{DC\ simulated}$
- $V_{DC\ measured} \geq TL = V_{OC} \cdot (1 + \gamma(\mathrm{T}_m - 25))$
- $I_{DC\ measured} \leq TL = 1\% \cdot I_{DC\ simulated}$

Supervised models	Classification accuracy
k-NN	99.2%
SVM	100%
Fuzzy Logic	100%



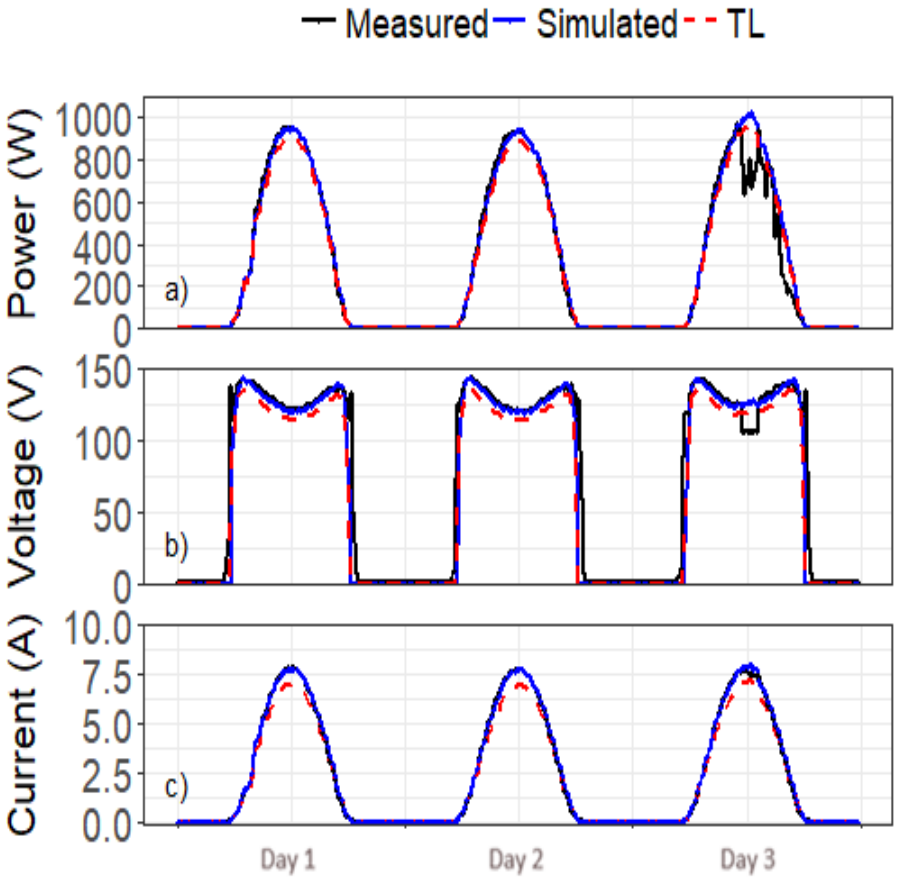
Results - Short-circuit fault

Fuzzy Logic Rules

- $P_{DC\ measured} \leq TL = P_{DC\ simulated} \cdot \left(1 - \frac{N_d}{N_t}\right)$
- $V_{DC\ measured} \leq TL = V_{DC\ simulated} \cdot (1 - \frac{N_d}{N_t})$
- $I_{DC\ measured} \geq TL = 90\% \cdot I_{DC\ simulated}$

where N_d is the number of shorted modules and N_t is the total number of the modules in the string

Supervised models	Classification accuracy
k-NN	99.2%
SVM	100%
Fuzzy Logic	100%

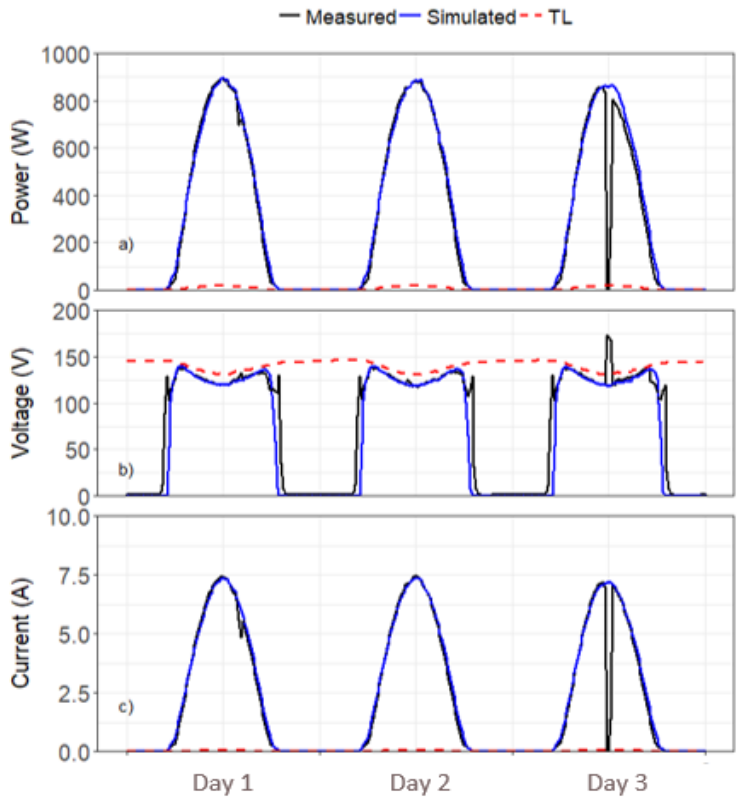


Results - Inverter failure

Fuzzy Logic Rules

- $P_{DC\ measured} \leq TL = 2\% \cdot P_{DC\ simulated}$
- $V_{DC\ measured} \geq TL = V_{OC} \cdot (1 + \gamma(\mathrm{T}_m - 25))$
- $I_{DC\ measured} \leq TL = 1\% \cdot I_{DC\ simulated}$

Supervised models	Classification accuracy
k-NN	98.5%
SVM	100%
Fuzzy Logic	100%



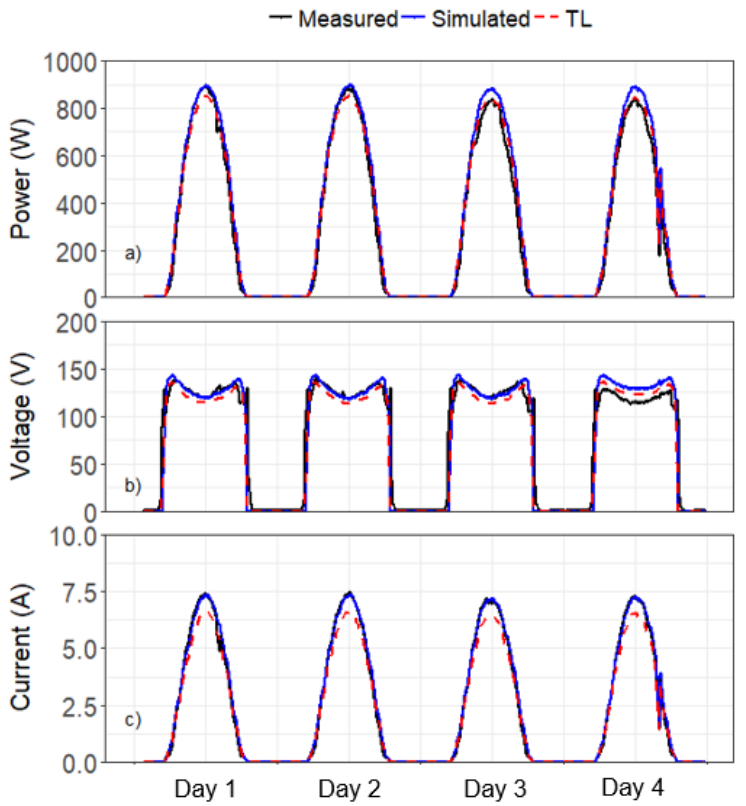
Results - Bypass diode failure

Fuzzy Logic Rules

- $P_{DC\ measured} \leq TL = P_{DC\ simulated} \cdot (1 - \frac{D_d}{D_t})$
- $V_{DC\ measured} \leq TL = V_{DC\ simulated} \cdot (1 - \frac{D_d}{D_t})$
- $I_{DC\ measured} \geq TL = 90\ \% \cdot I_{DC\ simulated}$

where D_d is the number of defective diodes and D_t is the total number of diodes in the string

Supervised models	Classification accuracy
k-NN	95.3%
SVM	96.15%
Fuzzy Logic	95.7%



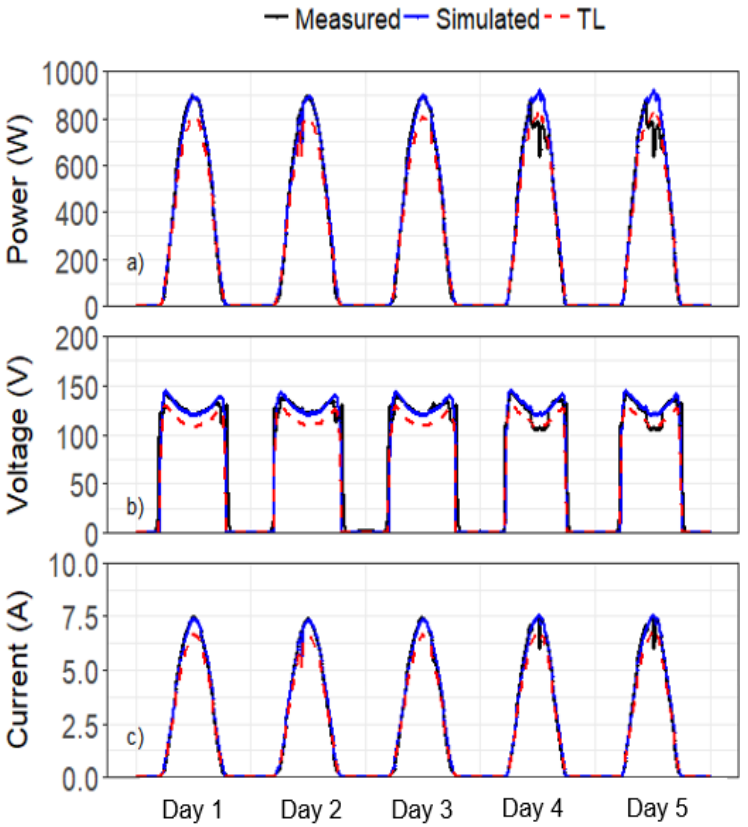
Results - Partial shading

Fuzzy Logic Rules

- $P_{DC\ measured} \leq TL = P_{DC\ simulated} \cdot (1 - \frac{C_d}{C_t})$
- $V_{DC\ measured} \geq TL = V_{DC\ simulated} \cdot (1 - \frac{C_d}{C_t})$
- $I_{DC\ measured} \geq TL = I_{DC\ simulated} \cdot (1 - \frac{C_d}{C_t})$

where C_d is the number of shaded cells and C_t is the total number of cells in the string

Supervised models	Classification accuracy
k-NN	94.7%
SVM	98.6%
Fuzzy Logic	97.8%



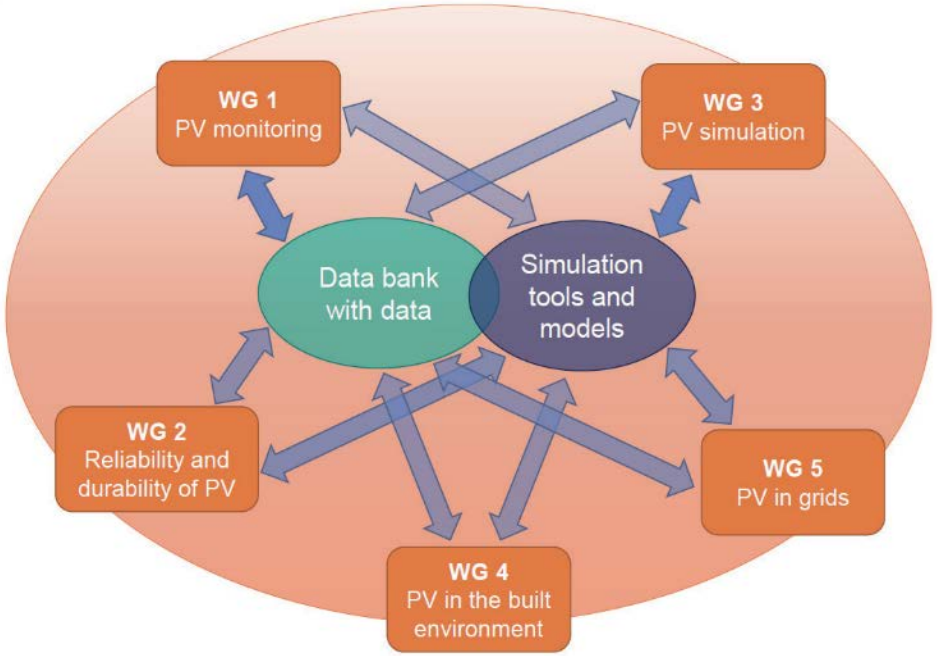
Results - Failure classification accuracy

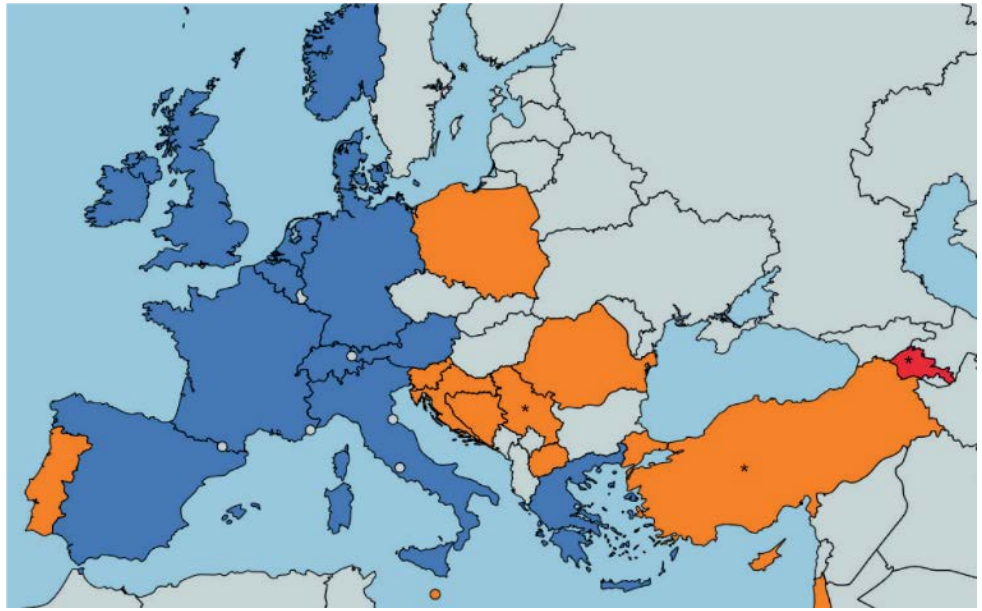
	Failures				
Supervised Models	**Open-circuit**	**Short-circuit**	**Partial shading**	**Inverter shutdown**	**Bypass diode**
k-NN	99.2%	98.4%	94.7%	98.5%	95.3%
SVM	**100%**	**100%**	**98.6%**	**100%**	**96.15%**
Fuzzy Logic	100%	99.2%	97.8%	100%	95.7%

Conclusions and Future work

- The developed failure detection stage was capable of detecting accurately the faults upon their occurrence.
- The classification models showed high accuracy of classifying each failure occurrence.
- Best performing classification algorithm in our investigation: SVM
- By integrating these algorithms on the monitoring systems, optimal level of operation of PV plants will be maintained thus reducing O&M costs and hence, LCOE.
- Future work will include the verification of the algorithms on large-scale PV plants, thus we are in search for relevant data.

EU COST Action PEARL-PV: Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data





SAVE THE DATES!!! Seminar of Working Group 1 and Training School (PV Performance Monitoring and Modeling) from the 22nd - 26th October in Nicosia, Cyprus hosted by the PV Technology Laboratory of the University of Cyprus.

More info available on https://www.pearlpv-cost.eu/ and also the poster session of the **2018 PV Systems Symposium**!

Thank you for your attention

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