Operational research for urban solar development

“PV failure detection based on operational time series”

09/12/2024
Alexandre Mathieu

UNIVERSITÉ SAVOIE MONT BLANC

Curriculum
Plan

Day	Time	Duration	Content
Wednesday 13/11/2024	11h15-12h45 14h15-15h45	1h30 + 1h30	50% Lecture / 50 % Hands-on
Tuesday 26/11/2024	9h45-13h00	1h30 + 1h30	25% Lecture / 75 % Hands-on
Monday 02/12/2024	13h15-16h15	3h	15% Lecture / 85 % Hands-on
Monday 09/12/2024	8h-11h 13h15-16h15	6h	10% Lecture / 90 % Hands-on/Project
Tuesday 10/12/2024	8h-11h	3h	10% Lecture / 90 % Project
Monday 16/12/2024	8-11h	3h	10% Lecture / 90 % Project
Thursday 19/12/2024	9h45-12h45	3h	10% Lecture / 90 % Project
Monday 06/01/2025	13h15-14h45	1h30	100% Project
Monday 13/01/2025	9h45-11h45	1h30	100% Project
Total		**27h**	

Agenda

Review notebook last week

PV performance model steps

Agenda

Review notebook last week

PV performance model steps

Review first notebook

Notebook recap 02/12/2024

Google collab link: https://colab.research.google.com/drive/1ncPYAOFvJvU_Tc5goPQL9F9wLNUh1FzQ?usp=sharing

Correction: https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy/blob/master/notebooks/ac_power_estimation.ipynb

Modeling steps

Notebook recap 02/02/2024

Python commands

```
import matplotlib.pyplot as plt

!pip install pvlib # In google collab, download the pvlib package

# Make a figure with one axis
fig, ax = plt.subplots(1, 1, figsize=(9,6))
df.plot(ax=ax) # Plot df (pd.Series or pd.DataFrame) on the axis "ax"

# Make a figure with two axes (two figures top/bottom) which share the same x axis
fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(9,6), sharex=True)

# Force values to be between 0 and 1 (any value lower than 0 will be changed to 0 and any value higher than 1 will be adjusted down to 1)
# "eta" must be a pd.Series or pd.DataFrame to apply the ".clip()" method
eta  = eta.clip(lower=0, upper=1)

# Select all df  values between two dates: 10/06/2020 & 15/06/2020 in this case
# The index must be "DateTime" index
df.loc["20200610":"20200615"]
```

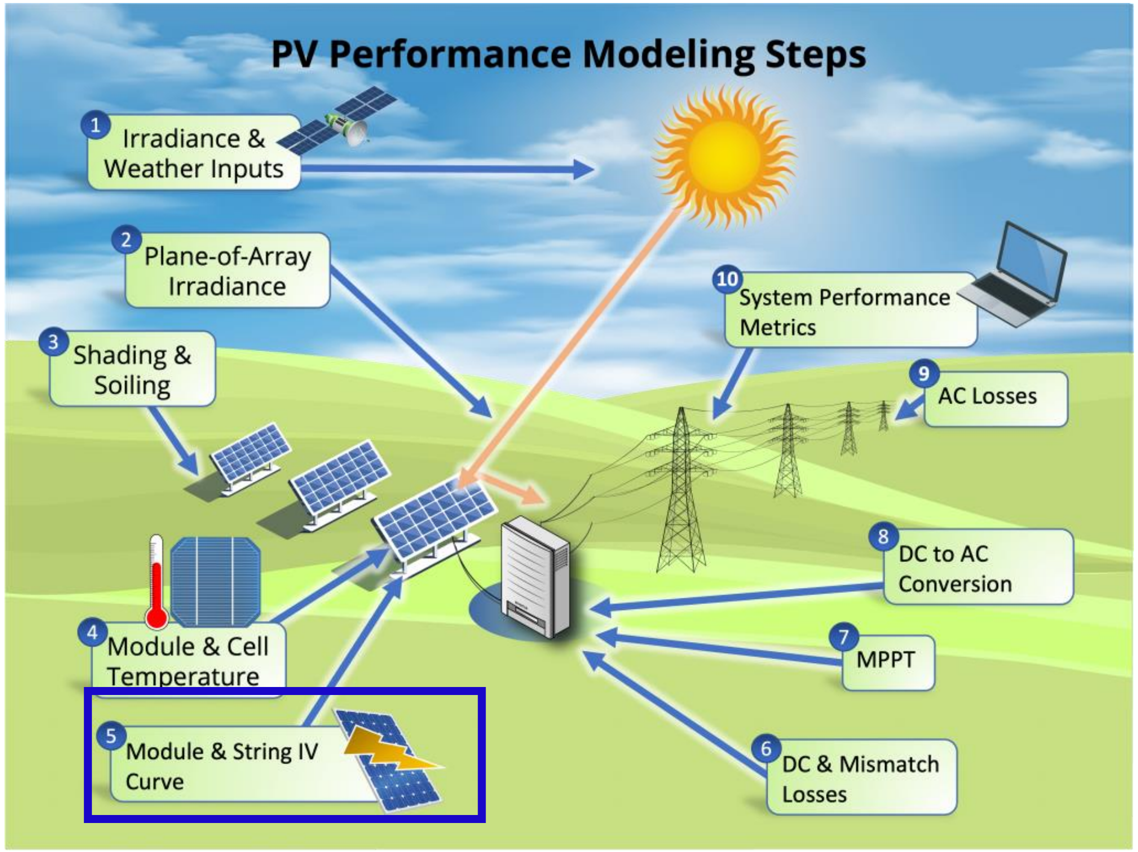
Agenda

Review notebook last week

PV performance model steps

Modeling steps

5. Module and String IV Curve



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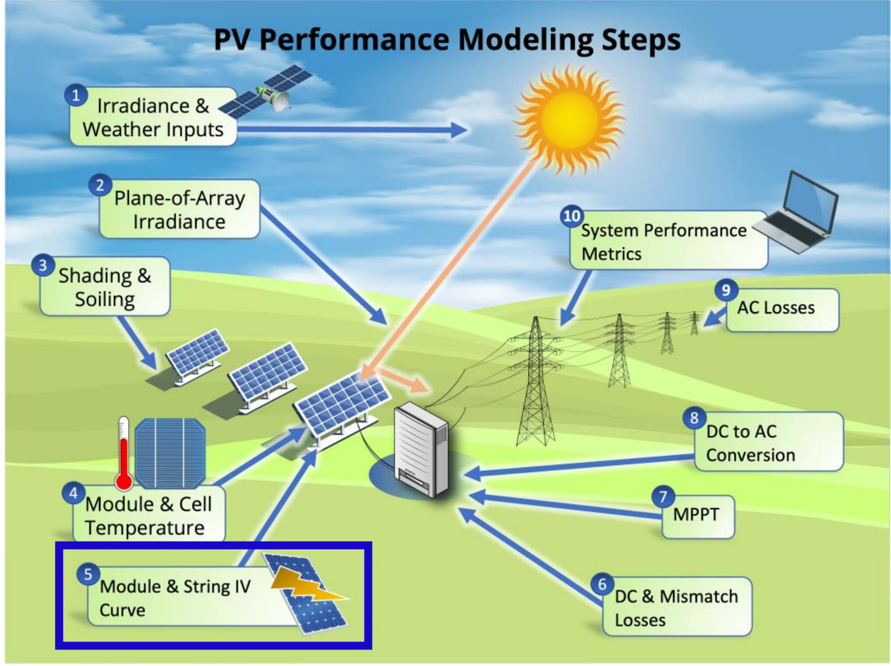
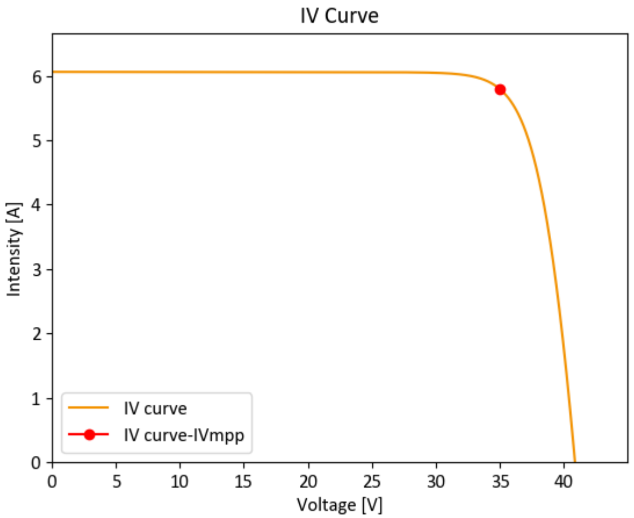
Modeling steps



5. Module and String IV Curve

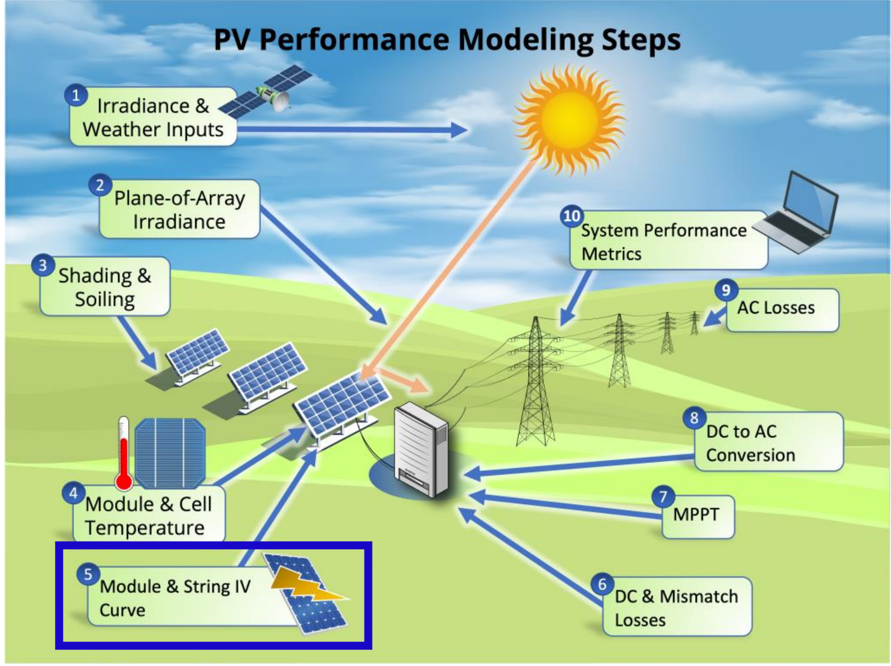
For a fixed irradiance and module temperature, the PV module has its I, current which depends on V, voltage and it can take many operating points.



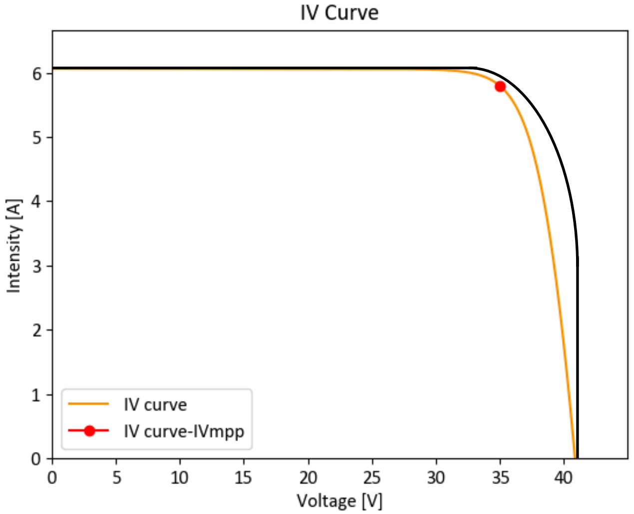
Modeling steps

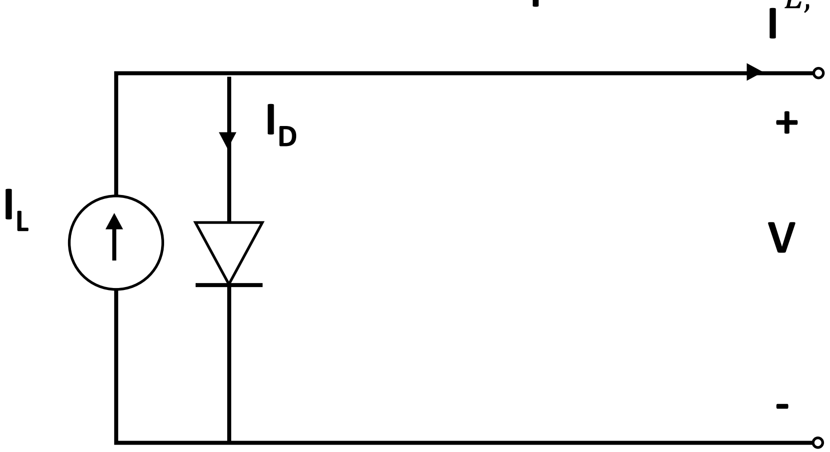
5. Module and String IV Curve

Equivalent-circuit model



Model 1 diode – 3 parameters $I_{L,}I_0, a$

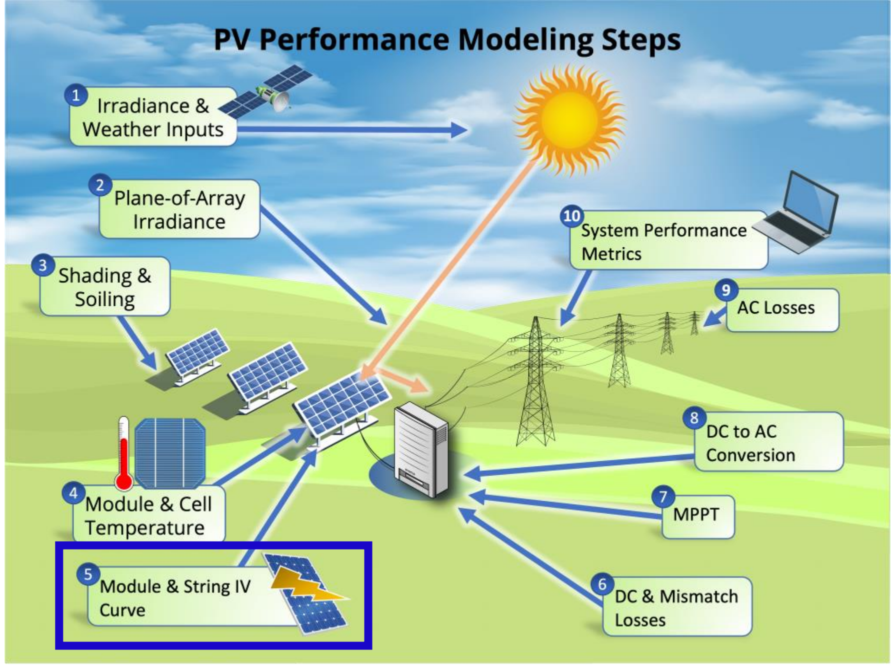




In parallel of the photocurrent I_L that is generated according to the irradiance, the model:

- Assumes that the PV module acts as a diode

$$I = I_L - I_0 \cdot \left(exp\left(\frac{V}{a}\right) - 1 \right)$$

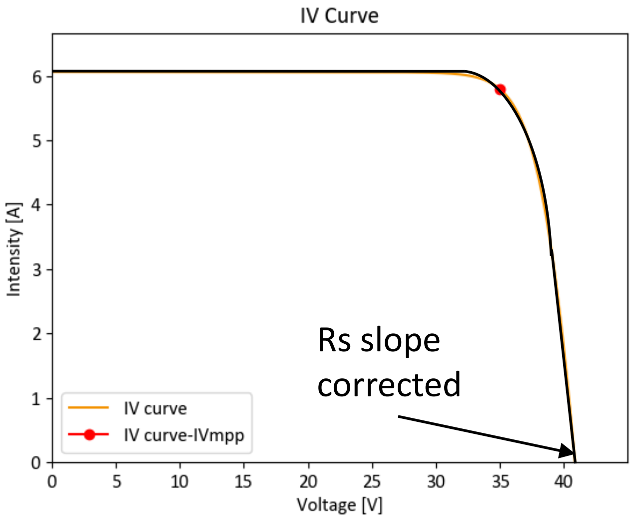


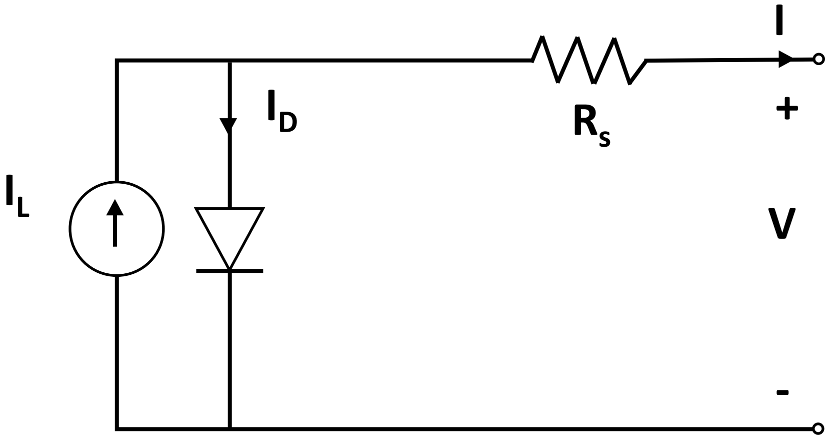
Modeling steps

5. Module and String IV Curve

Equivalent-circuit model

Model 1 diode – 4 parameters $I_{L,} I_0, a, R_s$





In parallel of the photocurrent I_L that is generated according to the irradiance, the model:

- Assumes that the PV module acts as a diode
- Estimates the conduction losses

$$I = I_L - I_0 \cdot \left(exp\left(\frac{V + I \cdot R_S}{a}\right) - 1 \right) + I \cdot R_S$$

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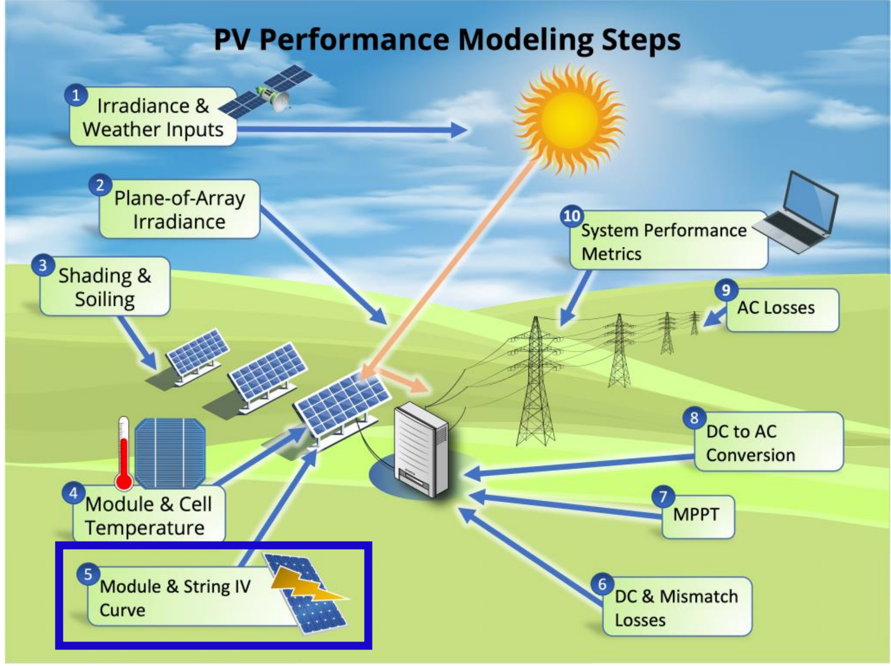
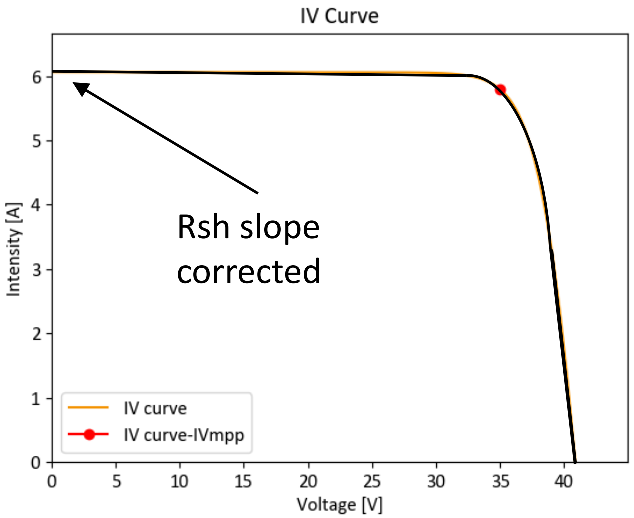


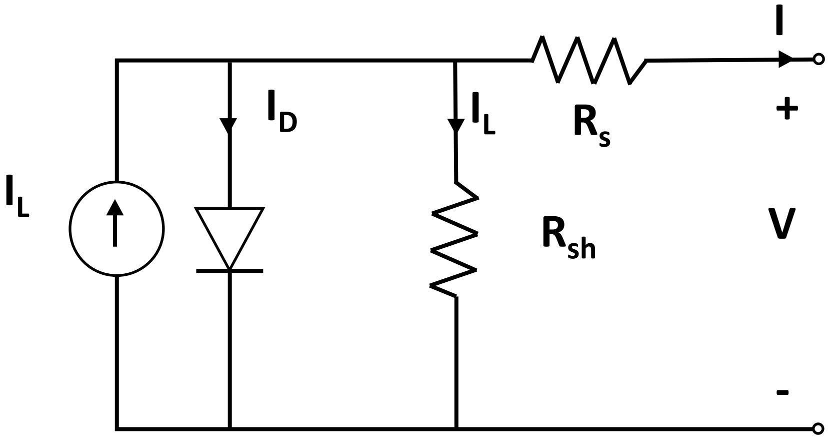
Modeling steps

5. Module and String IV Curve

Equivalent-circuit model

Model 1 diode – 5 parameters $I_{L,}I_0, a, R_S, R_{sh}$



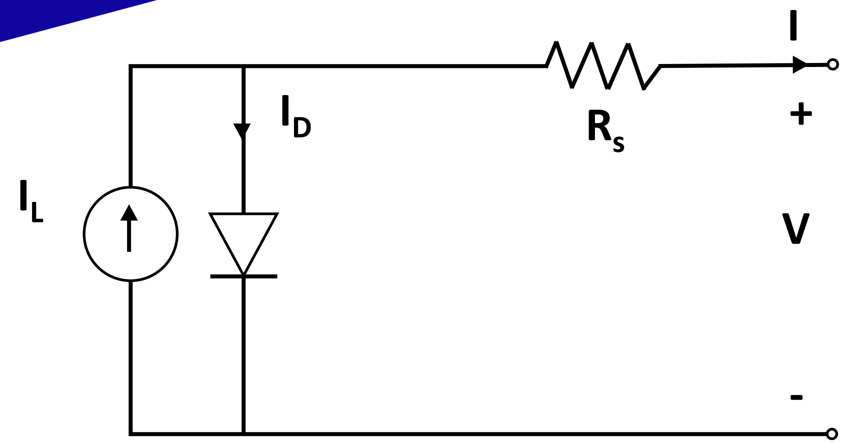


In parallel of the photocurrent I_L that is generated according to the irradiance, the model:

- Assumes that the PV module acts as a diode
- Estimates the conduction losses
- Estimates the leakage current (going through the module frame or others)

$$I = I_L - I_0 \cdot \left(exp\left(\frac{V + I \cdot R_S}{a}\right) - 1\right) + \frac{V + I \cdot R_S}{R_{sh}}$$

W. De Soto, S.A. Klein, W.A. Beckman, Improvement and validation of a model for photovoltaic array performance, Solar Energy, Volume 80, Issue 1, 2006



$$I = I_L - I_0 \cdot \left(exp\left(\frac{V+I\cdot R_S}{a}\right) - 1\right) + \frac{V+I\cdot R_S}{R_{sh}}$$

Modeling steps

5. Module and String IV Curve

Les 5 parameters $I_{L,STC}, I_{0,STC}, R_{s,STC}, a_{STC}, R_{sh,STC}$ are the 5-parameters at conditions STC ($G_{STC} = 1000\frac{W}{m^2}$ et $T_{STC} = 25\ °C$).

Then, the parameters at environmental conditions (G: POA irradiance, T_c: Cell temperature) vary according to the following relationships
<u>It expects temperatures in Kelvin !</u>

i. The photocurrent [A] $I_L = \frac{G}{G_{STC}} \cdot (I_{L,STC} + \alpha_{sc} \cdot (T_c - T_{STC}))$

ii. The reverse saturation current [A] $I_0 = I_{0,STC} \cdot \left(\frac{T_c}{T_{STC}}\right)^3 \exp(-\frac{1}{k}(\frac{E_g(T_c)}{T_c} - \frac{E_g(T_{STC})}{T_{STC}}))$

k, Boltzmann constant: 8,617x 10^{-5} [eV/K]

iii. The series resistance [Ω] $R_s = R_{s,STC}$

iv. The product of the diode ideality factor, number of cells and cell thermal voltage [V]: $a(T) = \frac{T_c}{T_{STC}}\ a_{STC}$

v. The shunt resistance [Ω] $R_{sh} = \boxed{R_{sh,STC} \cdot \frac{G_{STC}}{G}}$ Corrected on the 10/12/2024

vi. The silicon energy band in [eV] $E_g(T_c) = 1{,}121 \cdot (1 - 0.000267\ (T_c - T_{STC}))$

W. De Soto, S.A. Klein, W.A. Beckman, Improvement and validation of a model for photovoltaic array performance, Solar Energy, Volume 80, Issue 1, 2006

Modeling steps

5. Module and String IV Curve

Les 5 parameters I_L , I_0 , R_s, a, R_{sh} enable to formulate for any environmental conditions the following equation.

$$I = I_L - I_0 \cdot \left(exp\left(\frac{V + I \cdot R_s}{a}\right) - 1 \right) + \frac{V + I \cdot R_s}{R_{sh}}$$

W. De Soto, S.A. Klein, W.A. Beckman, Improvement and validation of a model for photovoltaic array performance, Solar Energy, Volume 80, Issue 1, 2006

Modeling steps

5. Module and String IV Curve

Les 5 parameters I_L , I_0 , R_s, a, R_{sh} enable to formulate:

$$I = I_L - I_0 \cdot \left(exp\left(\frac{V + I \cdot R_s}{a}\right) - 1 \right) + \frac{V + I \cdot R_s}{R_{sh}}$$

But… the equation resolution is not that direct:

$$I = \frac{I_L + I_0 - \frac{V}{R_{sh}}}{1 + \frac{R_s}{R_{sh}}} - \frac{a}{R_s} W(z)$$

W is the lambert function

With z

$$z = \frac{R_s I_0}{a\,(1 + \frac{R_s}{R_{sh}})} \exp\left(\frac{R_s \cdot (I_L + I_0) + V}{a\left(1 + \frac{R_s}{R_{sh}}\right)}\right)$$

W. De Soto, S.A. Klein, W.A. Beckman, Improvement and validation of a model for photovoltaic array performance, Solar Energy, Volume 80, Issue 1, 2006

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Modeling steps

5. Module and String IV Curve

Les 5 parameters $I_L\,, I_0\,, R_s, a, R_{sh}$ enable to formulate:

$$I \;=\; I_L - \; I_0 \cdot \left(exp\left(\frac{V + I \cdot R_s}{a}\right) - \;1\;\right) + \frac{V + I \cdot \; R_s}{R_{sh}}$$

But… the equation resolution is not that direct:

$$I = \frac{I_L + \; I_0 - \dfrac{V}{R_{sh}}}{1 \; + \dfrac{R_s}{R_{sh}}} - \frac{a}{R_s}\, W(z)$$

W is the lambert function

With z

$$z \; = \frac{R_s\, I_0}{a\;(1 \; + \dfrac{R_s}{R_{sh}})}\; \exp\left(\frac{R_s \cdot (\,I_L \; + \; I_0) + \; V}{a\left(1 \; + \dfrac{R_s}{R_{sh}}\right)}\right)$$

Fortunately, https://pvlib-python.readthedocs.io/en/v0.11.1/reference/generated/pvlib.pvsystem.v_from_i.html#pvlib.pvsystem.v_from_i

pvlib.pvsystem.v_from_i

```
pvlib.pvsystem.v_from_i(current, photocurrent, saturation_current,
resistance_series, resistance_shunt, nNsVth, method='lambertw')
```
[source]

Device voltage at the given device current for the single diode model.

Uses the single diode model (SDM) as described in, e.g., Jain and Kapoor 2004 [1]. The solution is per Eq 3 of [1] except when resistance_shunt=numpy.inf, in which case the explict solution for voltage is used. Ideal device parameters are specified by resistance_shunt=np.inf and resistance_series=0. Inputs to this function can include scalars and pandas.Series, but it is the caller's responsibility to ensure that the arguments are all float64 and within the proper ranges.

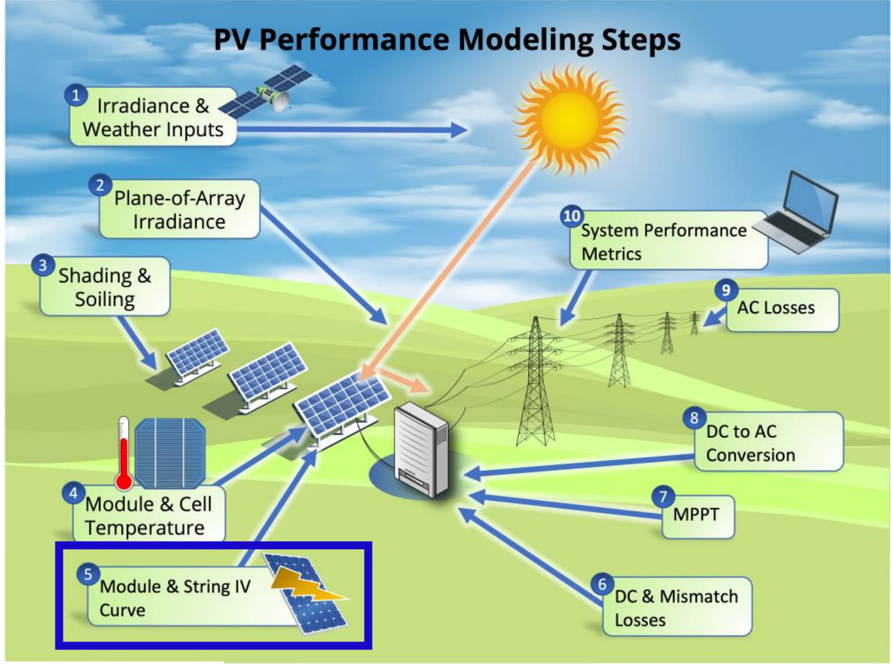
Changed in version 0.10.0: The function's arguments have been reordered.

Parameters:

- **current** (*numeric*) – The current in amperes under desired IV curve conditions.
- **photocurrent** (*numeric*) – Light-generated current (photocurrent) in amperes under desired IV curve conditions. Often abbreviated `I_L`. 0 <= photocurrent
- **saturation_current** (*numeric*) – Diode saturation current in amperes under desired IV curve conditions. Often abbreviated `I_0`. 0 < saturation_current
- **resistance_series** (*numeric*) – Series resistance in ohms under desired IV curve conditions. Often abbreviated `Rs`. 0 <= resistance_series < numpy.inf

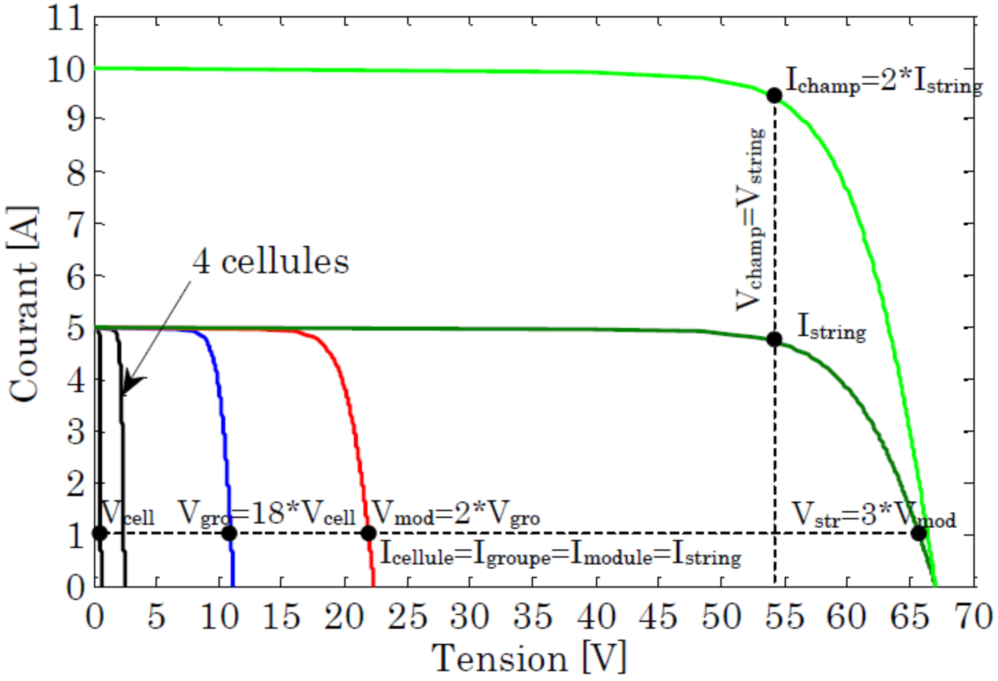
W. De Soto, S.A. Klein, W.A. Beckman, Improvement and validation of a model for photovoltaic array performance, Solar Energy, Volume 80, Issue 1, 2006

Modeling steps



5. Module and String IV Curve / Reminder

By the way… the IV curves can be summed up when the modules are connected in series or parallel! The inverter, then, maximizes the power of the PV array IV curve.



Bun, L.. "Détection et localisation de défauts pour un système PV." (2011).

In series, the voltages are added up

In parallel, the currents are added up

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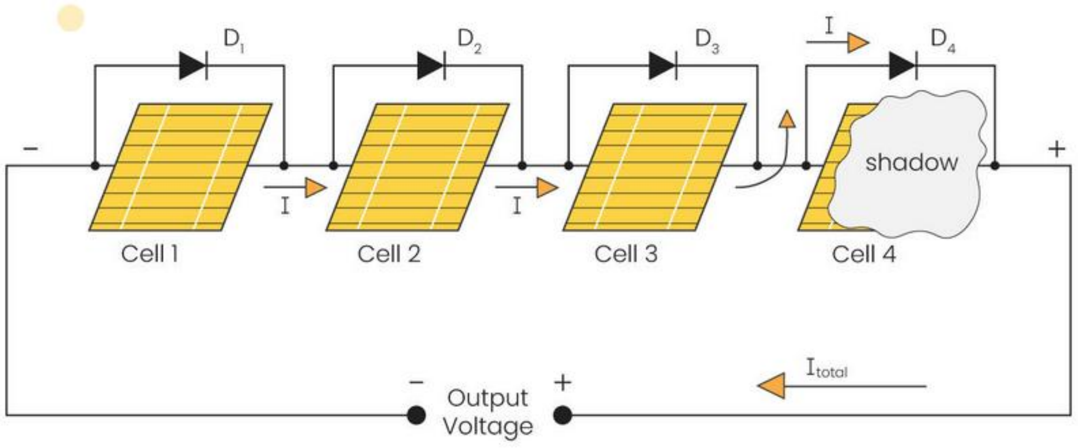
Modeling steps

5. Module and String IV Curve

<u>Bypass diodes</u>

Bypass diodes in PV modules are used to handle important mismatch cases such as shading, cell crack, uneven soiling, etc... to prevent significant losses at the module level and high reverse voltages which would induce hotspots at the cell level.

Those are typically Schottky diodes which are commonly 3 (between 2 and 5) per PV module, each in parallel of a group of around 20 cells.



Bypass diode protection

Reference Image: https://pvcase.com

Modeling steps

5. Module and String IV Curve

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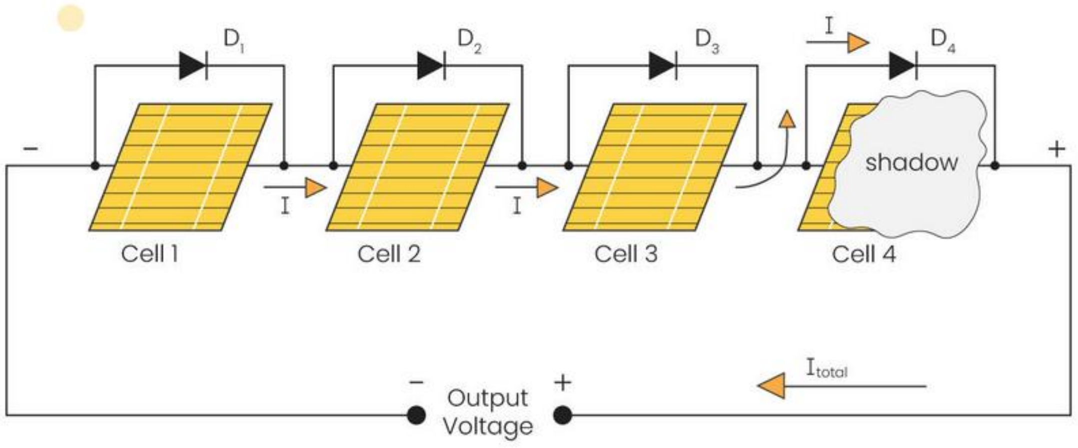
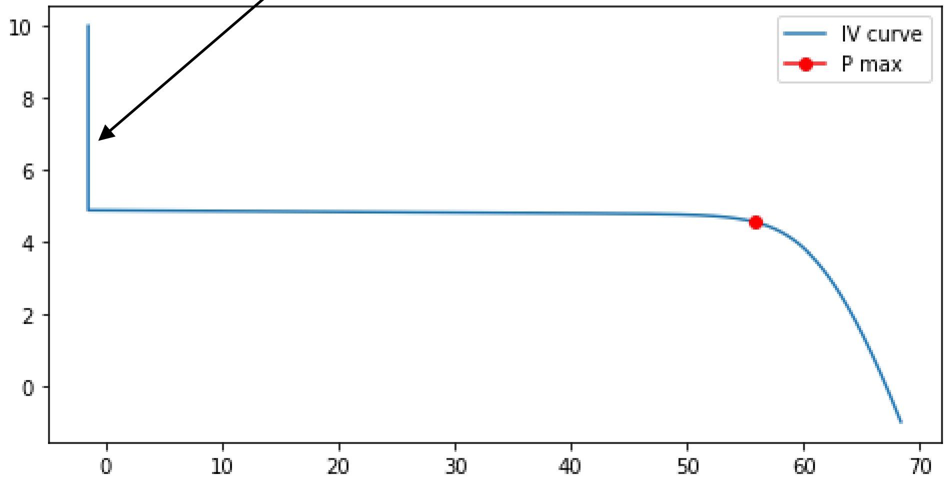


Bypass diode protection

<u>(Ideal) Diode effect:</u>
Around -1.5 V
Limit negative voltages



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How can Machine Learning Tools enable better estimation and failure detection ?

Methods like **Polynomial Regression**, **Decision Trees**, and **KNN** deliver high accuracy when applied to sensible training datasets.

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PVWatts Model

Perfect use case for **Regression** techniques to optimize P_{dc0} and γ_{pdc} to minimize model errors.

$$P_{dc} = P_{dc0} \cdot \frac{G_{POA}}{1000\ W/m^2} \cdot \left(1 + \gamma_{pdc} \cdot (T_{cell} - 25°C)\right)$$

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PVWatts Model

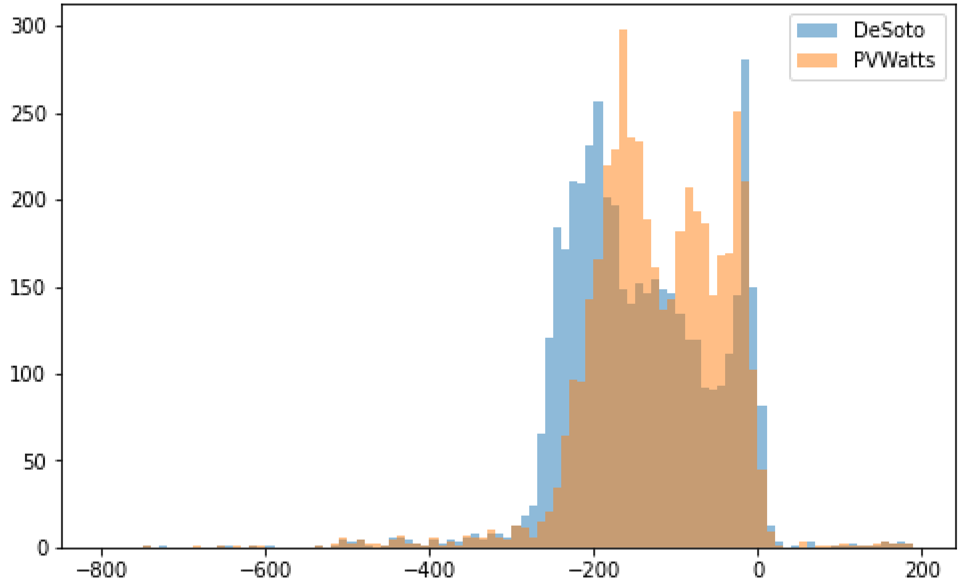
Perfect use case for **Regression** techniques to optimize P_{dc0} and γ_{pdc} to minimize model errors.

Importance of Residual Analysis:

Always analyze residuals (**actual – model**) values to:

- Identify biases using **histograms** or **scatter plots**.
- Understand model limitations.
- Add **post-processing layers** for error correction.

Residual histogram



- Residual mainly contained between -500 W and 0W
- Constant biais
- Two/Three local peaks

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Methods like **Polynomial Regression**, **Decision Trees**, and **KNN** deliver high accuracy when applied to sensible training datasets.

PVWatts Model

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Error Metrics :

Mean Error

$$ME = \frac{1}{n}\sum_{i}^{n} O_i - P_i$$

Mean Absolute Error

$$MAE = \frac{1}{n}\sum_{i}^{n} | O_i - P_i |$$

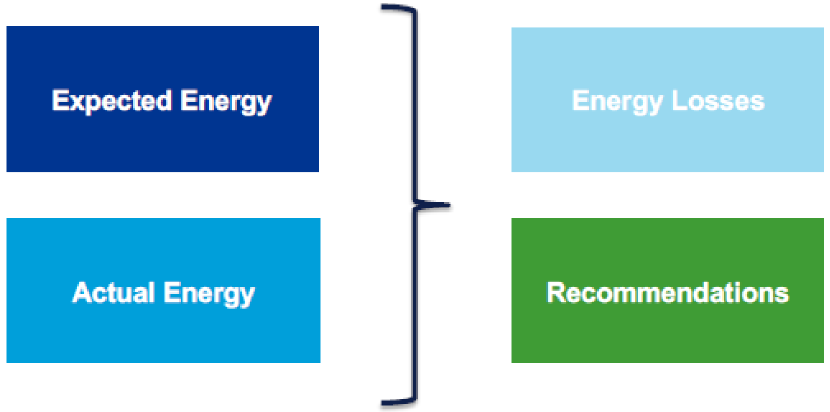
- O_i Observed value at instance i.
- P_i: Predicted value at instance i.
- n: Total number of observations.

Failure detection: Few insights

Failure detection: Few insights

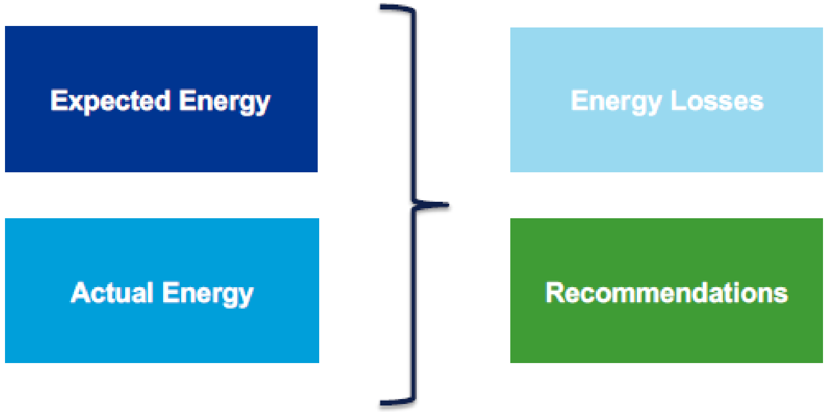
Threshold-Based Approach:

- Sets predefined performance thresholds.
- Failure Identification: Flags deviations when performance metrics (e.g., voltage, current) exceed the thresholds



Reference image: DNV

Failure detection: Few insights



Reference image: DNV

Threshold-Based Approach:

- Sets predefined performance thresholds.
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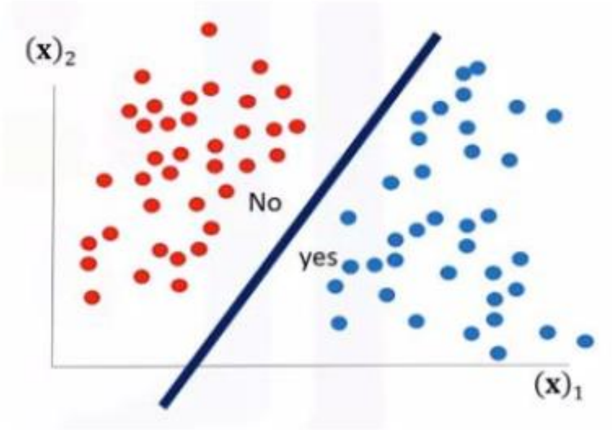
Unsupervised Learning:

Detects anomalies by clustering or analyzing patterns without labeled data.

Common Techniques:

- K-Means Clustering
- Principal Component Analysis (PCA)



Reference image: The Use of Advanced Algorithms in PV Failure Monitoring 2021, IEA Report

Time for some hands-on exercises !

Modeling steps

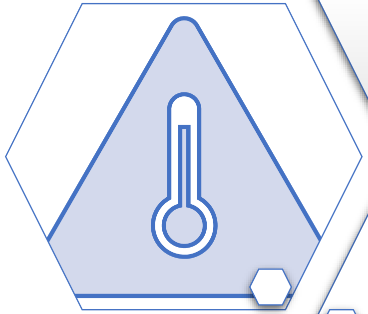
Implement the 1-diode parameter model, improve the accuracy of DC power models and detect underperformances
https://colab.research.google.com/drive/1nADZ1DH7rbXfohQS8HPEDMRc8VrOuh-1?usp=sharing

Agenda

PV « expected » losses

Wooclap survey

PV « expected » losses



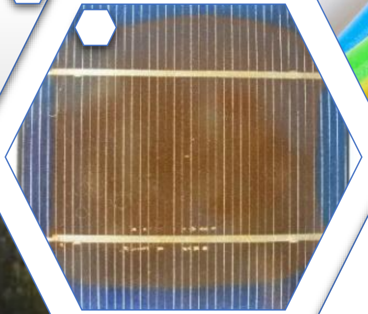
Non-optimal array production extraction (example: mismatch)

Module temperature losses

Non-optimal irradiance collection (light, reflection, known shading)

Natural system ageing

Joule losses in the cables



Inverter losses

Bun, L., 2011. Détection et localisation de défauts dans un système photovoltaïque (Theses). Université de Grenoble.

Agenda

PV Failure

PV failure definition

Inspired from the IEA definition*, a failure occurs when**:

$$P_m(t) + \Delta P_m(t) < P_{expected}(t) - \Delta P_{expected}(t)$$

$P_m(t)$ the system power measured according to IEC 60904
$\Delta P_m(t)$ the total uncertainty of the measurement
$P_{expected}(t)$ the expected system power
$\Delta P_{expected}(t)$ the expected system power tolerance

In other words, a failure is an underperformance which is not planned at the design phase.

*M. Köntges et al., "Review of Failures of Photovoltaic Modules," IEA PVPS T13, IEA-PVPS T13-01:2014, 2014.
***A. Mathieu, G. Fraisse, M. Thebault, S. Thebault, S. Boddaert, and L. Gaillard, 'Failure Risk Analysis of Photovoltaic Systems Based on Literature Review', presented at the Eurosun 2022, Kassel, Germany, Sep. 2022.

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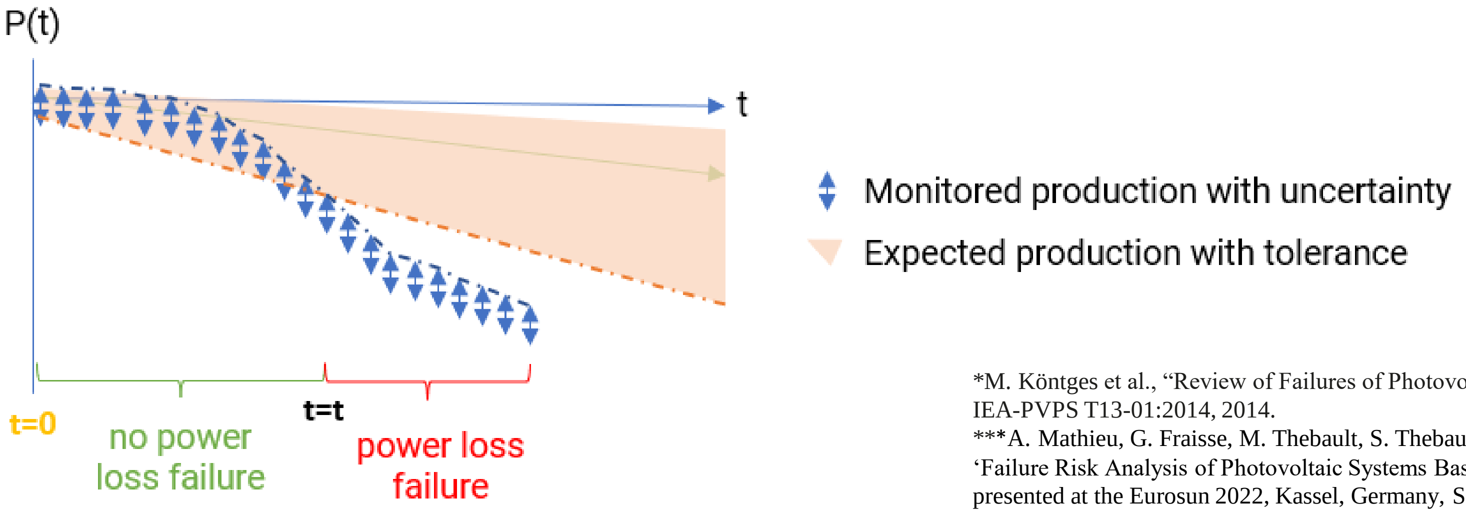

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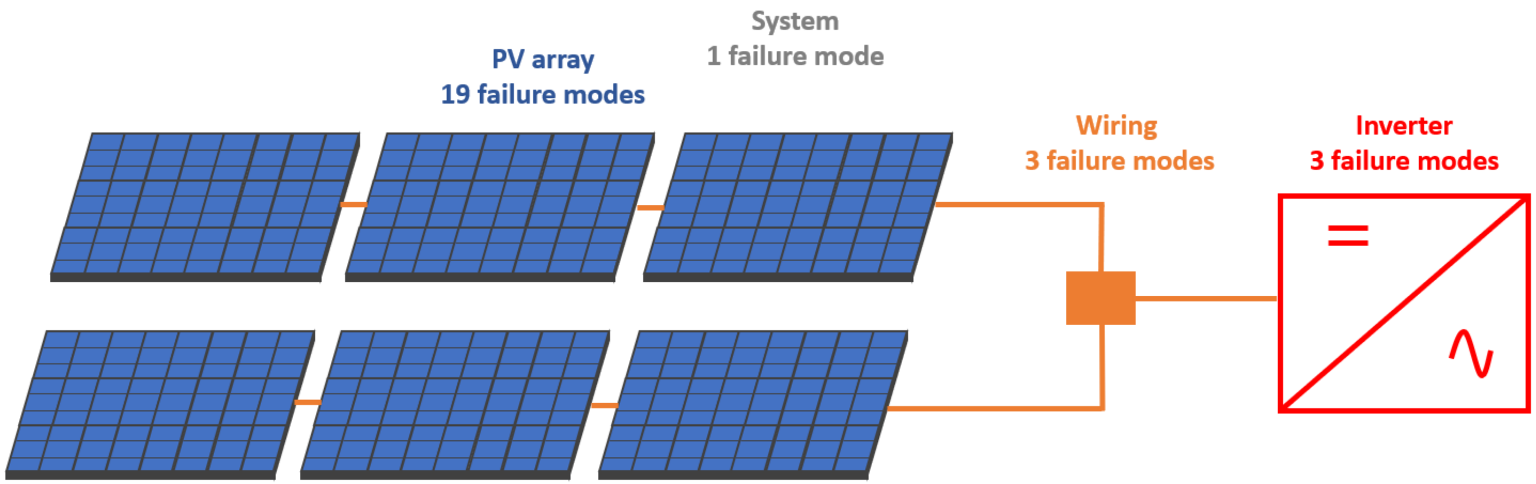
Failures

One list of failures…

Total: **26**



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Failures

One list of failures…

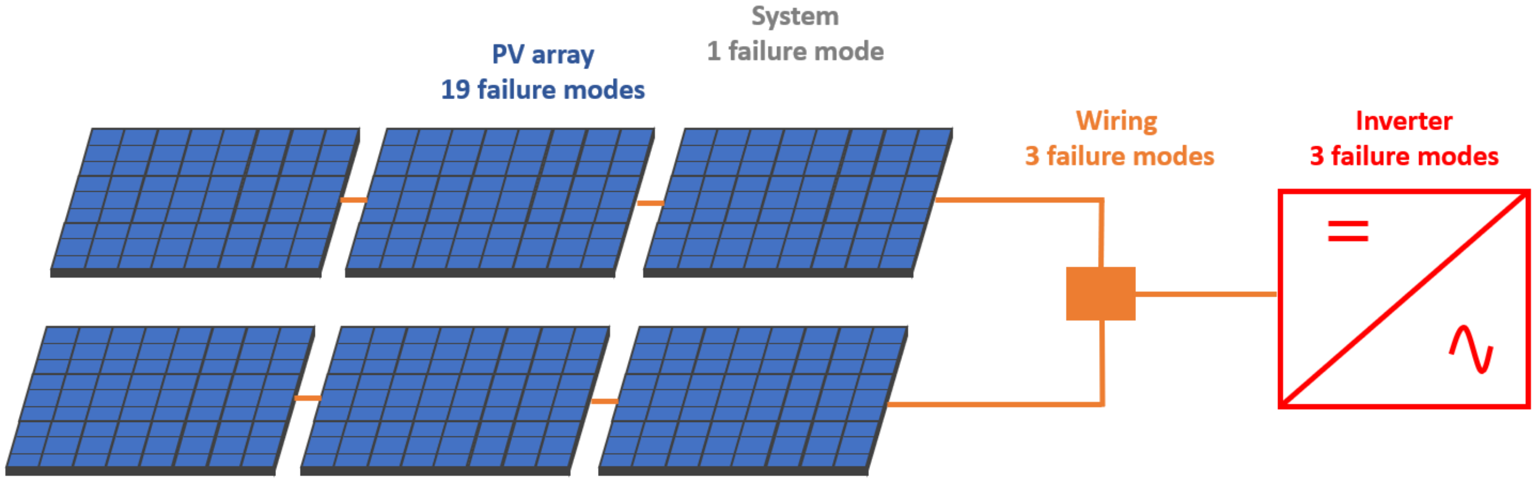
Total: **26**

System
Insulation failure and ground connection defect

Inverter
Inverter defect
Inverter overheating
Unexpected inverter derating

Wiring
Combiner box defect
Connector defect
DC cable defect

Module/Array
Backsheet degradation
Burn marks
Bypass diode defect
Cell cracks
Cell interconnection defect
Corrosion
Delamination
Encapsulant degradation
Frame/Mounting structure defect
Glass breakage
Hot spot
Junction box defect
Light Induced Degradation (LID) and Light and elevated Temperature Induced Degradation (LETID)
Module under-ventilation
Not conform power rating
Potential Induced Degradation (PID)
Shading
Soiling



*A. Mathieu, G. Fraisse, M. Thebault, S. Thebault, S. Boddaert, and L. Gaillard, 'Failure Risk Analysis of Photovoltaic Systems Based on Literature Review', presented at the Eurosun 2022, Kassel, Germany, Sep. 2022.

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Failures

One list of failure…

System
Insulation failure and ground connection defect

Inverter
Inverter defect
Inverter overheating
Unexpected inverter derating

Wiring
Combiner box defect
Connector defect
DC cable defect

Module/Array
Backsheet degradation
Burn marks
Bypass diode defect
Cell cracks
Cell interconnection defect
Corrosion
Delamination
Encapsulant degradation
Frame/Mounting structure defect
Glass breakage
Hot spot
Junction box defect
Light Induced Degradation (LID) and Light and elevated Temperature Induced Degradation (LETID)
Module under-ventilation
Not conform power rating
Potential Induced Degradation (PID)
Shading
Soiling

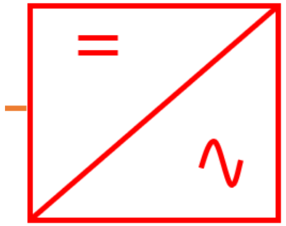
The 12 most critical according to *

*A. Mathieu, G. Fraisse, M. Thebault, S. Thebault, S. Boddaert, and L. Gaillard, 'Failure Risk Analysis of Photovoltaic Systems Based on Literature Review', presented at the Eurosun 2022, Kassel, Germany, Sep. 2022.

Agenda

Common PV Failures

Inverter
3 failure modes



Inverter defect

The inverter is often responsible for most of the maintenance events. Several failures can occur over the inverter lifespan due to unexpected events or aging mechanisms.

The most common failures in the inverter due to aging come from components such as the relays, the capacitors, the semiconductor modules (IGBT and diodes), cooling fan, and the printed circuit board.

Software issues or a lack of restart after an event can also shut down the inverter and can be solved by rebooting the software or updating the firmware.

K. Sinclair, M. Sinclair, "Silicon solar module visual inspection guide: Catalogue of Defects to be used as a Screening Tool

Detection Hints:
- Abrupt performance drop from a specific date.
- Complete shutdown: Produces 0 W.

Inverter clipping

« Inverter clipping » occurs when the generated DC power exceeds the inverter limit.

Then, the inverter caps the generated DC power by moving the operating point to reduce the DC production and fit within the inverter input limits.

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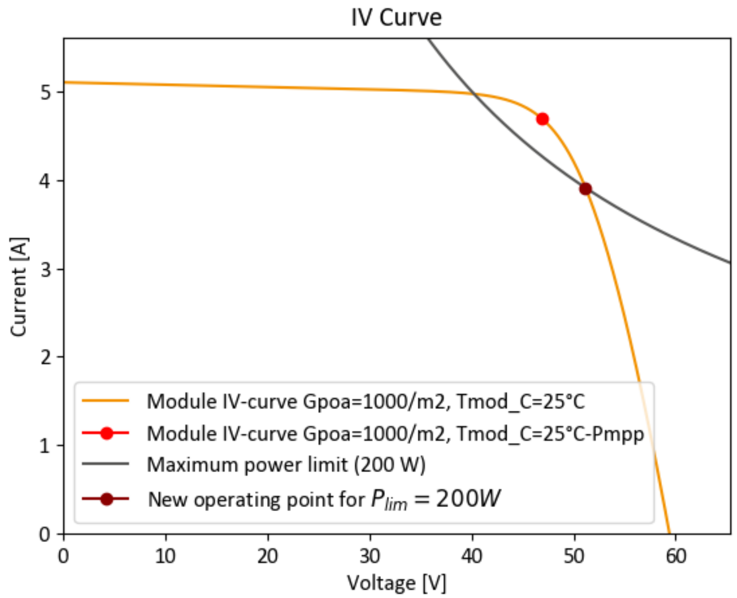

Example where the inverter increases the tension to reduce the DC power.

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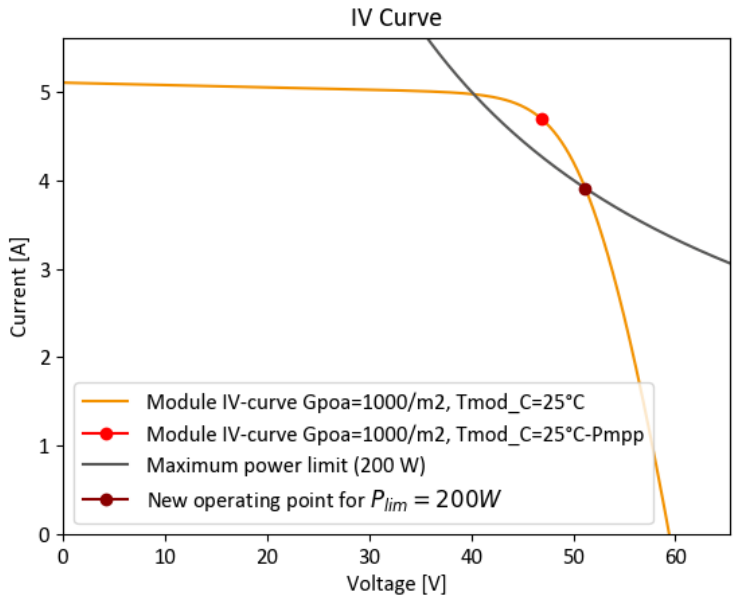

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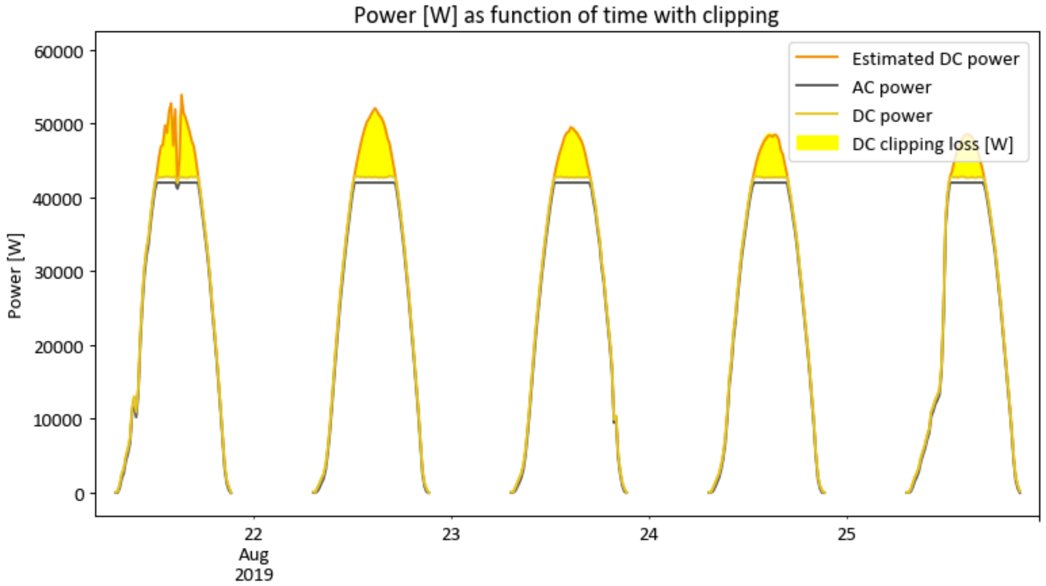
Signature



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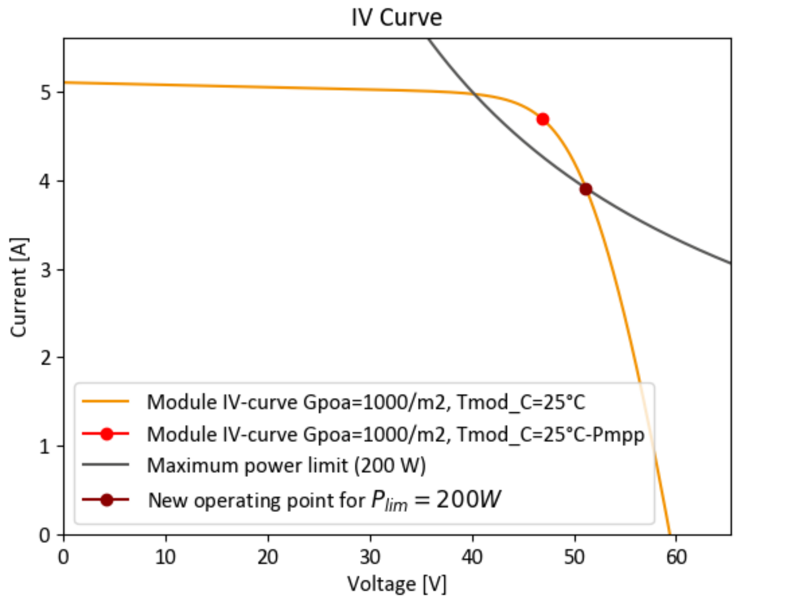

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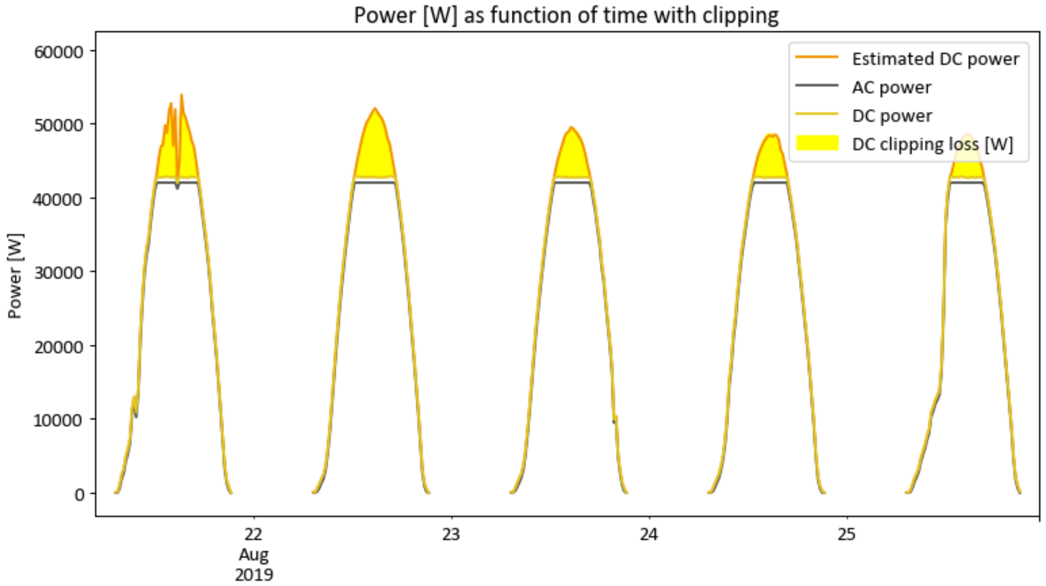

Detection Hints:

- Clipping threshold is generally fixed.
- Occurs at high sunny conditions.
- Power Slope = 0 W/m2/h.
- Slight increase of voltage compared to standard operation.
- Current loss.

Cable/Connector defect: Open-circuited string

Images. M. Köntges et al. , Review of Failures of Photovoltaic Modules, Report IEA-PVPS T13-01: ISBN 978-3-906042-16-9, 2014.

Wiring defect might lead to fire.

DC cable failure can occur due to various reasons at different phases.

- At the design phase, cables which are incorrectly dimensioned may result in overheating and early cable degradation.
- During the installation, pinching or pulled cables can also lead to early defects.
- During the exploitation, DC cables might also deteriorate faster or might corrode if exposed to harsh environments such as UV radiation, rodents, or birds.

Connector failures come typically from forcing different types of connectors to connect or not-well crimped connectors.

Even if aging mechanisms with corrosion due to long exposure to weather with UV and humidity are identified for connectors, failures are most likely to be related to installation issues.

Detection Hints:
- Abrupt performance change from a specific date
- The voltage is not expected to vary.
- Loss of current proportional to the number of strings which are open-circuited.

Shading

Shading refers to the obstruction of sunlight on the PV array.

Shading / Full shading

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One example

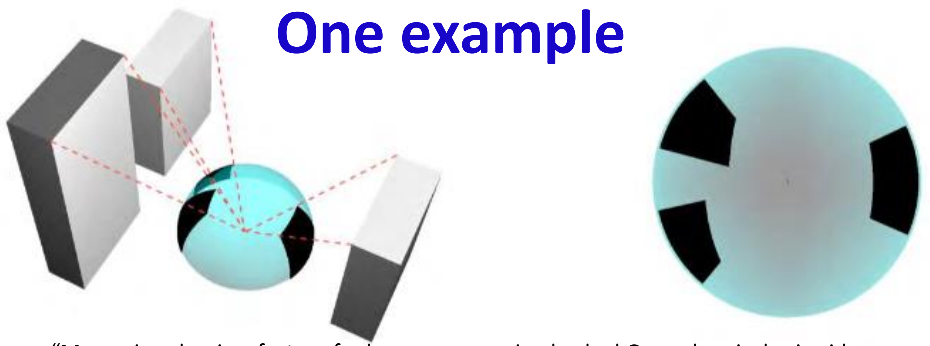

Image: "Measuring sky view factor of urban canyons using hacked Gopro hemispheric video processing", December 2015, Conference, Melbourne, Australia, White et Kimm

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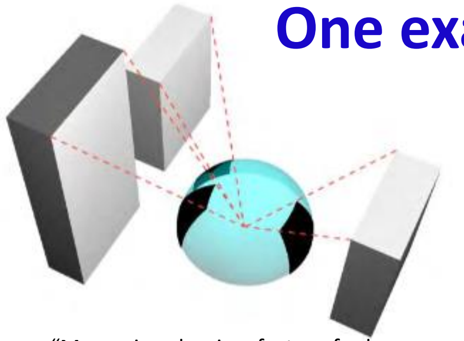

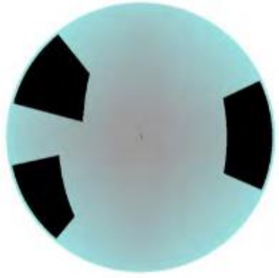

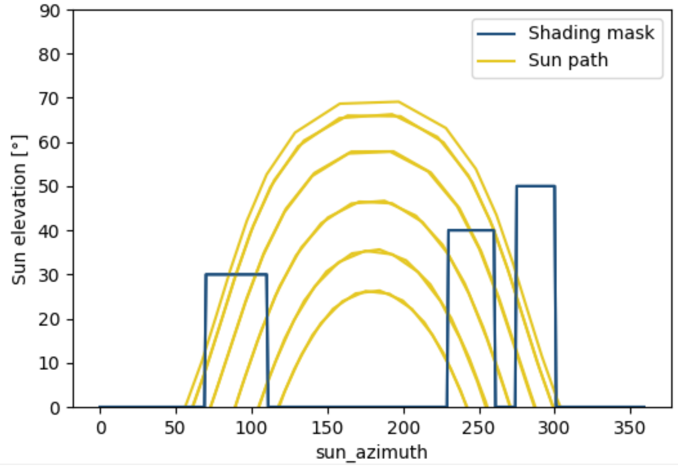

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*Process illustration, assumptions made on the building masks.

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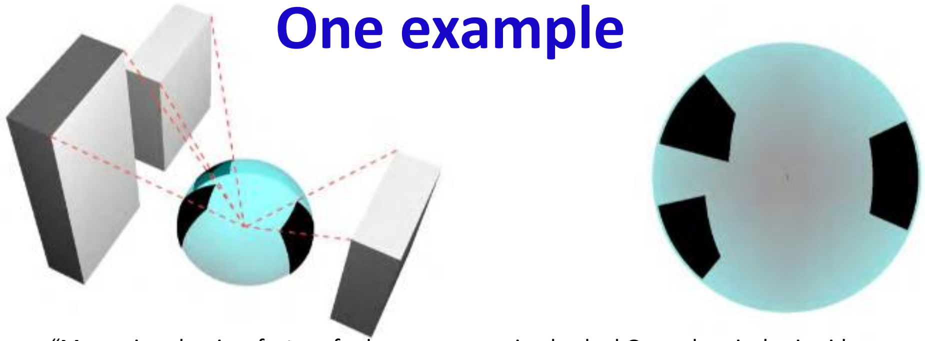

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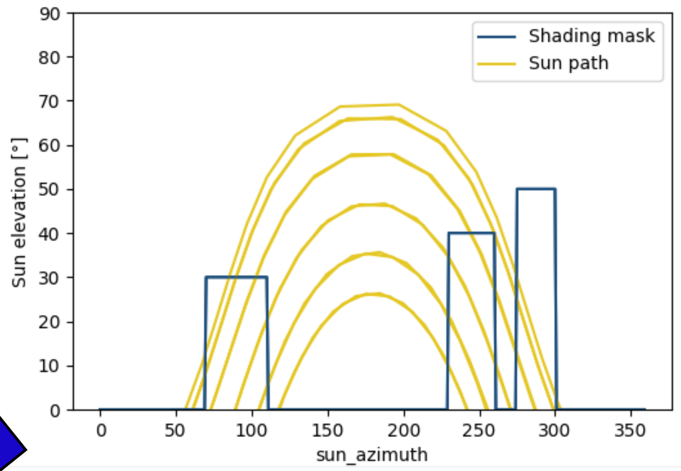

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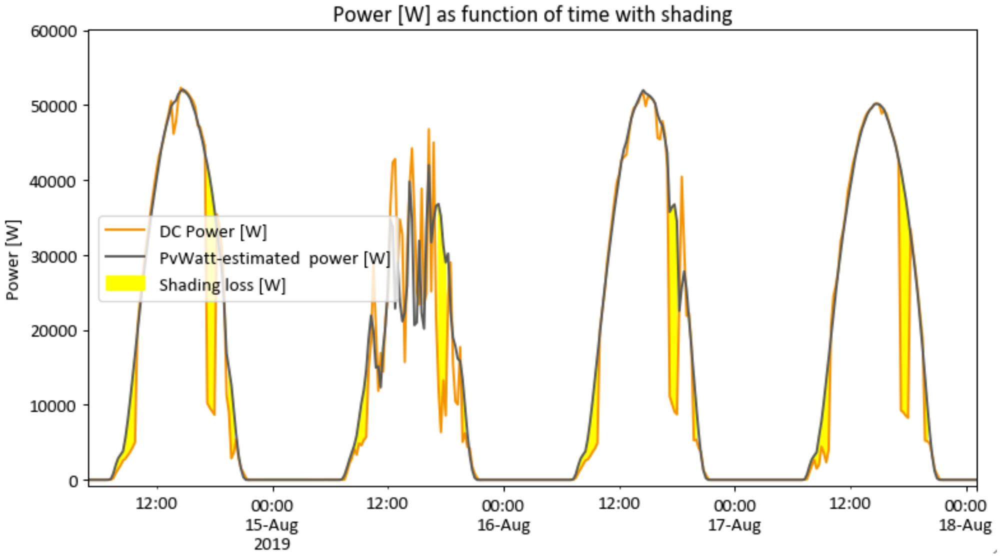

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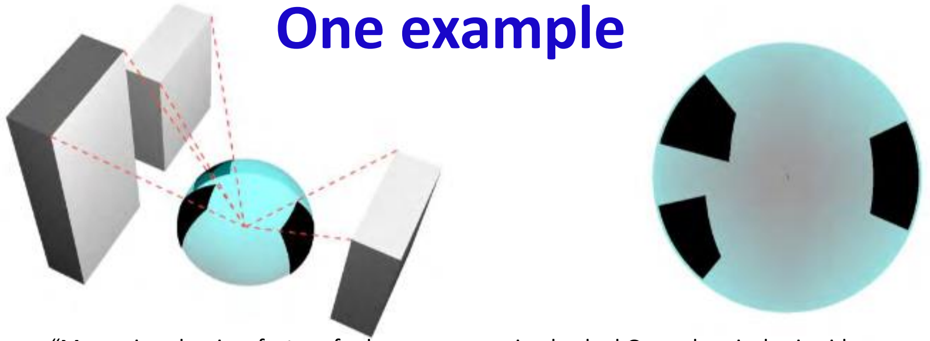

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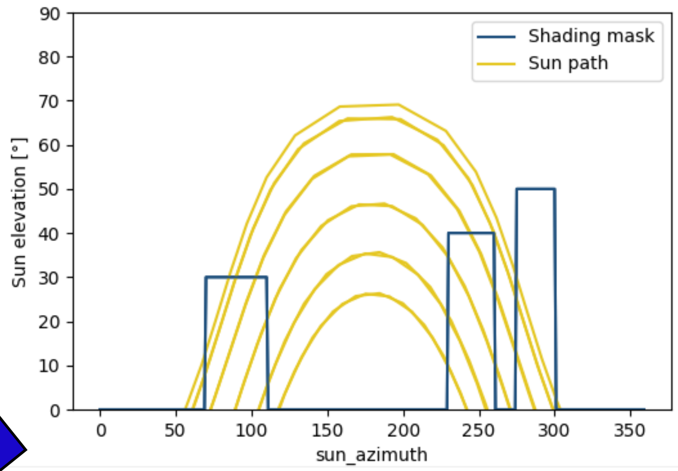

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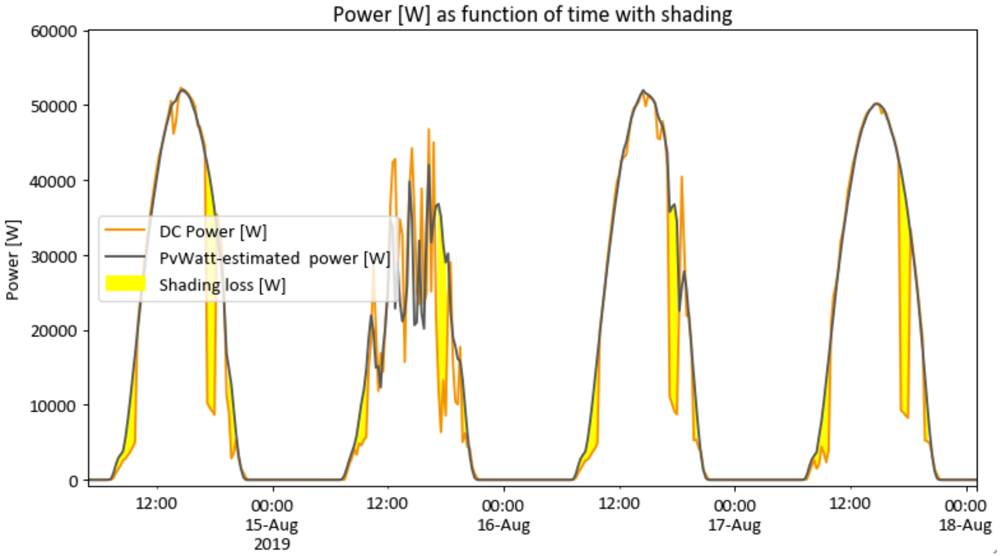

Detection Hints:

- Temporal cycle
- Correlated with the sun position (Low sun horizons have higher chances to result in shading.)
- Power/Current decrease in the same order of magnitude as the POA-direct component vs POA-global
- Sudden drops/increase

Bypass short-circuit

Image reference: Romenia G. Vieira et al. “A Comprehensive Review on Bypass Diode Application on Photovoltaic Modules”. In:Energies13.10 (2020)

Diode failures can appear at different stages:

- **Manufacturing**: wrong specification, non-functional diode..
- **Installation**: Wrong installation (inversed or not properly connected),mechanical stress on junction boxes, shocks. . .
- **Operation**: Diode aging mechanisms, junction box corrosion, events with mechanical stresses, repetive activation (partial shadings).

Failed diodes are either blocked in short-circuit or open-circuit.

Detection Hints:

- Short-circuited bypass diodes constantly lower the module voltage by around 1/3 if there are 3 diodes in the module.
- Abrupt performance change from a specific date

That’s it