Operational research for urban solar development

“PV failure detection based on operational time series”

27/11/2023 - Morning
Alexandre Mathieu

Agenda

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Curriculum

Audience

PV performance model steps

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Curriculum

Initial plan

Day	Time	Duration	Content
Monday 27/11/2023	9h45-11h15 12h30-14h	1h30 + 1h30	50% Lecture / 50 % Hands-on
Tuesday 05/12/2023	8h-9h30 9h45-11h15	1h30 + 1h30	50% Lecture / 50 % Hands-on
Thursday 07/12/2023	8h-11h 12h45-15h45	6h	25% Lecture / 75 % Project
Monday 11/11/2023	8h-11h 12h30-15h30	6h	10% Lecture / 90 % Project
Friday 22/12/2023	8h-9h30	1h30	100 % Project

Curriculum

Content

PV performance modeling from weather variables (Irradiance in the plane of array, ambient temperature etc..) and system configuration, which includes:

- Module temperature
- DC power
- AC/DC efficiency
- Performance metric calculations.

Failure detection based on real production time series.

Hands-on with **python** notebooks.

Curriculum

Motivations

PV capacity increases exponentially

+20%/year worldwide since 2010[1]

Complex in-situ O & M:

No one-fit-all O&M[2]

Expensive[3]

15%[4] of underperformances:

« Recoverable » Energy: 5%[4,5]

[1] Masson, G., Kaizuka, I., 2021. Trends in Photovoltaic Applications (IEA-PVPS T1-41:2021). IEA PVPS

[2] U. Jahn et al., ‘Guidelines for Operation and Maintenance of Photovoltaic Power Plants in Different Climates’, IEA, Technical Report IEA-PVPS T13-07:2022, Oct. 2022.

[3] « Coûts et rentabilités du grand photovoltaïque en métropole continentale », CRE, 2019

[4] Leloux, J., Narvarte, L., Trebosc, D., 2011. Performance analysis of 10,000 residential PV systems in France and Belgium. Presented at the 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany.)

[5] Raycatch, ‘Solar Asset Optimization, Industry Benchmark Study’, Tel Aviv, Israel, Feb. 2021.

Curriculum

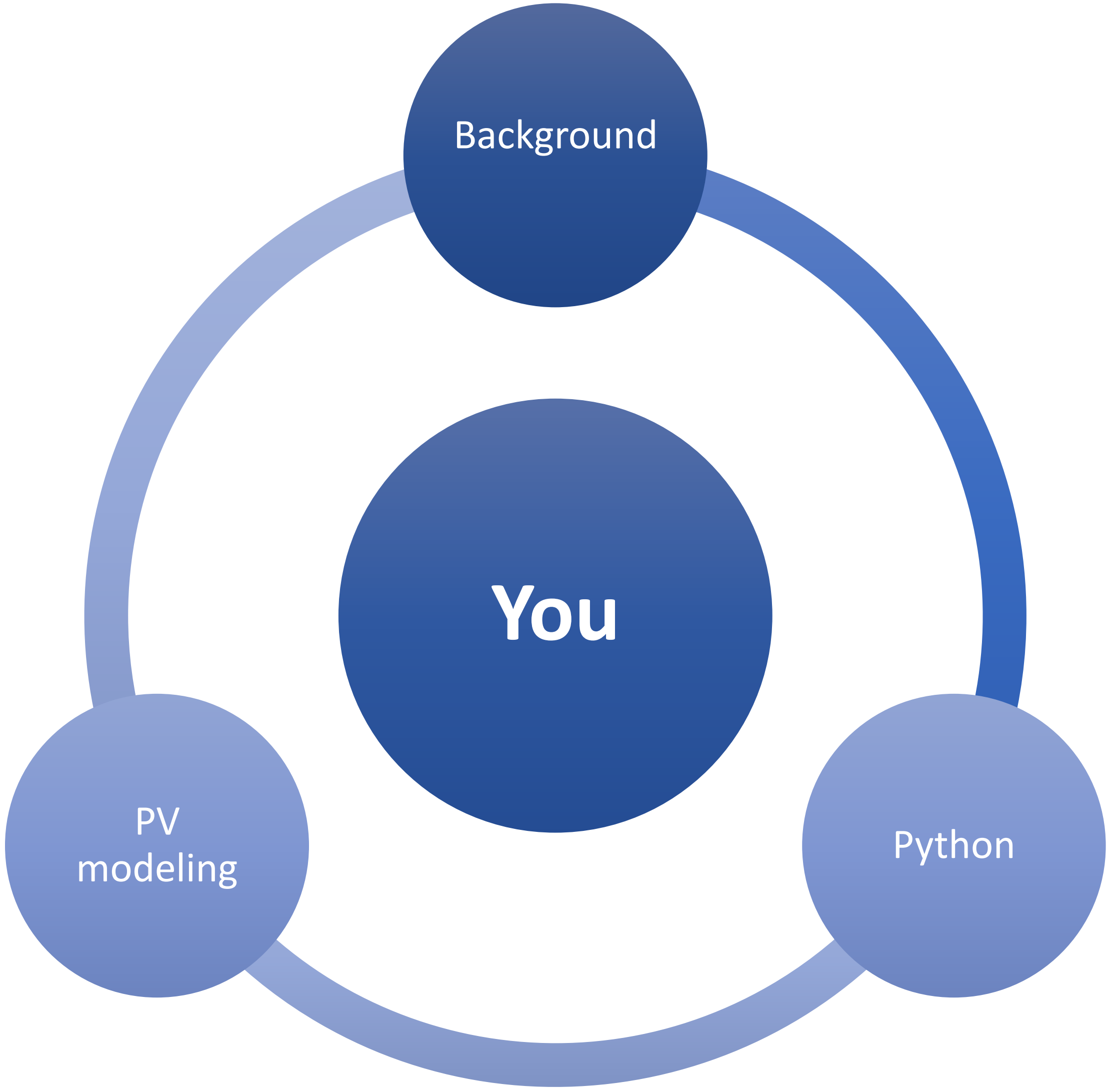
Objectives

At the end of this course, you should be able to:

- Perform data treatment and analysis with Python on operational PV time series.
- Model and calculate the performance of a PV installation.
- Detect and quantify underperformances.

Audience

Audience



Agenda

Curriculum

Audience

PV performance model steps

Modeling steps

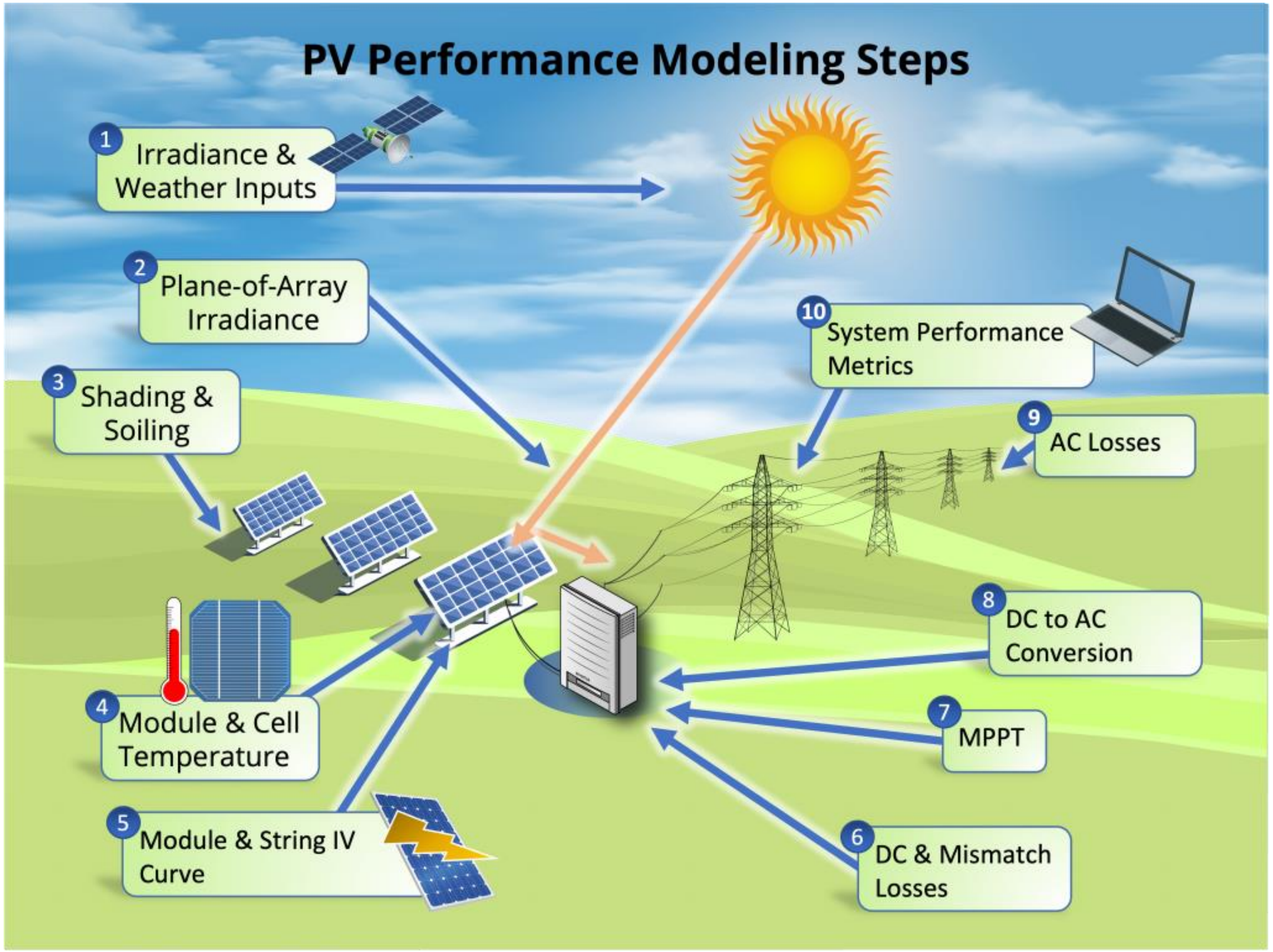
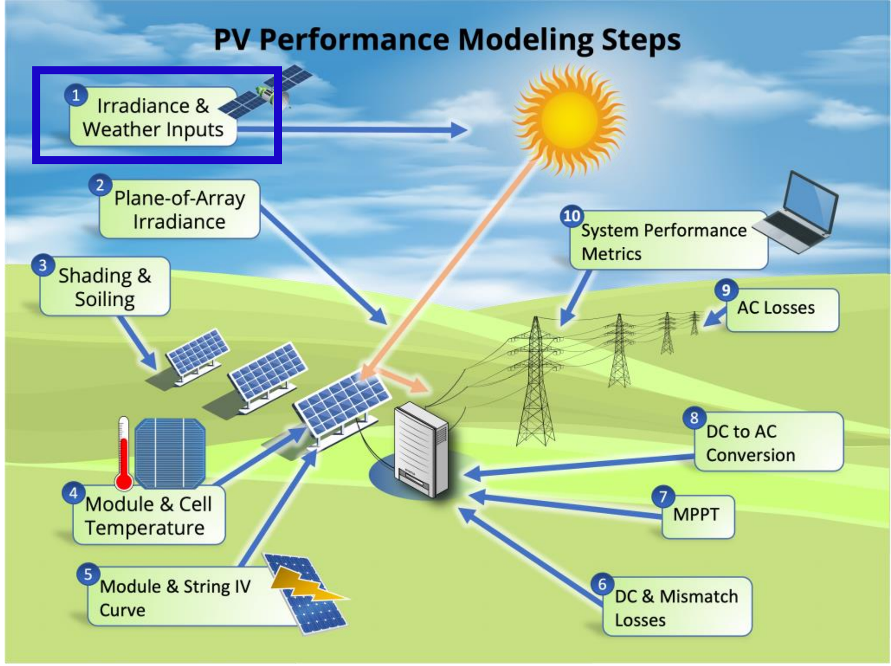


*image from: PVSC48 python tutorial

Modeling steps



1. **Weather data:** Irradiance, ambient temperature, humidity, rain, snow…

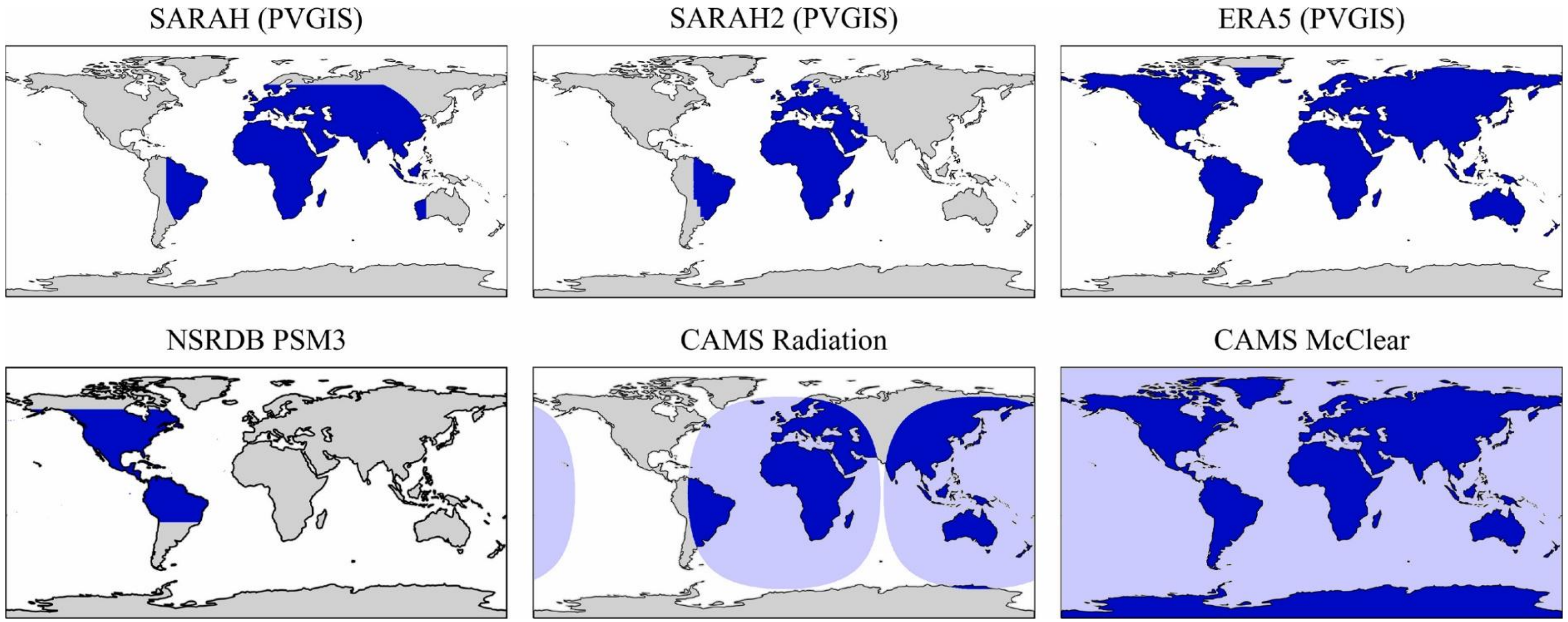
Modeling steps

1. **Weather data:**

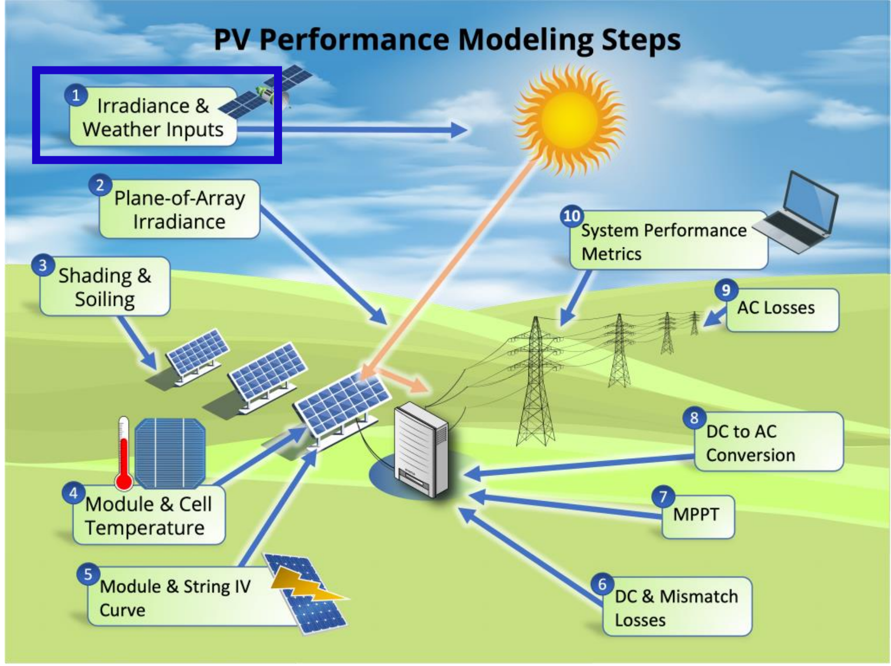
Irradiance, measured in W/m2, with max instantaneous values around 1000 W/m2 is obtained from:

   a. Satellite data (CAMS, NSSRDB, SolarGis…)

Some Irradiance datasets, supported by pvlib [1]



[1] Adam R. Jensen, Kevin S. Anderson, William F. Holmgren, Mark A. Mikofski, Clifford W. Hansen, Leland J. Boeman, Roel Loonen, pvlib iotools—Open-source Python functions for seamless access to solar irradiance data, Solar Energy, 2023



Modeling steps

1. Weather data:

Irradiance, measured in W/m2, is obtained from:

a. Satellite data (CAMS, NSSRDB, SolarGis…)
b. In-situ instrumentations

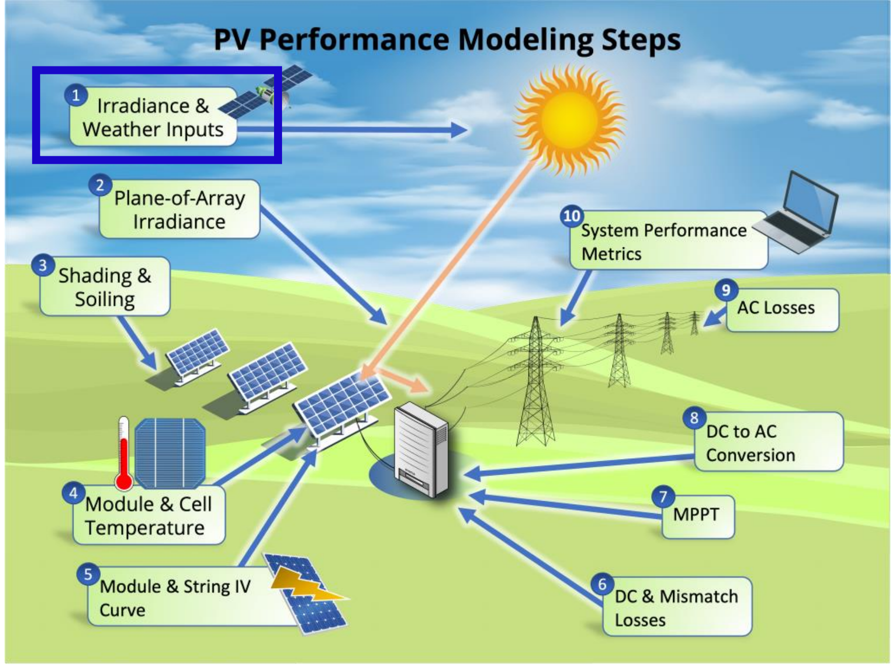
Pyranometer:
Global/Inclined Irradiance

Pyrheliometer:
Direct irradiance

(Hukseflux product)

Pyranometer with shadow ring:
Diffuse Irradiance

Modeling steps



1. Weather data:

Irradiance, measured in W/m2, is obtained from:

a. Satellite data (CAMS, NSSRDB, SolarGis…)

b. In-situ instrumentations

Reference cell: Inclined Irradiance (without reflection/spectral effects)

Modeling steps

1. Weather data

Reminder, the Global Horizontal Irradiance (GHI) can be broken down into 2 components (ignoring reflections from other surrounding elements):

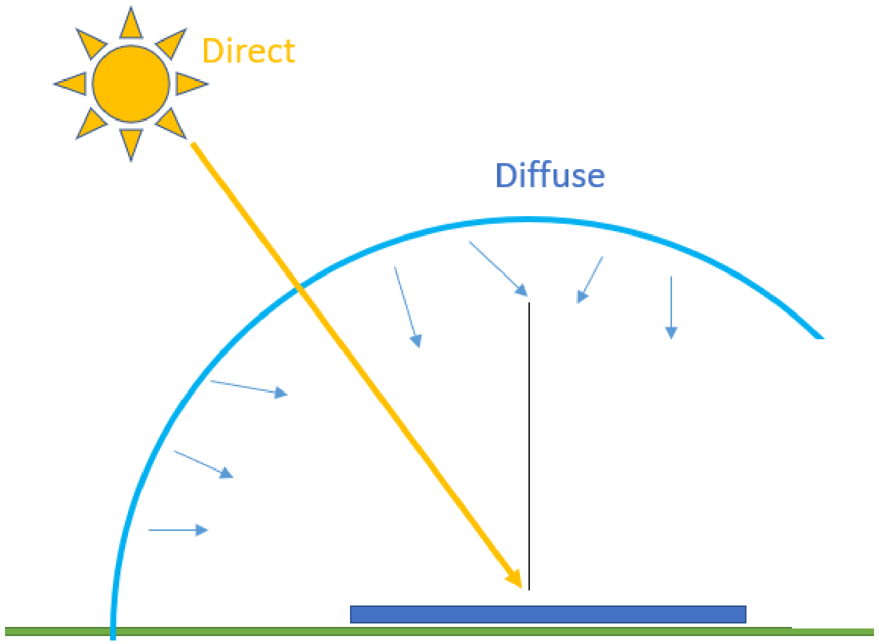


*image from PVSC48 tutorial

$$GHI = BHI + DHI$$

BHI (Beam Horizontal Irradiance): Power received from the Beam of the sun on the horizontal plan.

DHI (Diffuse Horizontal Irradiance): Power received from the sky diffusion of the light.

Modeling steps

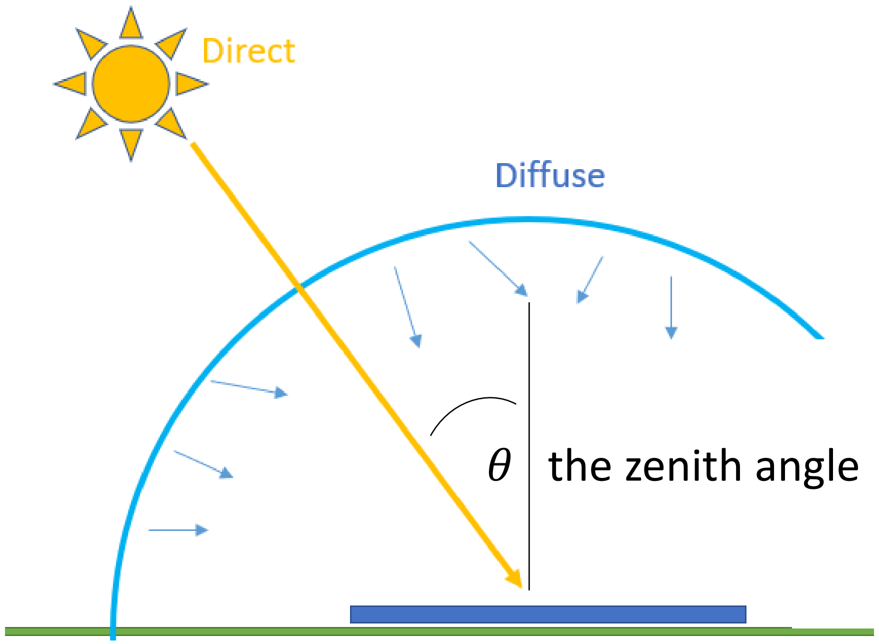


*image adapted from PVSC48 tutorial

1. Weather data

Reminder, the Global Horizontal Irradiance (GHI) can be broken down into 2 components (ignoring reflections from other surrounding elements):

$$GHI = BHI + DHI$$

BHI (Beam Horizontal Irradiance): Power received from the Beam of the sun on the horizontal plan.
BHI is usually deducted from DNI, the Direct Normal Irradiance, which is most commonly the output of weather models.

$$BHI = DNI \cdot \cos(\theta)$$

DHI (Diffuse Horizontal Irradiance): Power received from the sky diffusion of the light.

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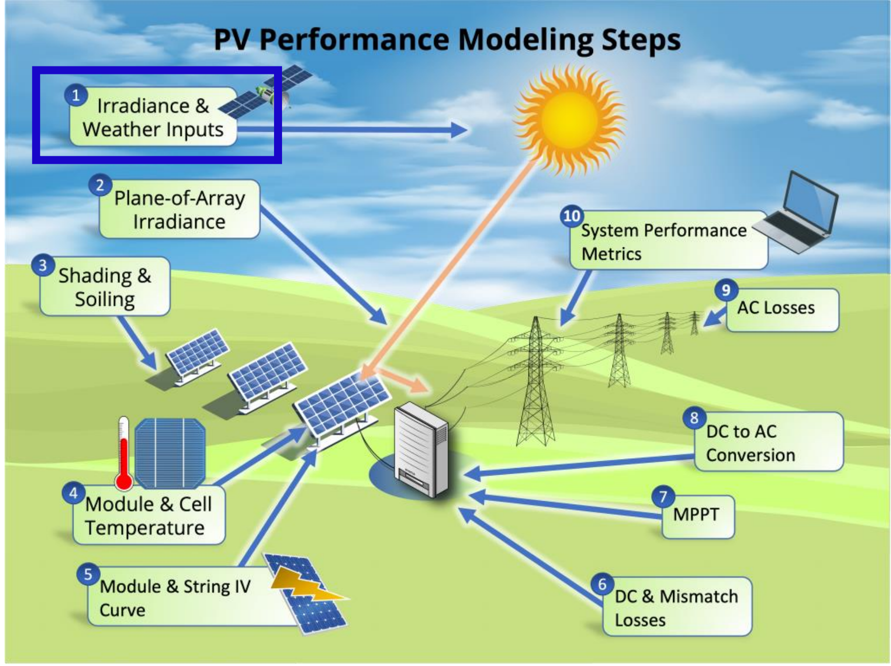
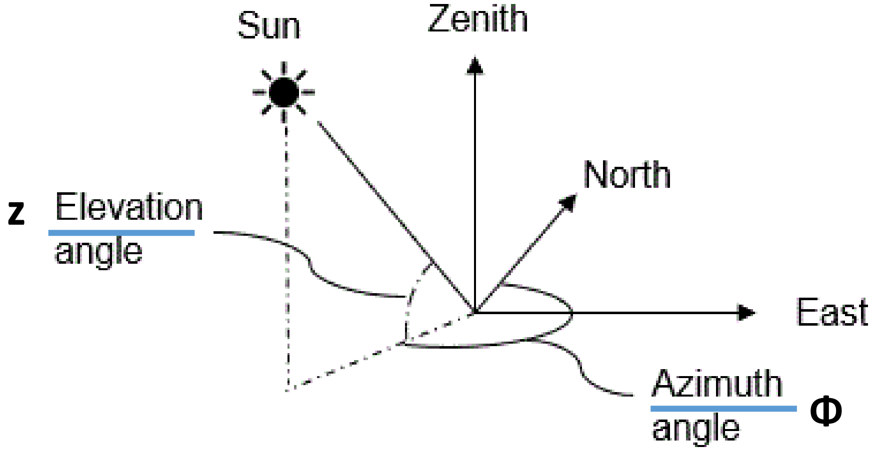
Modeling steps



1. Weather data:

Sun path



azimuth angle: north=0, east=90, south=180, west=270 degree

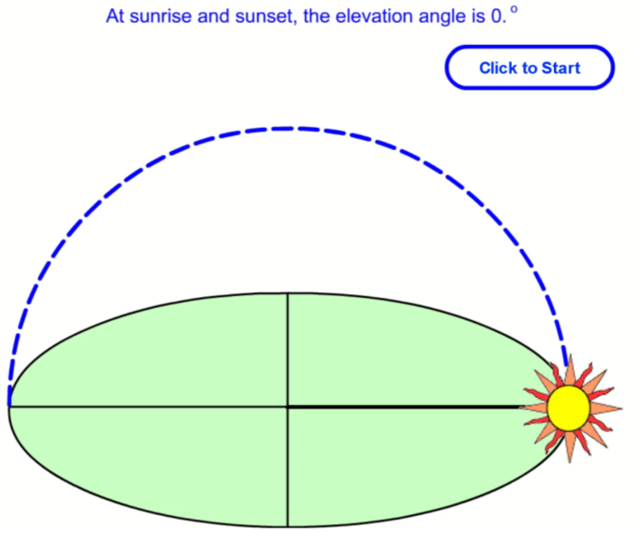
Image: https://www.prairielittlebighouse.com/prairie-blog/archives/03-2021

Modeling steps

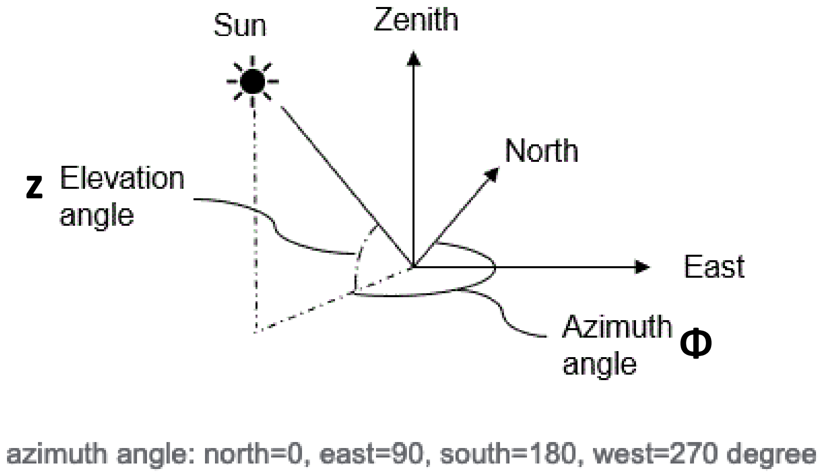
1. Weather data:

The sun path is characterized by:

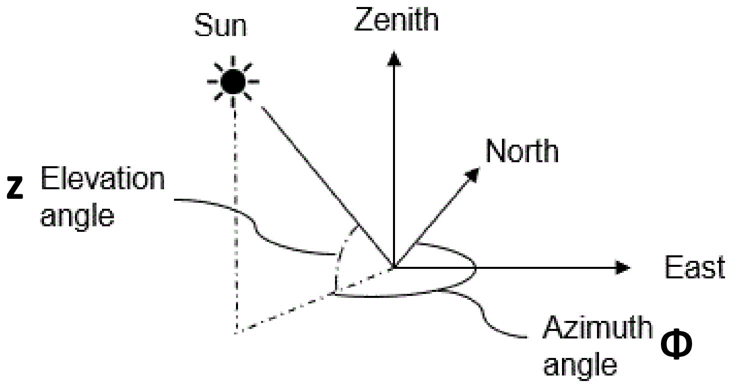
- **z** [°], elevation angle, height of the sun in the sky



*animation from pveducation



Modeling steps



azimuth angle: north=0, east=90, south=180, west=270 degree

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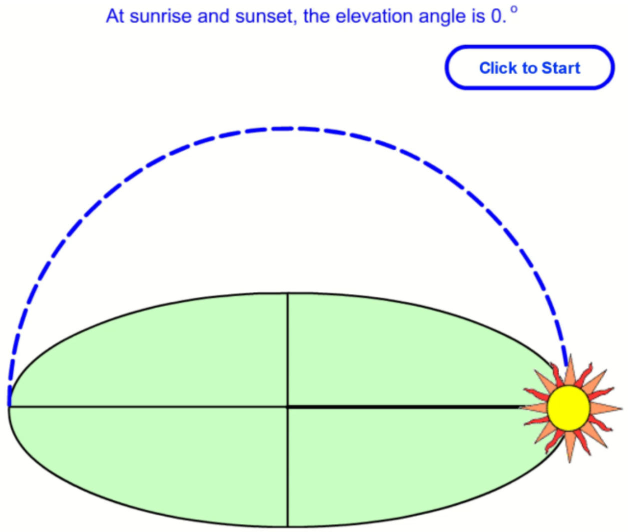
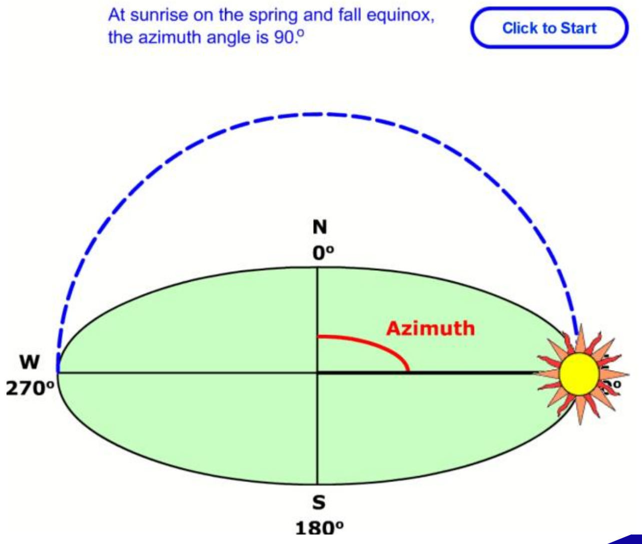


*animation from pveducation

- **Φ** [°], the azimuth angle: angle of sun between north and sun direction



*animation from pveducation

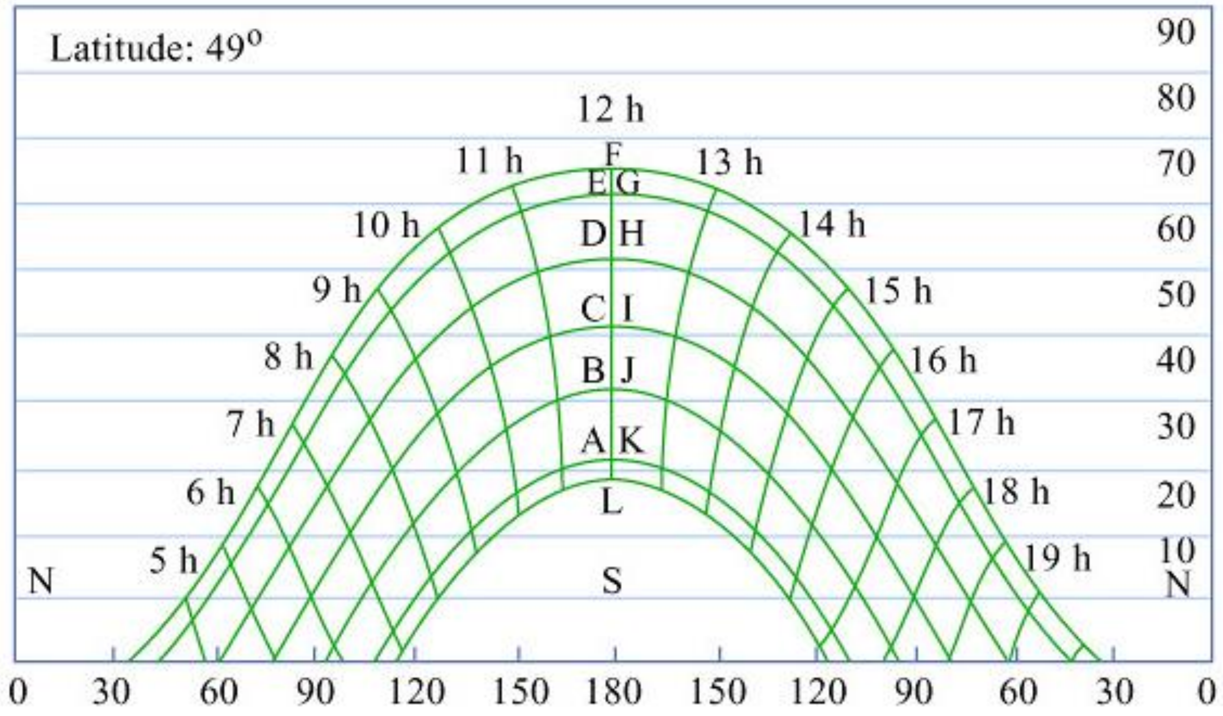
Modeling steps

1. Weather data:

The sun path is characterized by:

- **z** [°], elevation angle, height of the sun in the sky
- **Φ** [°], the azimuth angle: angle between north and the sun direction

Typical sun path diagram



z [°]

Φ [°]

Modeling steps

1. Weather data:

The sun path is characterized by:

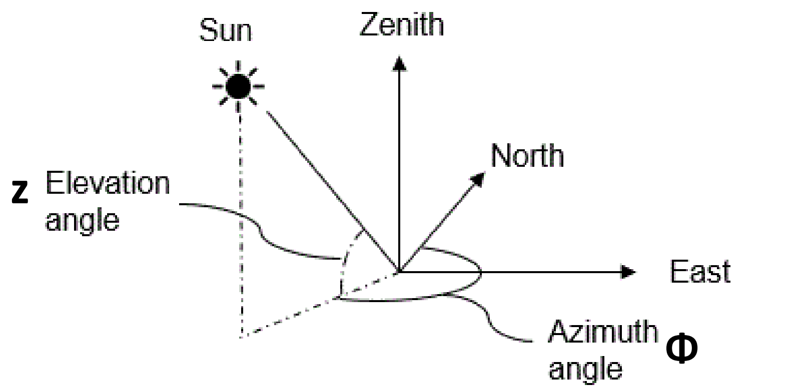
- **z** [°], elevation angle, height of the sun in the sky
- **Φ** [°], the azimuth angle: angle between north and the sun direction

Remember ? To calculate BHI:

$$BHI = DNI \cdot \cos(\theta)$$

With θ, the zenith angle

$$\theta = 90° - z$$



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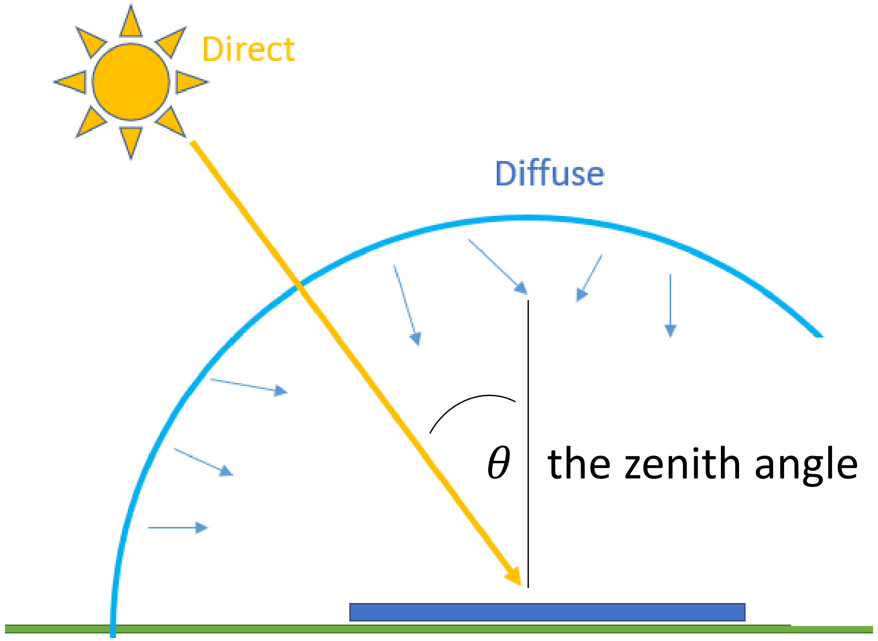
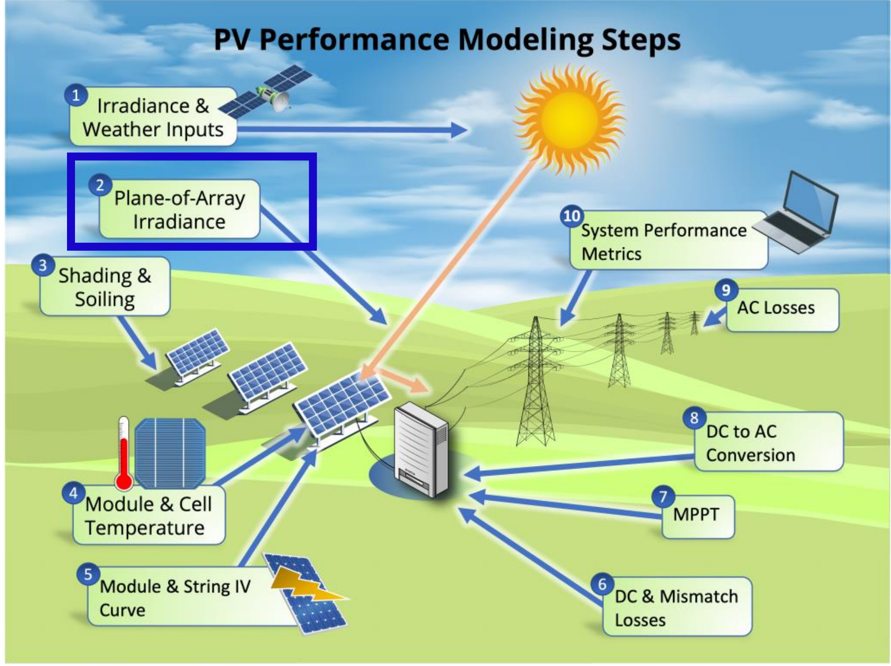


*image adapted from PVSC48 tutorial

Modeling steps

2. Plan-of-Array Irradiance

Reminder, the Global Plane-Of-Array (GPOA) irradiance can be calculated from DHI, **GHI** and DNI.



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Modeling steps

2. Plan-of-Array Irradiance

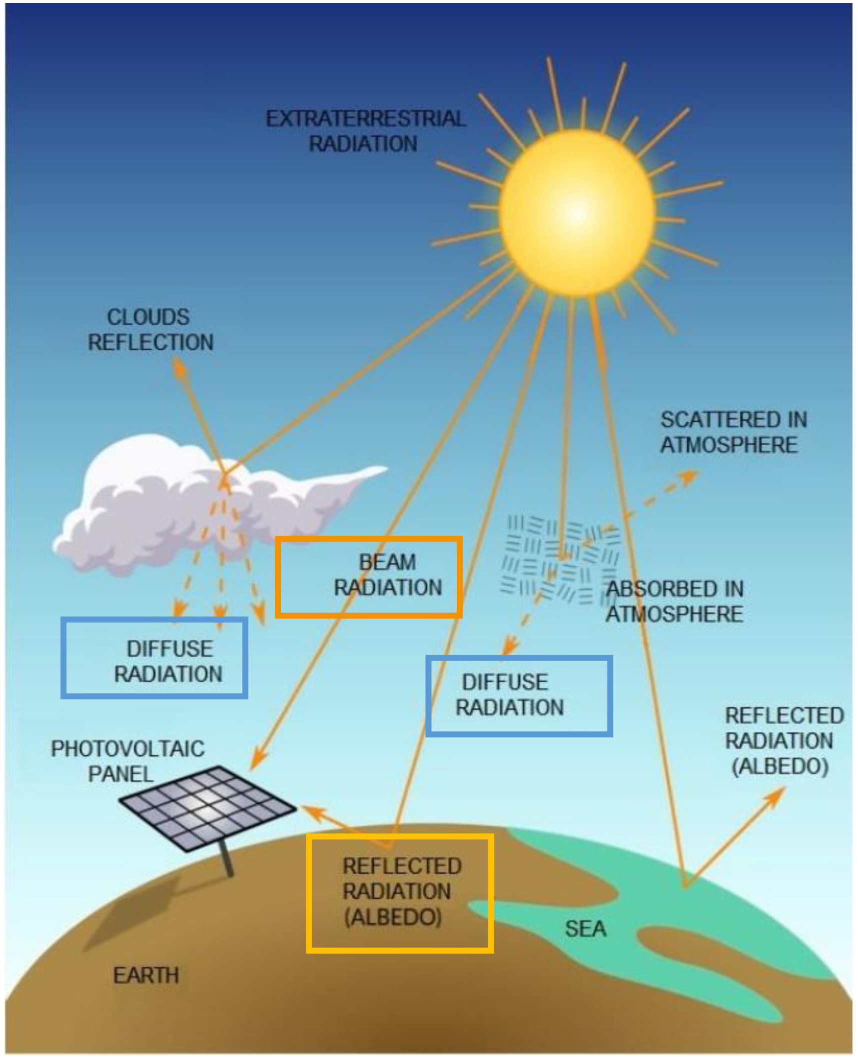
Reminder, the Global Plane-Of-Array (GPOA) irradiance can be calculated from DHI, **GHI** and DNI and are broken down into 3 components:

$$GPOA = POA_b + POA_d + POA_{grd}$$

POA_b: **The direct component -** Power received from the Beam of the sun on the horizontal plan

POA_d: **The diffuse component** - Power received from the sky diffusion of the light,

POA_{grd}**: The ground-reflected component** - Power received from reflections from the ground



Souza, Muriele et al. (2019). Determination of Diffused Irradiation from Horizontal Global Irradiation - Study for the City of Curitiba.

Modeling steps

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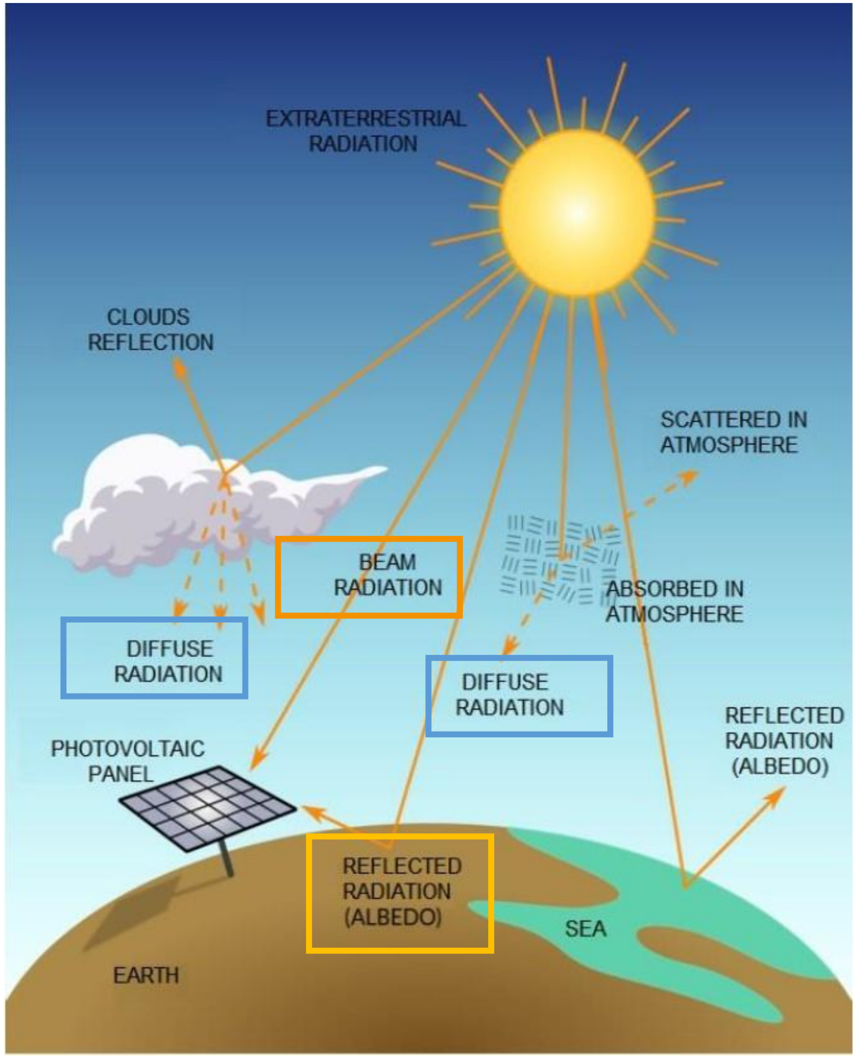
$$GPOA = POA_b + POA_d + POA_{grd}$$

- $POA_b = DNI \cdot \cos(AOI)$

Under the isotropic/no-shading assumption

- $POA_d = DHI \cdot \frac{1+\cos(\beta)}{2}$
- $POA_{grd} = \boldsymbol{GHI} \cdot \rho \cdot \frac{1-\cos(\beta)}{2}$



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With:

- β, PV installation tilt

Modeling steps

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Reminder, the Global Plane-Of-Array (GPOA) irradiance can be calculated from DHI, **GHI** and DNI and are broken down into 3 components:

$$GPOA = POA_b + POA_d + POA_{grd}$$

- $POA_b = DNI \cdot \cos(AOI) \longleftarrow \cos(AOI) = [\cos(\beta) \cdot \sin(z) + \sin(\beta) \cdot \cos(z) \cdot \cos(\boldsymbol{\Phi} - \boldsymbol{\Phi}_{install})]$

Under the isotropic/no-shading assumption

- $POA_d = DHI \cdot \frac{1+\cos(\beta)}{2}$
- $POA_{grd} = \boldsymbol{GHI} \cdot \rho \cdot \frac{1-\cos(\beta)}{2}$

With:

- AOI, angle of incidence
- β, PV installation tilt
- $\boldsymbol{\Phi}_{install}$, PV installation azimuth
- z, Sun elevation
- $\boldsymbol{\Phi}$, sun azimuth

Modeling steps

2. Plan-of-Array Irradiance

Time for some
hands-on exercises

Use the notebook:
https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy/blob/master/notebooks/python_intro_poa.ipynb

Follow the python tutorial and calculate the 3 POA components for:

- One timestep
- Over one year

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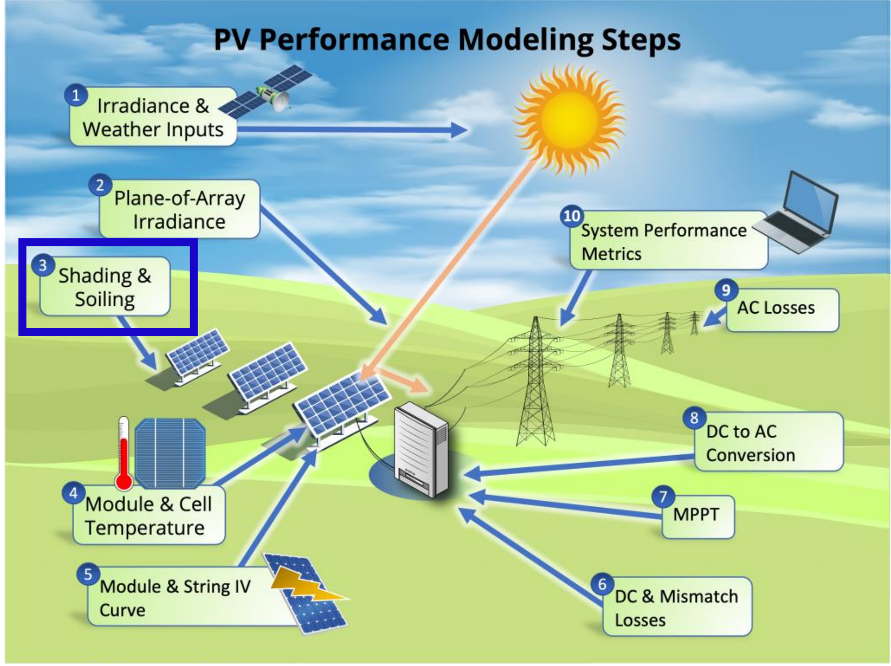
Modeling steps

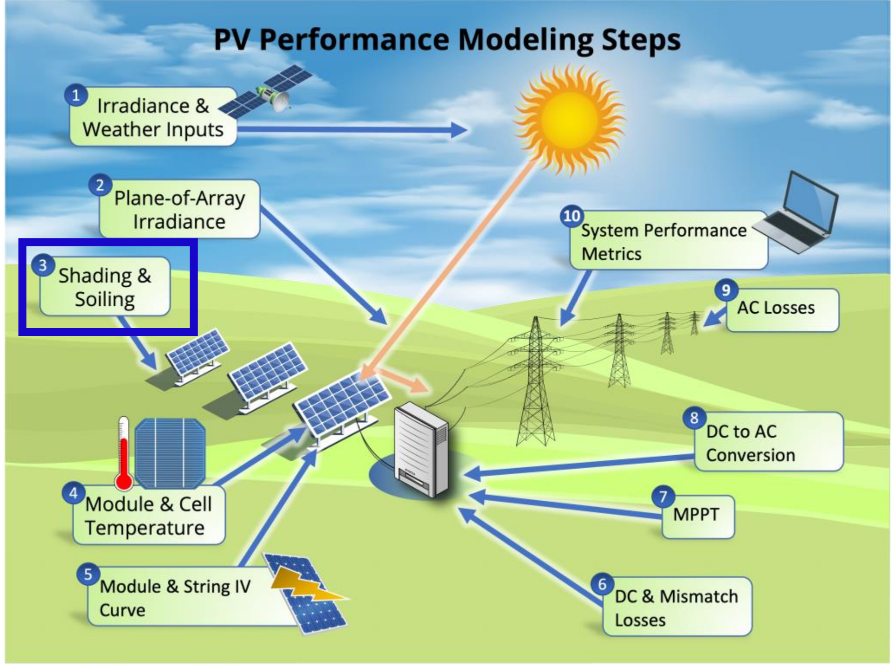


3. Shading

Shadow can come from near and far elements and their impact can be distinguished into two categories

1. **Partial shading** refers to a condition where some but not all of the solar cells or panels in a PV array are exposed to sunlight while others are shaded.
2. **Full shading** occurs when the entire PV array is covered and deprived of direct sunlight.

*https://mcisolutions.ca/effect-of-shade-on-solar-panels/



Modeling steps

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Not treated in this course but, in average, if a PV panel is around 8% covered, the whole PV panel is bypassed and then, do not produce.

Demonstrated in one of pvlib example:
https://pvlib-python.readthedocs.io/en/stable/gallery/shading/plot_partial_module_shading_simple.html

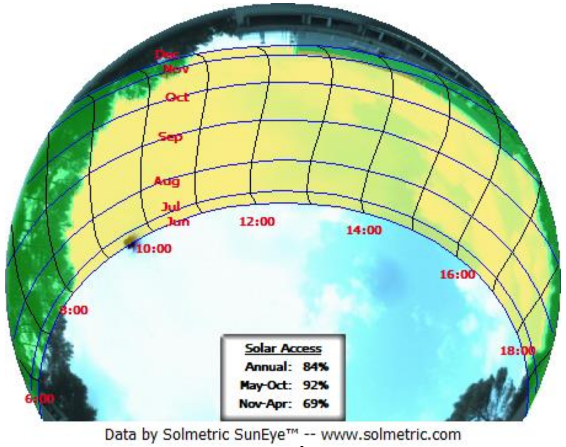
Modeling steps

3. Shading

The Fisheye camera enables to account for the in-situ (full) shading in PV modeling.

South

East



West

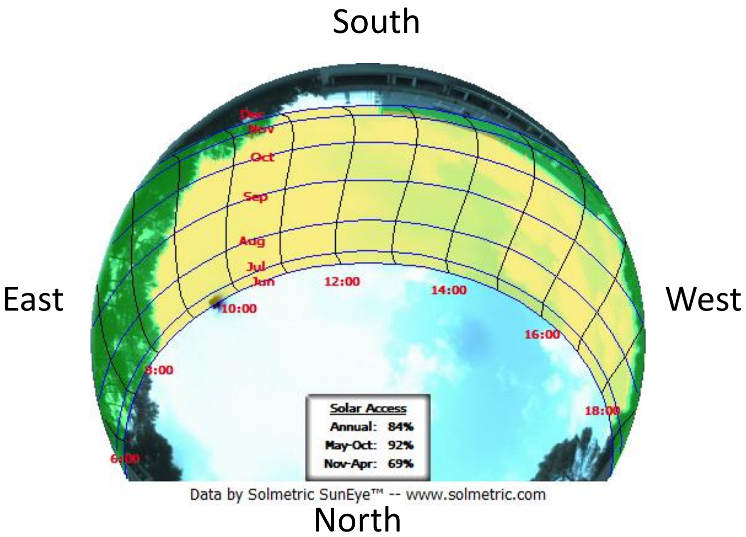
North

Example in South of France

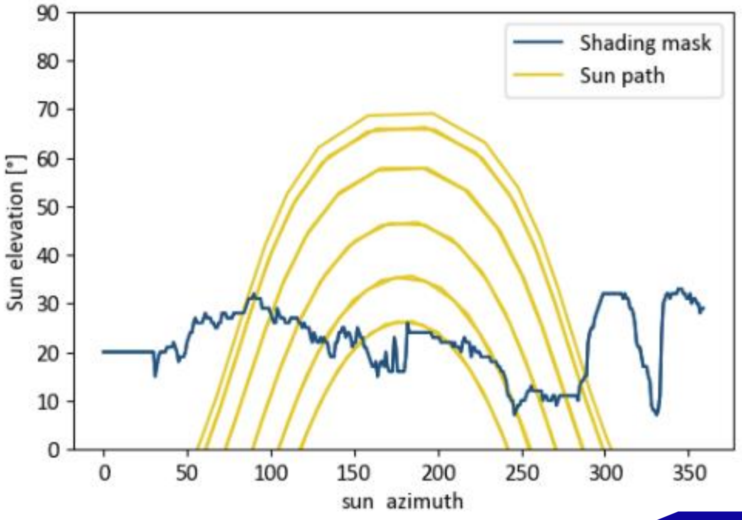
Modeling steps

3. Shading

The Fisheye camera enables to account for the in-situ (full) shading in PV modeling.



Example in South of France



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Modeling steps

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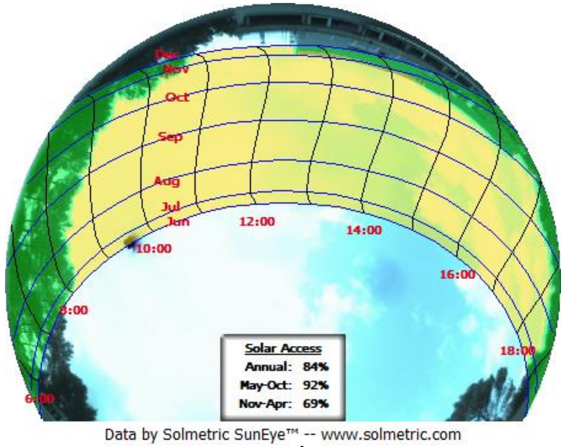
South

East



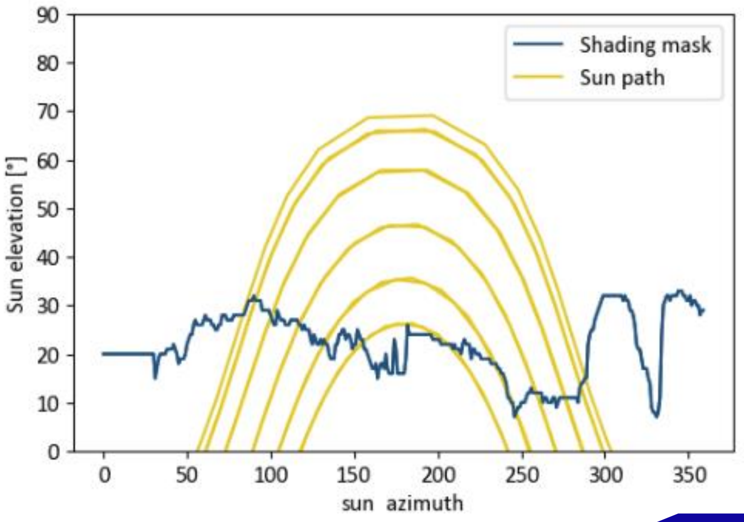
West

North

Example in South of France

Under the black curve, simple assumptions lead to:

- $POA_b = 0 \frac{W}{m2}$
- POA_d, POA_{grd} are not significantly modified

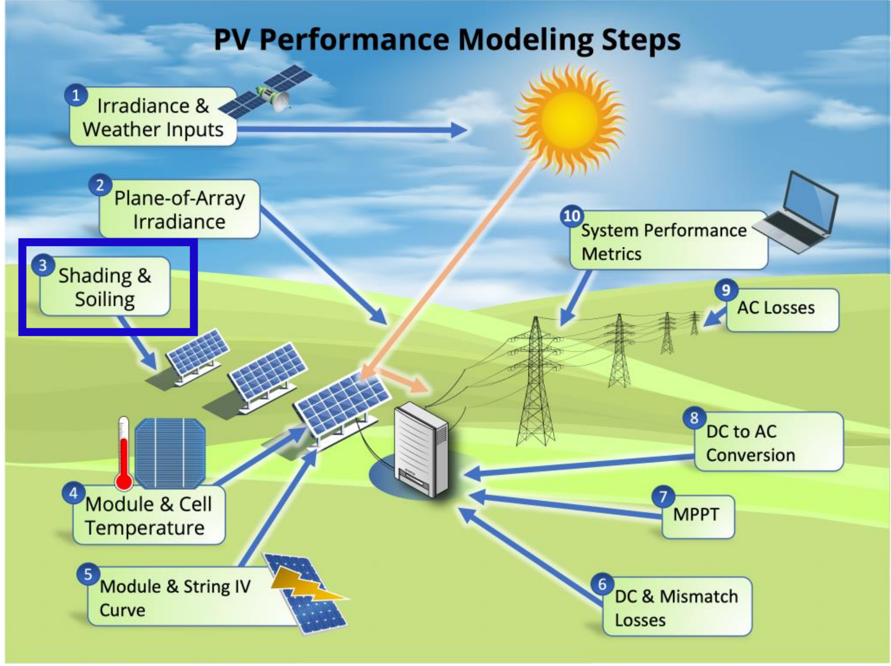


Modeling steps

3. Soiling losses

Big subject in the PV industry:

Report of 130 pages on PV soiling: IEA PVPS, Soiling Losses – Impact on the Performance of Photovoltaic Power Plants 2022



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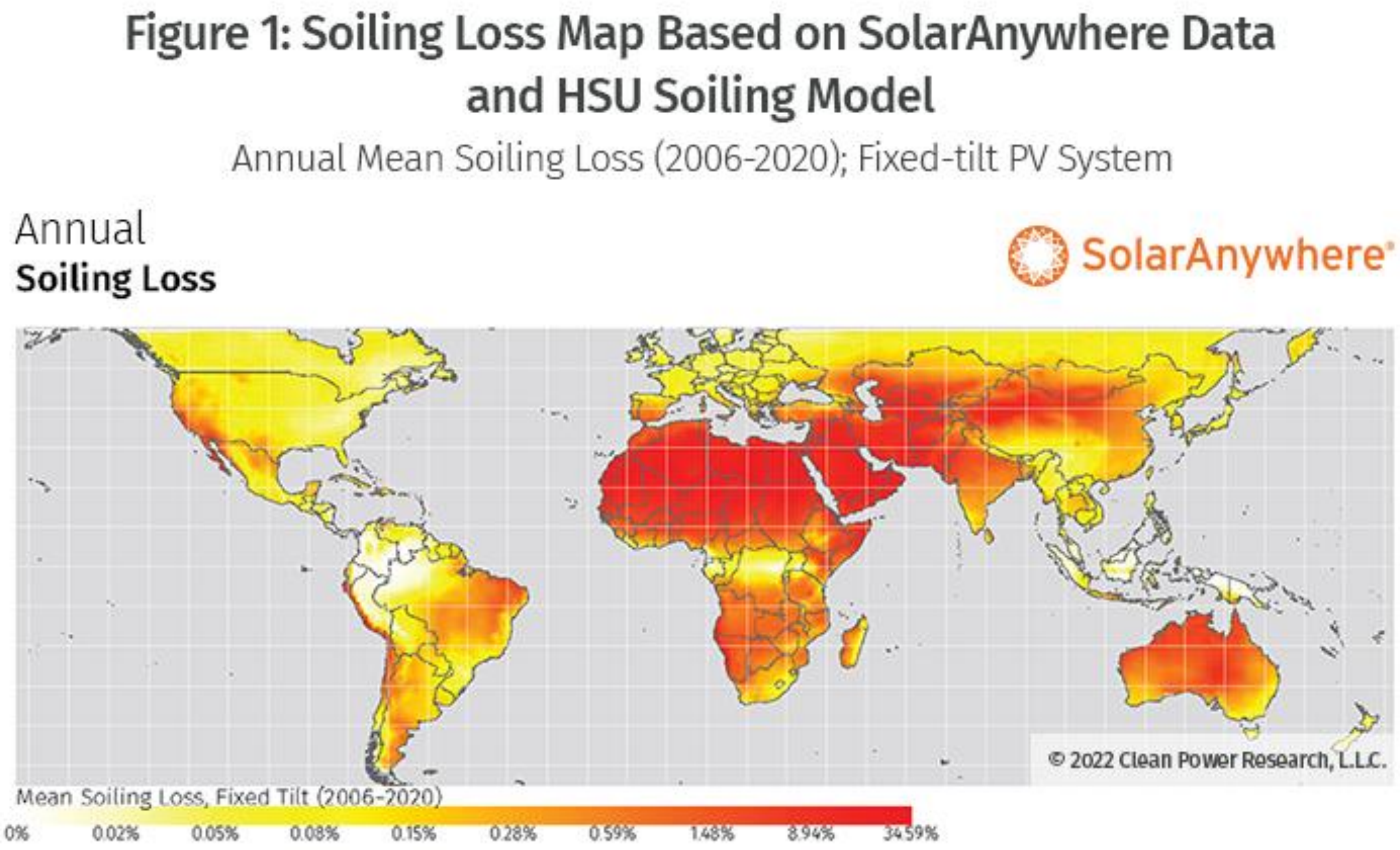
Modeling steps

3. Soiling losses

Can roughly be ignored in France according to the HSU model.



Model HSU: M. Coello and L. Boyle, "Simple Model for Predicting Time Series Soiling of Photovoltaic Panels, Sept. 2019.

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Modeling steps

3. Shading / Terrain horizon mask

Time for some hands-on exercises, Again!

Modeling steps

3. Shading / Terrain horizon mask

PVGIS: Website/Online Tool to estimate power production:

- Enables to extract the horizon mask with a Digital Surface Model (DSM).

Go to: https://re.jrc.ec.europa.eu/pvg_tools/en/

Time for some hands-on exercises, Again !

Modeling steps

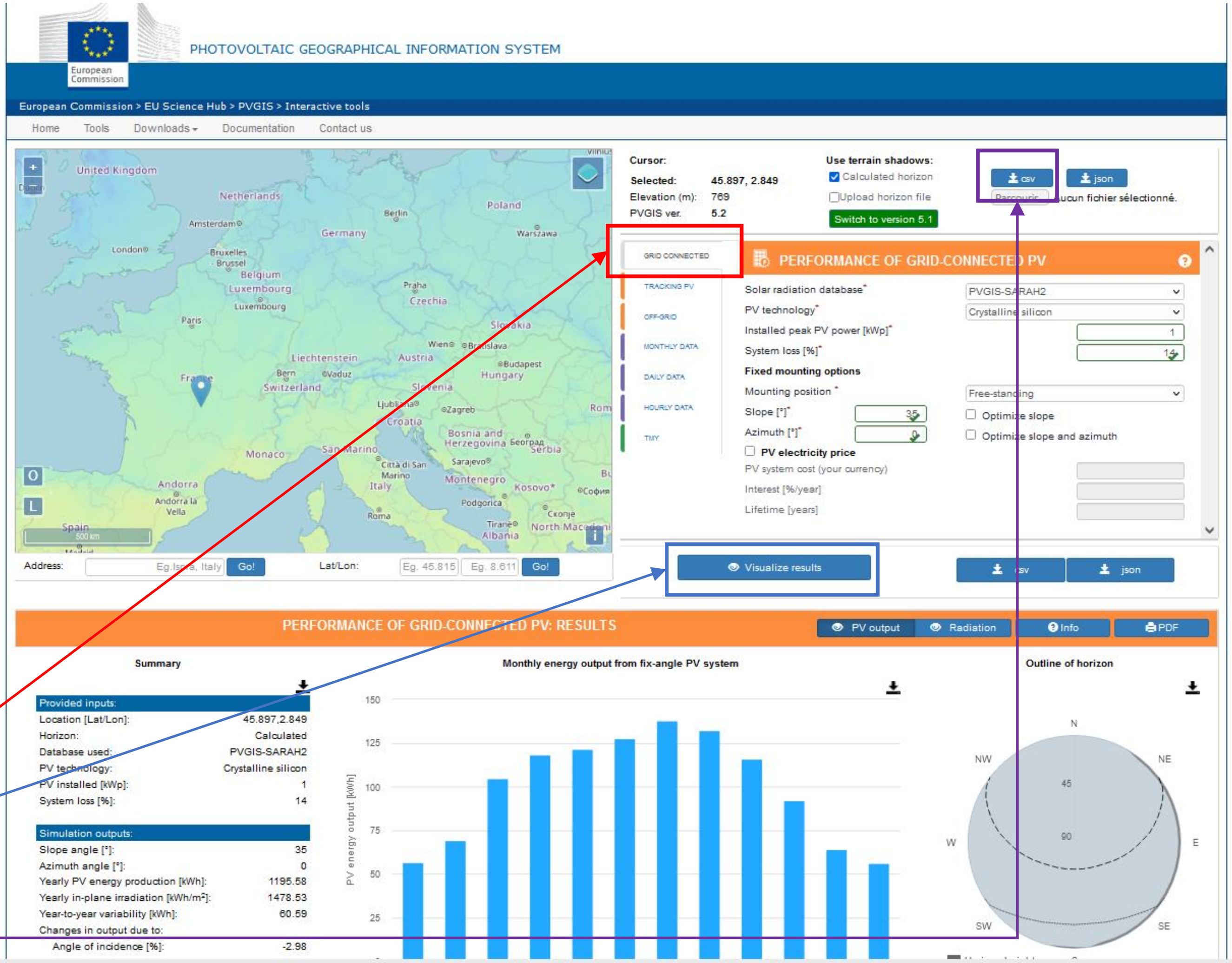
3. Shading / Terrain horizon mask

PVGIS: Website/Online Tool to estimate power production: https://re.jrc.ec.europa.eu/pvg_tools/en/

- Enables to extract the horizon mask with a Digital Surface Model (DSM).

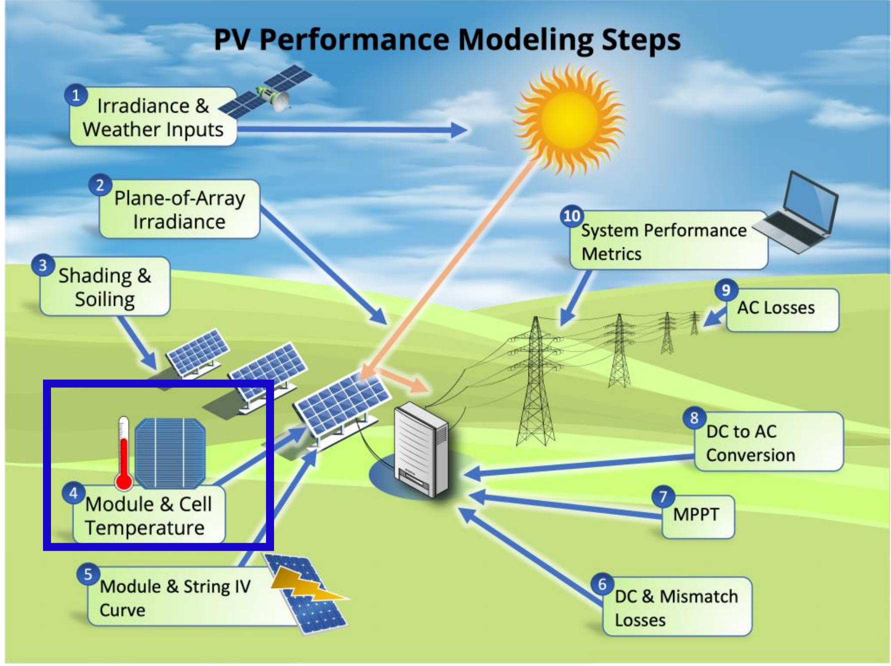
Instructions:

1. Generate a simulation on PVGIS
    a. Click on the map on Grenoble and select the « Grid connected tab »
    b. Vizualize
    c. Extract the horizon file in csv format



2. Follow the instructions on the jupyter notebook and calculate the modified POA on one year.
https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy/blob/master/notebooks/python_intro2_horizon_mask.ipynb

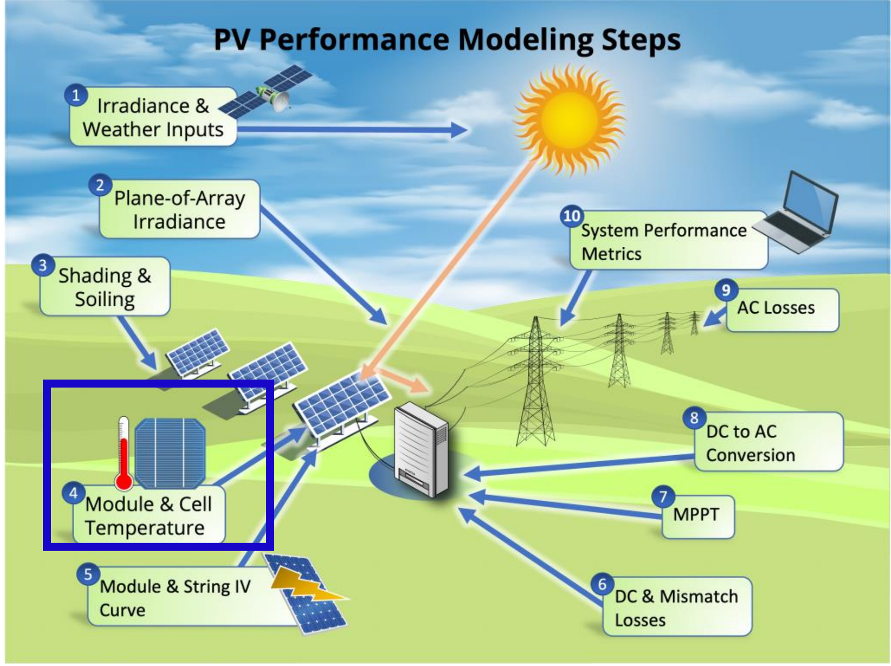
Modeling steps



4. Module and Cell temperature

The hotter a module is, the less efficient it is !

Modeling steps



4. Cell temperature

Ross model:
Model to estimate the cell temperature $\boldsymbol{T_c}$ [°C] as function of ambient temperature and irradiance $\boldsymbol{G_{POA}}$ [W/m²].

$$T_c = T_a + G_{POA} \cdot k_{Ross}$$

k_{Ross}, typically in the range 0.02-0.05 K/m²/W.

Ross, R. G. Jr., (1981). "Design Techniques for Flat-Plate Photovoltaic Arrays"

Modeling steps

k_{Ross} can be fitted from datasheet values.
NOCT conditions:
G_{POA} = 800 W/m²
T_a = 20°C

4. Cell temperature

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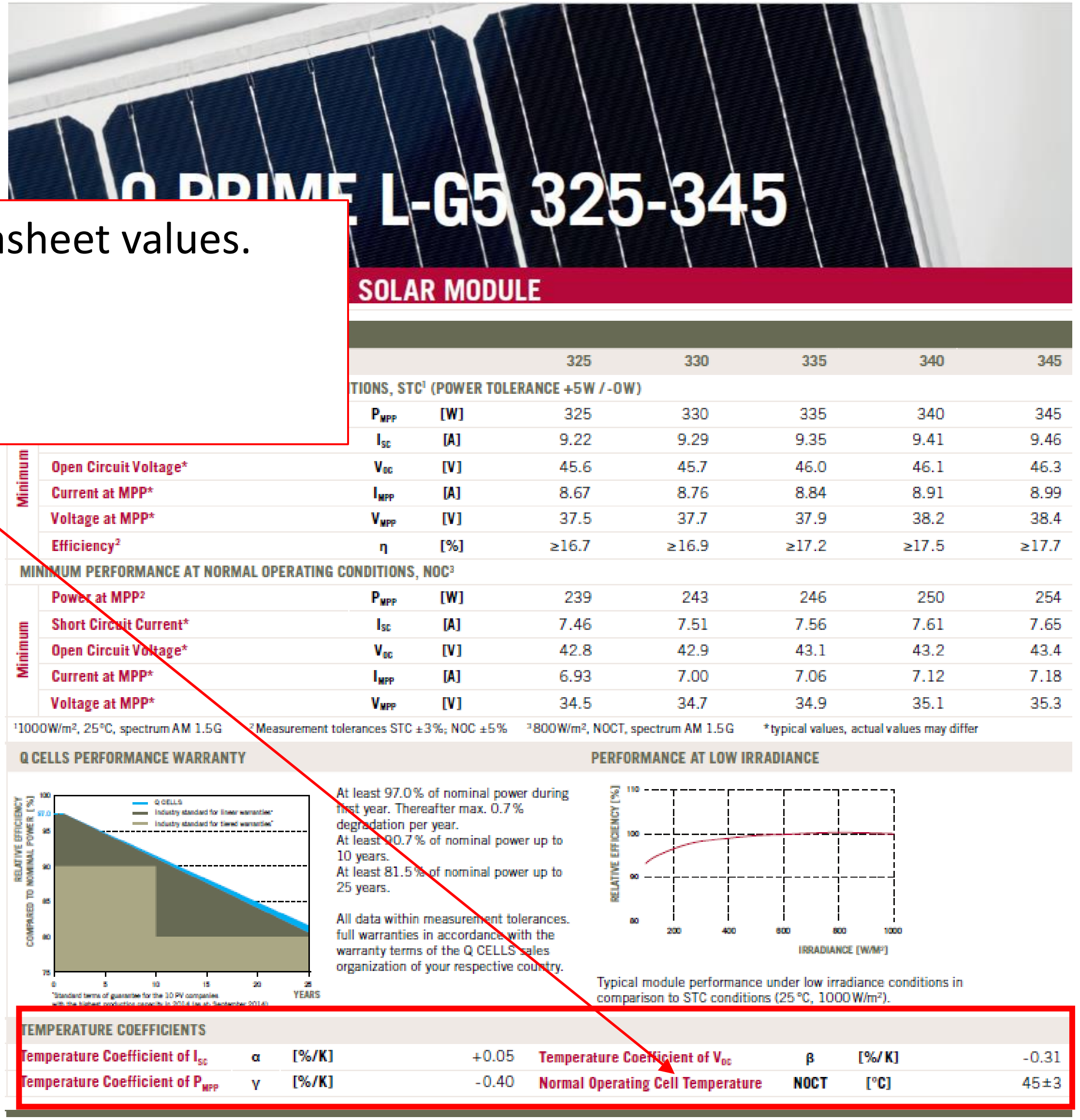


L-G5 325-345

SOLAR MODULE

			325	330	335	340	345
TIONS, STC[1] (POWER TOLERANCE +5W / -0W)							
	P_{MPP}	[W]	325	330	335	340	345
	I_{SC}	[A]	9.22	9.29	9.35	9.41	9.46
Open Circuit Voltage*	V_{OC}	[V]	45.6	45.7	46.0	46.1	46.3
Current at MPP*	I_{MPP}	[A]	8.67	8.76	8.84	8.91	8.99
Voltage at MPP*	V_{MPP}	[V]	37.5	37.7	37.9	38.2	38.4
Efficiency[2]	η	[%]	≥16.7	≥16.9	≥17.2	≥17.5	≥17.7
MINIMUM PERFORMANCE AT NORMAL OPERATING CONDITIONS, NOC[3]							
Power at MPP[2]	P_{MPP}	[W]	239	243	246	250	254
Short Circuit Current*	I_{SC}	[A]	7.46	7.51	7.56	7.61	7.65
Open Circuit Voltage*	V_{OC}	[V]	42.8	42.9	43.1	43.2	43.4
Current at MPP*	I_{MPP}	[A]	6.93	7.00	7.06	7.12	7.18
Voltage at MPP*	V_{MPP}	[V]	34.5	34.7	34.9	35.1	35.3

[1]1000 W/m², 25°C, spectrum AM 1.5G [2]Measurement tolerances STC ±3%; NOC ±5% [3]800 W/m², NOCT, spectrum AM 1.5G *typical values, actual values may differ

Q CELLS PERFORMANCE WARRANTY

At least 97.0% of nominal power during first year. Thereafter max. 0.7% degradation per year.
At least 90.7% of nominal power up to 10 years.
At least 81.5% of nominal power up to 25 years.

All data within measurement tolerances. full warranties in accordance with the warranty terms of the Q CELLS sales organization of your respective country.

PERFORMANCE AT LOW IRRADIANCE

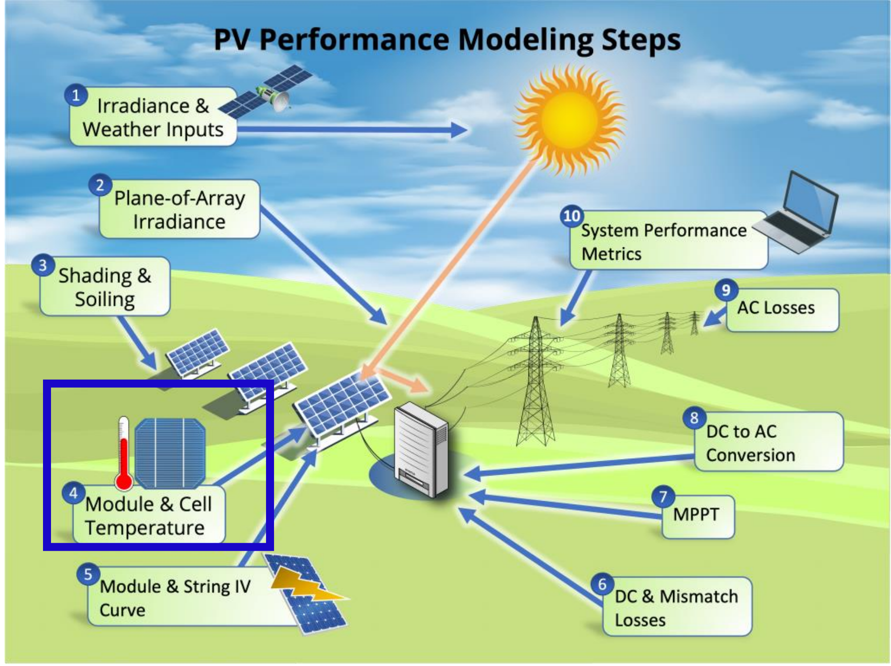
Typical module performance under low irradiance conditions in comparison to STC conditions (25°C, 1000 W/m²).

TEMPERATURE COEFFICIENTS

Temperature Coefficient of I_{SC}	α	[%/K]	+0.05	Temperature Coefficient of V_{OC}	β	[%/K]	-0.31
Temperature Coefficient of P_{MPP}	γ	[%/K]	-0.40	Normal Operating Cell Temperature	NOCT	[°C]	45±3

Ross, R. G. Jr., (1981). “Design Techniques for Flat-Plate Photovoltaic Arrays”

Modeling steps



4. Cell temperature

Faiman model:

Model to estimate the cell temperature $\boldsymbol{T_c}$ [°C] as function of ambient temperature and irradiance $\boldsymbol{G_{POA}}$ [W/m²] AND wind WS $[\frac{m}{s}]$.

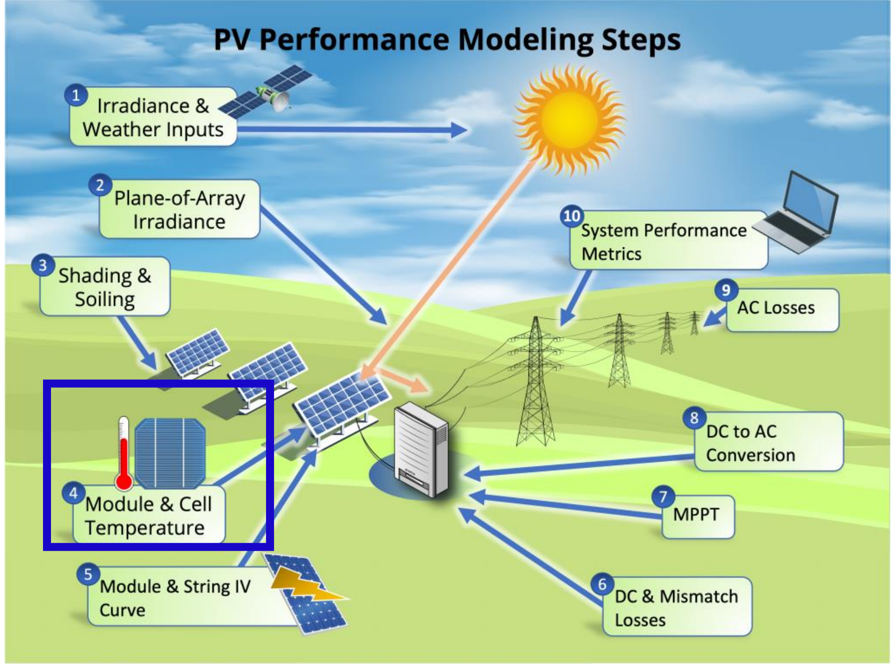
$$T_m = T_a + \frac{G_{POA}}{U_0 + U_1 \cdot WS}$$

U_0 is the constant heat transfer component $[\frac{W}{Km^2}]$

U_1 is the convective heat transfer component$[\frac{W}{Km^2(\frac{m}{s})}]$

Faiman, D. (2008). Assessing the outdoor operating temperature of photovoltaic modules.

Modeling steps



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$$T_m = T_a + \frac{G_{POA}}{U_0 + U_1 \cdot WS}$$

In some cases, $T_c \simeq T_m$ can be assumed
Between T_c and T_m, only few degrees of difference

U_0 is the constant heat transfer component $[\frac{W}{Km^2}]$

U_1 is the convective heat transfer component $[\frac{W}{Km^2(\frac{m}{s})}]$

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Modeling steps

4. Cell temperature

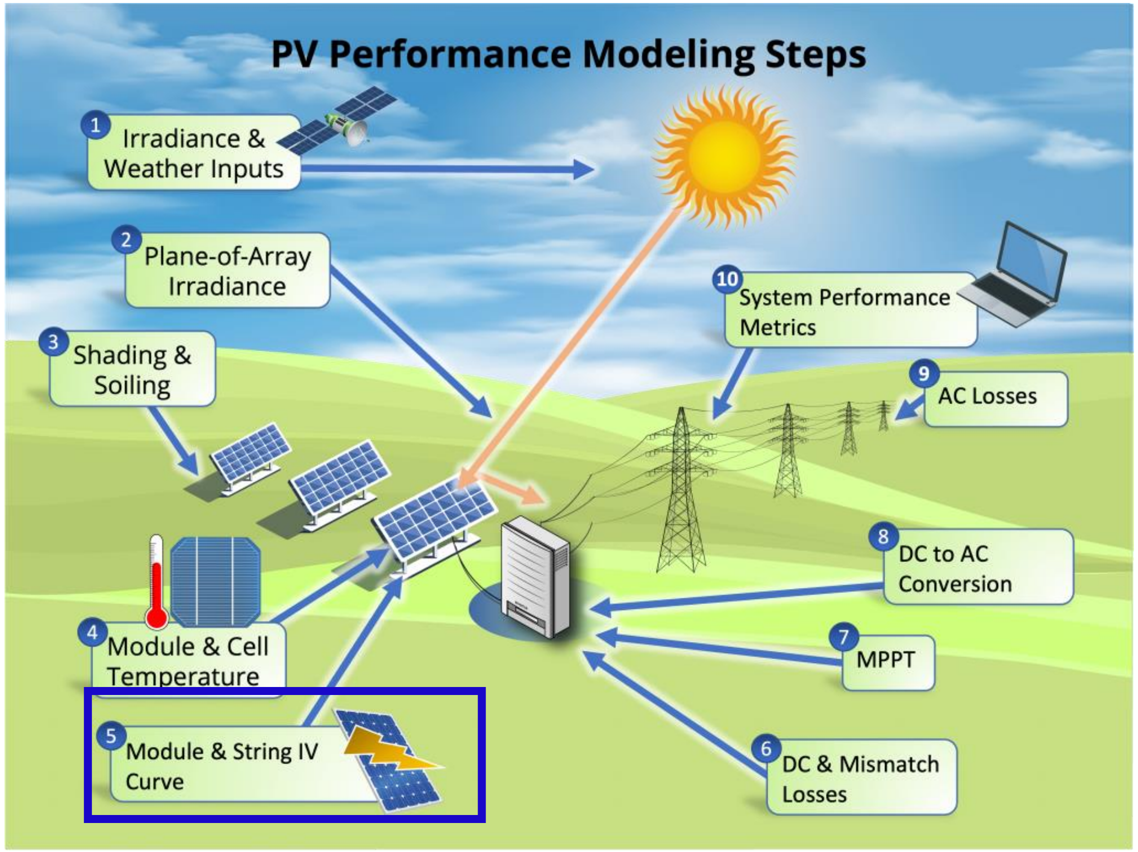
Time for some hands-on exercises !

Use the following notebook: https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy/blob/master/notebooks/dc_power_estimation.ipynb

Follow the python tutorial and estimate the cell temperature for one year.

Modeling steps

5. Module and String IV Curve



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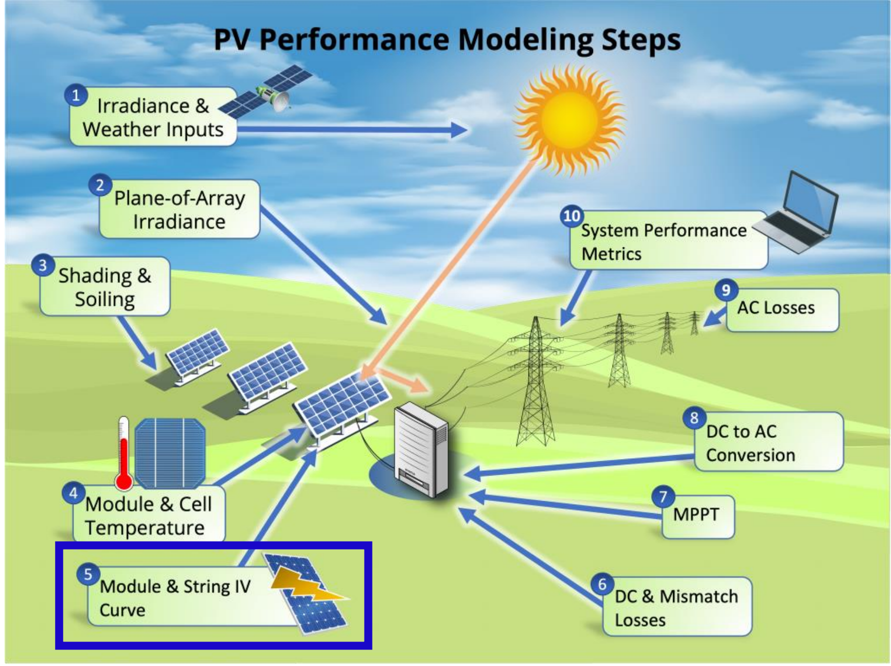
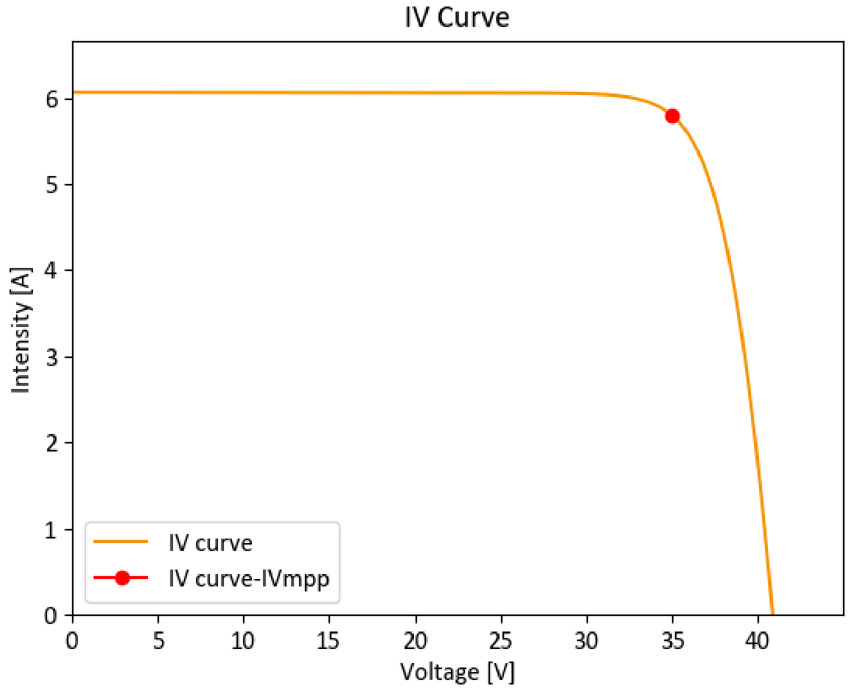
Modeling steps



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.



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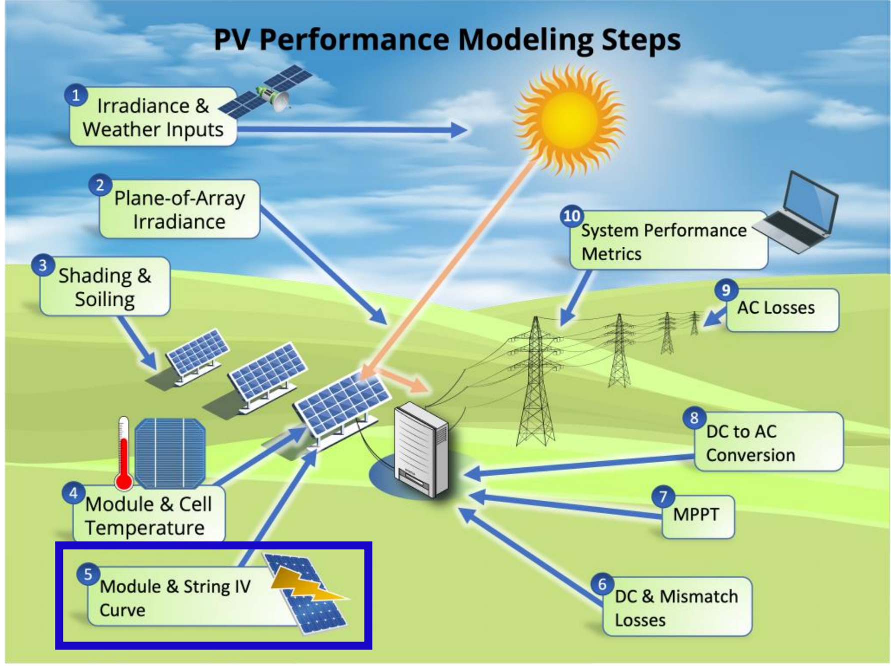
Modeling steps



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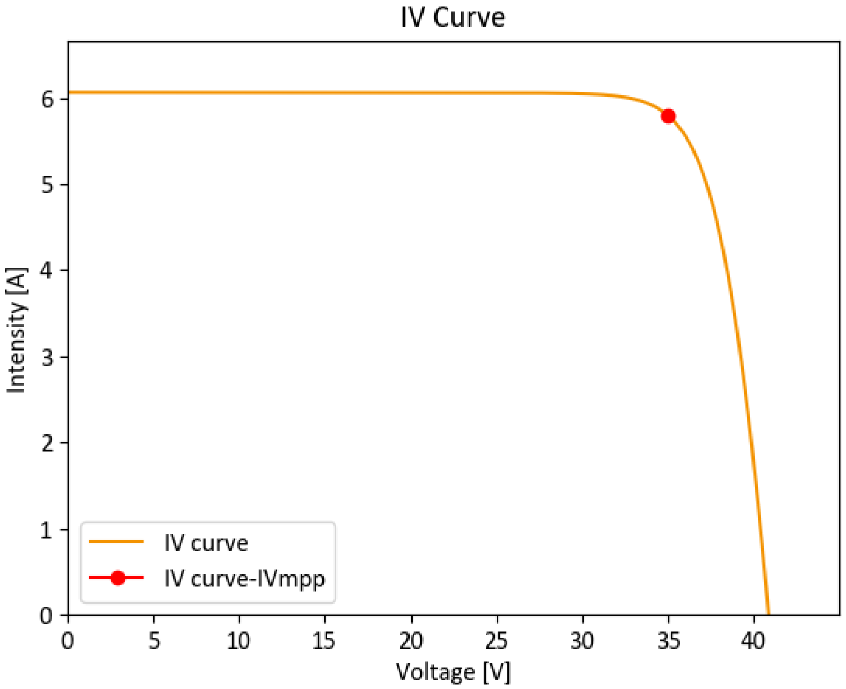
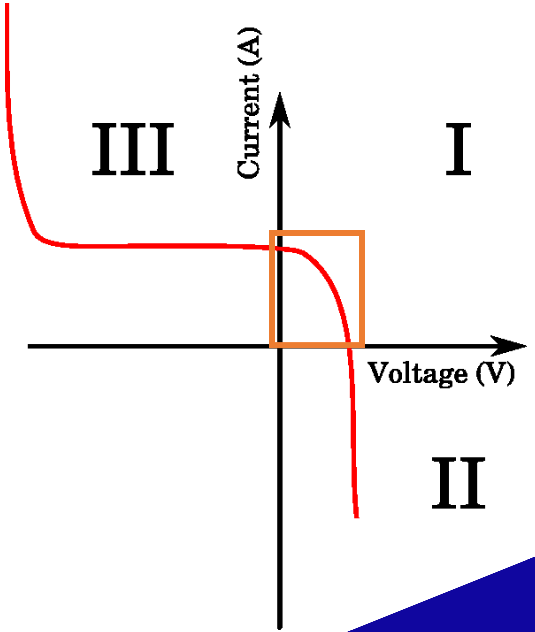
For a fixed irradiance and module temperature, the PV module has its I, current which depends on V, voltage and it can take many operating points.



In reality, the IV characteristics go out of the 1st quadrant and the module can potentially consume power.



Modeling steps

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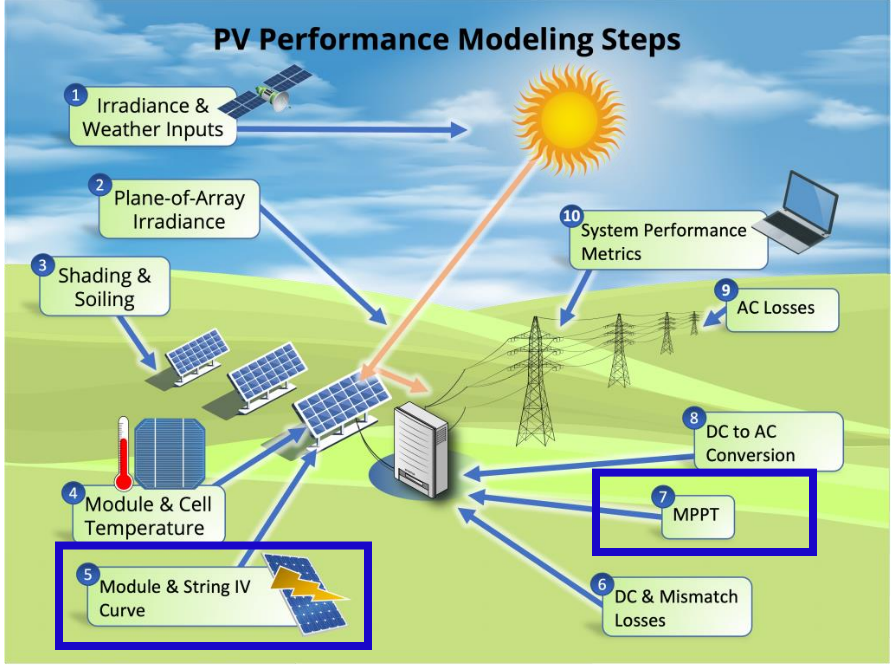

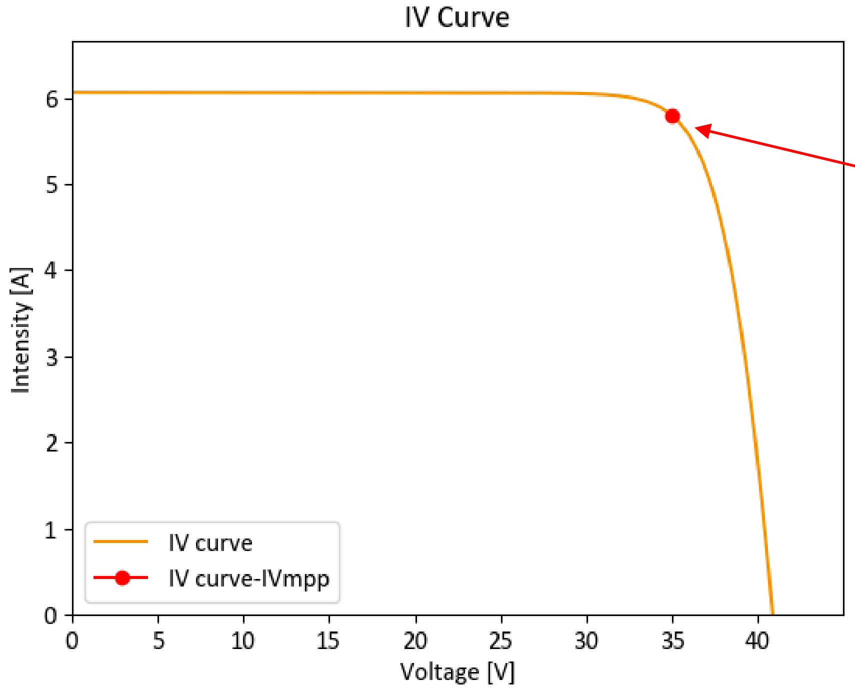

Then, the inverter is constantly searching for the operating point which maximizes the power MPP: Maximum Power Point.

Modeling steps

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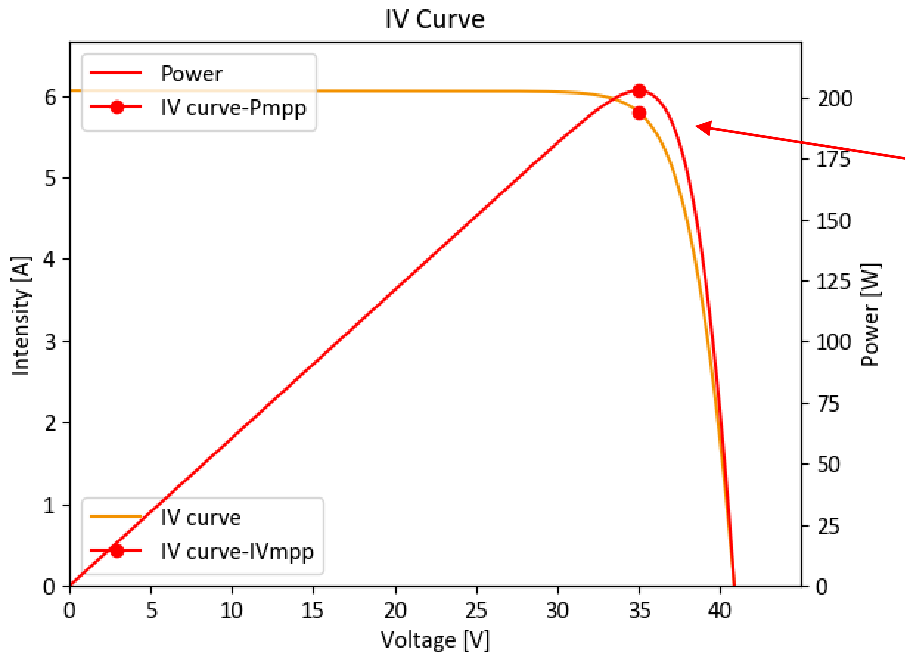
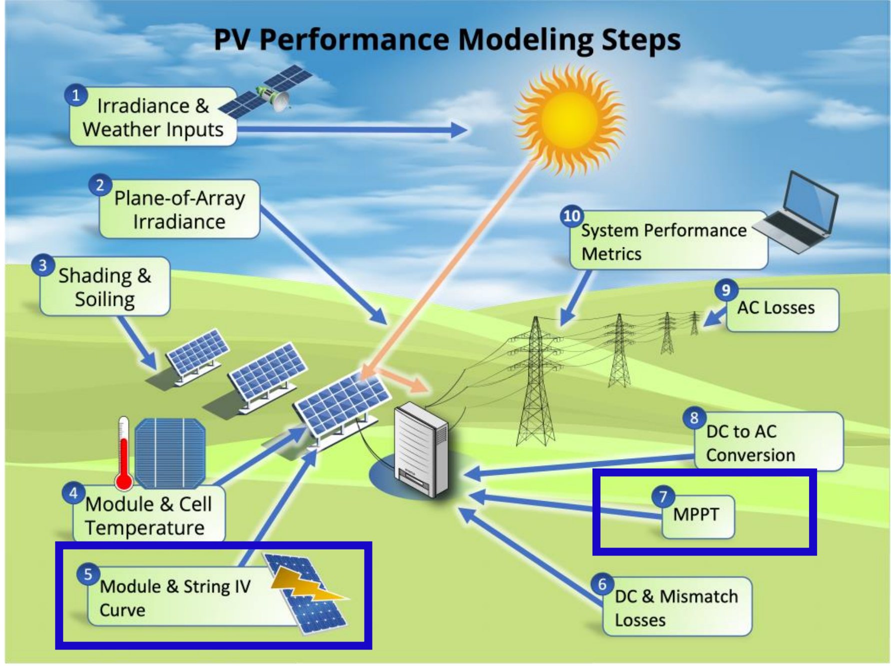
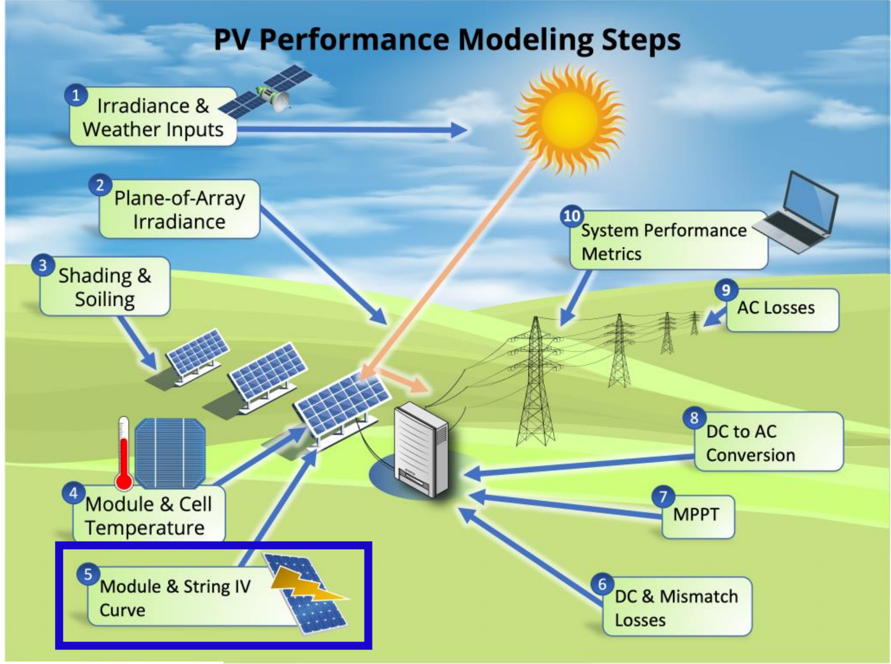


Then, the inverter is constantly searching for the operating. point which maximizes the power MPP: Maximum Power Point.

Especially, it changes the voltage with the MPP-Tracker (MPPT) to maximize power.

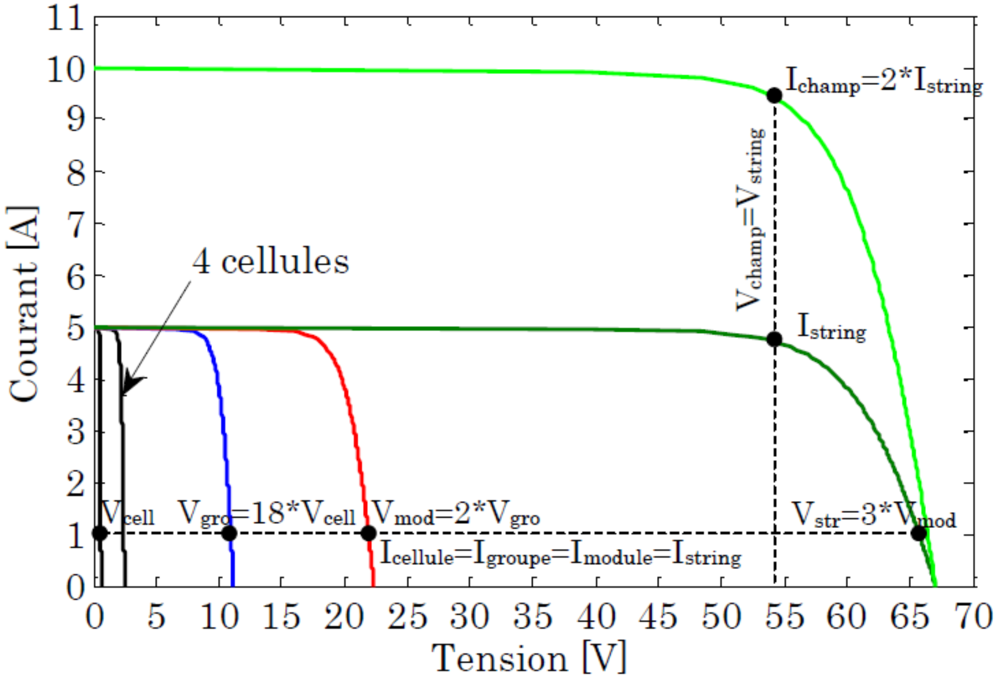




Modeling steps

5. Module and String IV Curve

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).

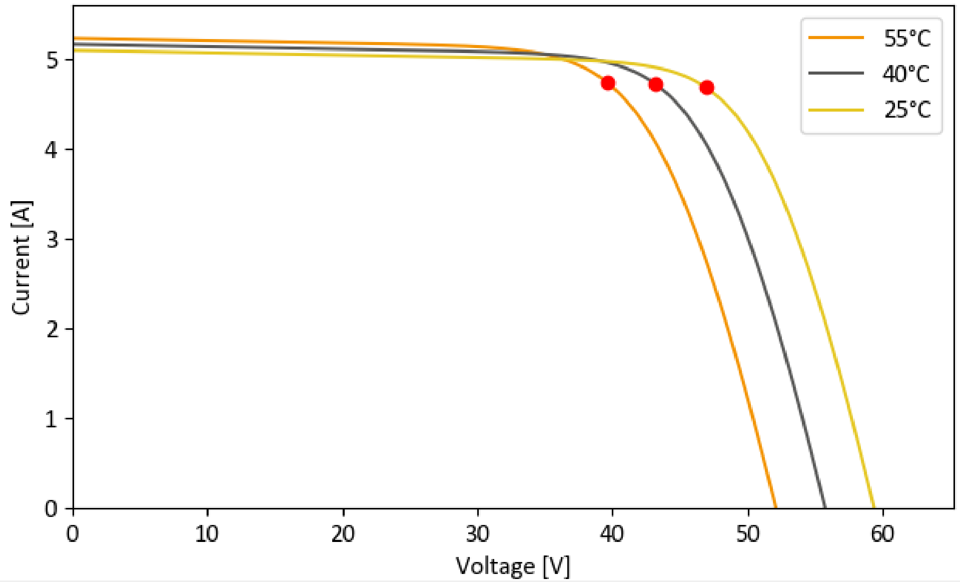
Modeling steps

5. Module and String IV Curve

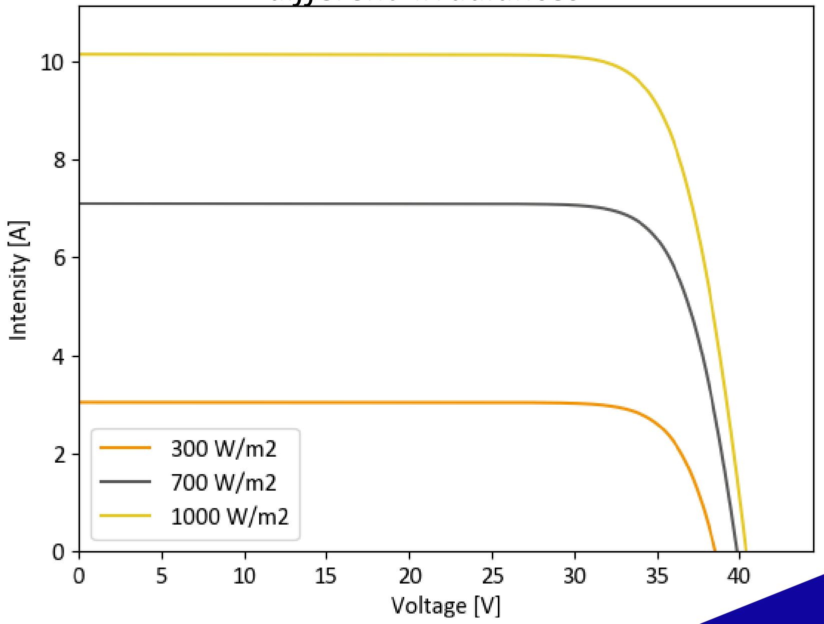
The IV curves' dependencies:

- Higher cell temperatures mostly decrease the voltage
- Higher irradiance level mostly increase the current

Example of I-V curves as function of different module temperature



Example of I-V curves as function of different irradiances



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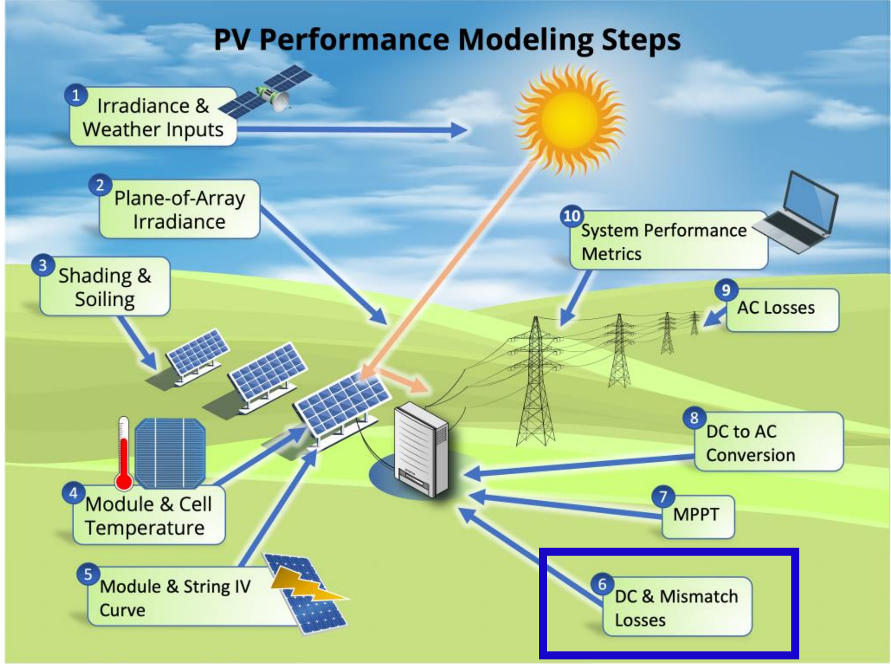
Modeling steps

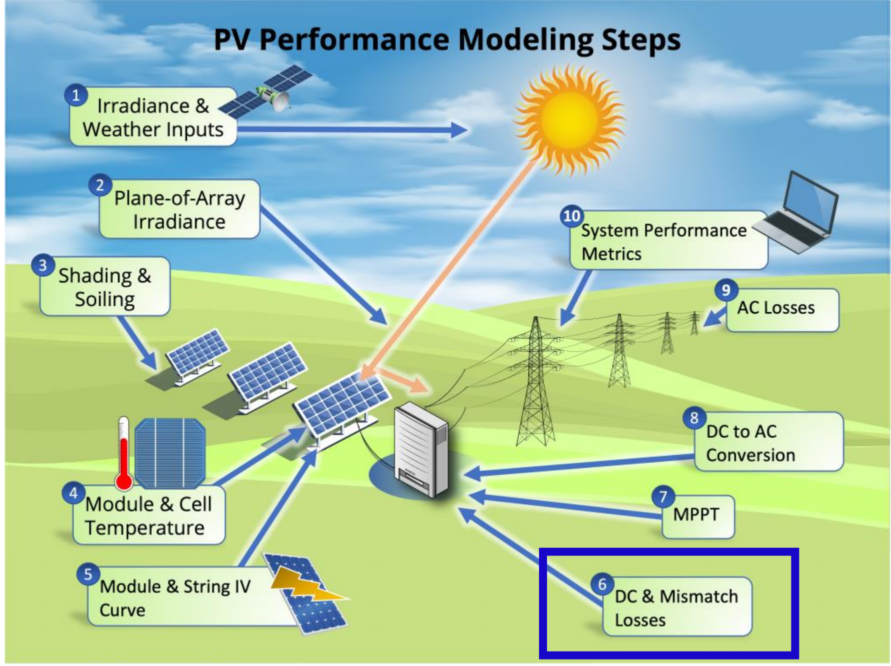


6. DC & Mismatch Losses

Not the focus of this class. However, keep in mind that:

- **DC wiring losses** are around 0.5%-2%.
- **Mismatch losses** refer to the fact that PV modules have different IV curves and this can entail significant losses.

Modeling steps



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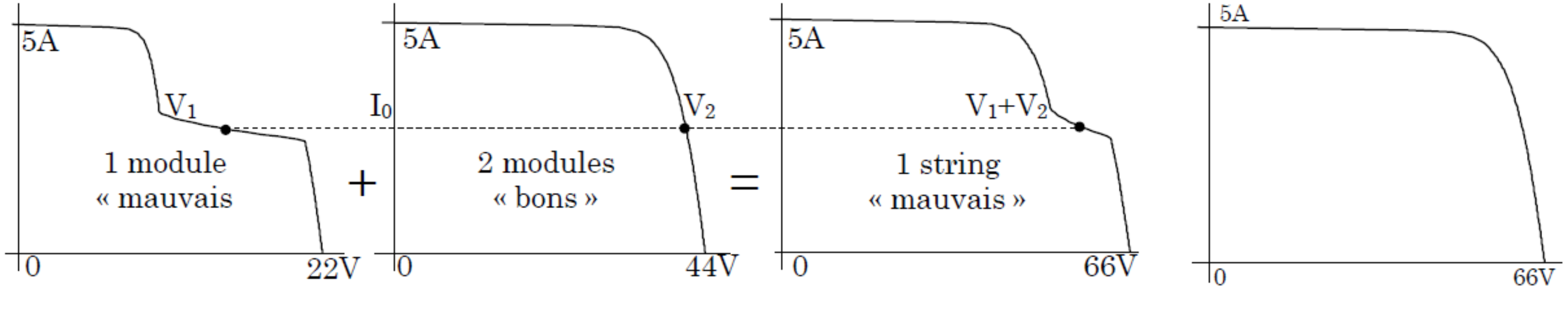
Not the focus of this class. However, keep in mind that:

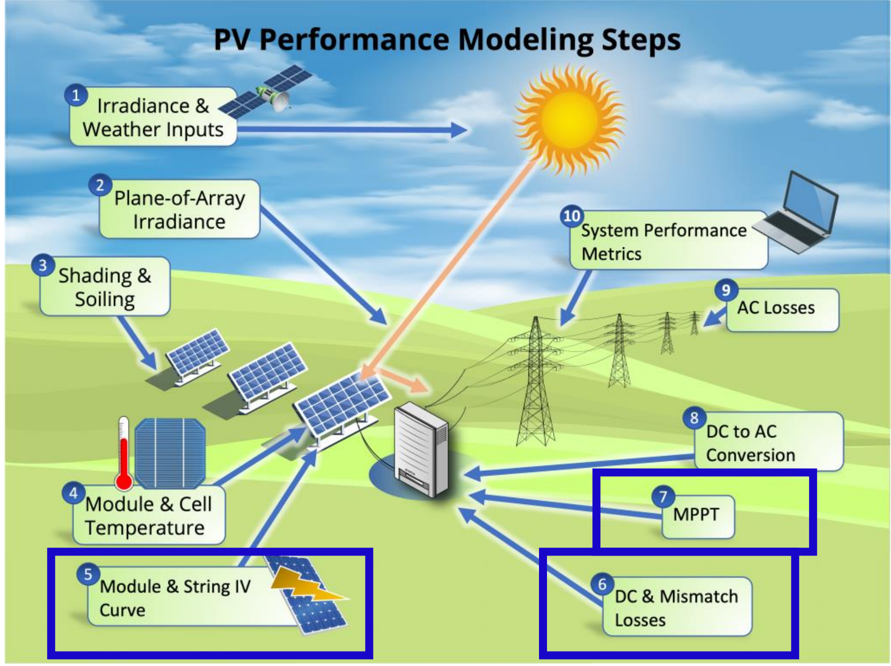
- **DC wiring losses** are around between 0.5% and 2%.
- **Mismatch losses** refers to the fact that PV modules have different IV curves and this can entail significant losses.
  For instance, if one of them has a very degraded IV curve (shading or other), it can significantly degrade the IV curve at the array level.



(a) string « mauvais » (b) string « bon »

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

Modeling steps



5./6./7. Power model

<u>Constant efficiency model:</u>

$$P_{dc} = \eta \cdot G_{POA} \cdot A$$

With:

- P_{dc}, DC power in [W]
- η efficiency around 20% (from datasheet)
- G_{POA} the irradiance in the plane of array [W/m²]
- A, the PV installation area [m2]

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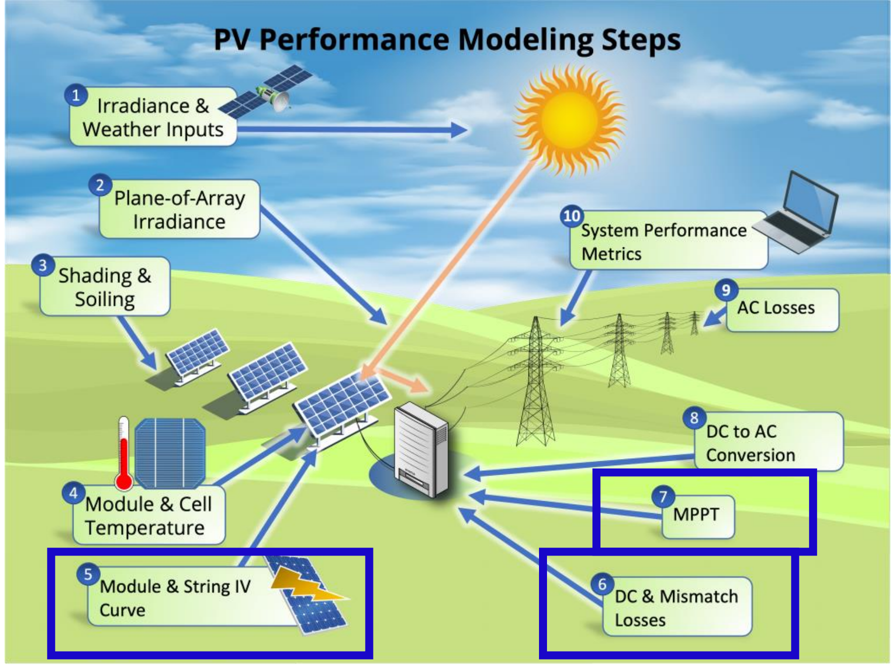
Modeling steps



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Not really precise for instantaneous values

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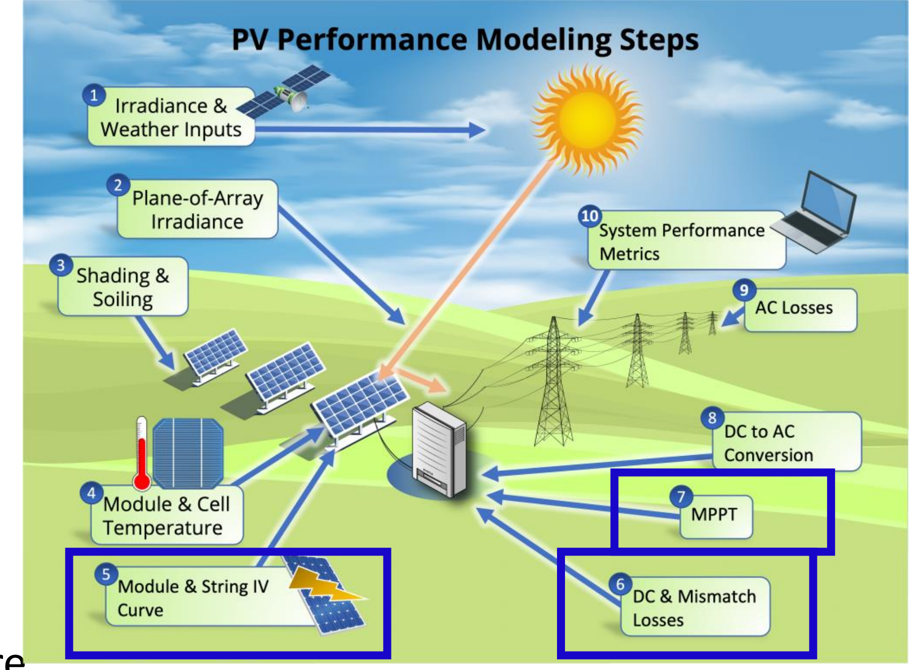
Modeling steps



5./6./7. Power model

The PVWatts model enables to take into account the effect of the cell temperature

$$P_{dc} = \eta_0 \cdot G_{POA} \cdot A \cdot \left(1 + \gamma_{pdc} \cdot (T_{cell} - 25°C)\right)$$

With:

- η_0, the reference efficiency (around 20%) [%]
- G_{POA} the irradiance in the plane of array [W/m²]
- A, the PV installation area [m2]
- γ_{pdc}, the temperature coefficient (negative, usually between -0.2 – -0.5 % W/m²/°C)
- T_{cell}, the cell temperature [°C]

PVWatts model: A. P. Dobos, “PVWatts Version 5 Manual” (2014).

Modeling steps

5./6./7. Power model

The Huld model (used in PVGIS) enables to take into account the module temperature and non-lineary with irradiance.

$$P_{dc} = \eta_{Huld}(G, T_m) \cdot G_{POA} \cdot A$$

$$\eta_{Huld}(G) = \eta_0 \cdot (1 + k_1 \cdot \ln(G') + k_2 \cdot \ln(G')^2 + k_3 \cdot T_m' + k_4 \cdot T_m' \cdot \ln(G') + k_5 \cdot T_m' \cdot \ln(G')^2 + k_6 \cdot T_m'$$

With:

- η_0, the reference efficiency (around 20%) [%]
- G_{POA} the irradiance in the plane of array [W/m²]
- A, the PV installation area [m2]
- $G' = \frac{G_{POA}}{1000\, W/m^2}$ the normalized irradiance
- $T_m' = T_m - 25°C$, the module temperature delta [°C]
- $k_1 \ldots k_6$, the model coefficients

Huld model: Thomas Huld et al., A power-rating model for crystalline silicon PV modules, 2011,

Modeling steps

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Reference values from PVGIS

Coefficient	c-Si	CIS	CdTe
k_1	-0.017237	-0.005554	-0.046689
k_2	-0.040465	-0.038724	-0.072844
k_3	-0.004702	-0.003723	-0.002262
k_4	0.000149	-0.000905	0.000276
k_5	0.000170	-0.001256	0.000159
k_6	0.000005	0.000001	-0.000006

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Modeling steps

5./6./7. Power model

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Follow the python tutorial and estimate the DC power for one year.

Resources

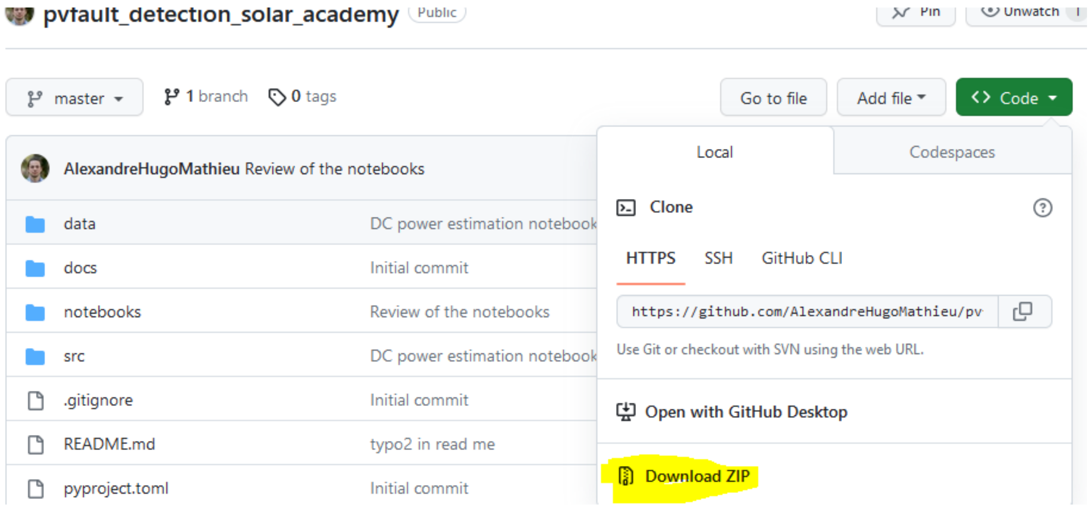
- Modeling guide PVPMC: https://pvpmc.sandia.gov/modeling-guide/
- Python / Pvlib tutorial: https://pvsc-python-tutorials.github.io/PVSC48-Python-Tutorial/
- To go further:
    - The Use of Advanced Algorithms in PV Failure Monitoring: https://iea-pvps.org/wp-content/uploads/2021/10/Final-Report-IEA-PVPS-T13-19_2021_PV-Failure-Monitoring.pdf

Appendix

How to install Python and import the course repository to use the notebooks on your local PC.

1. Install python: www.python.org/downloads/, download and install the 3.9.13 “release” (Add python to your Path)

2. Go to https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy, click on the green “Code” button and then download the folder as the zip



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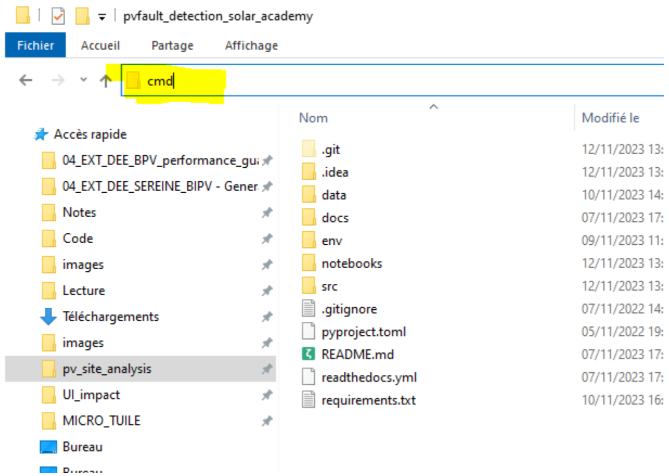

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    1. Go in the folder and open the command line from that same folder by writing “cmd” in the path bar (with Windows)

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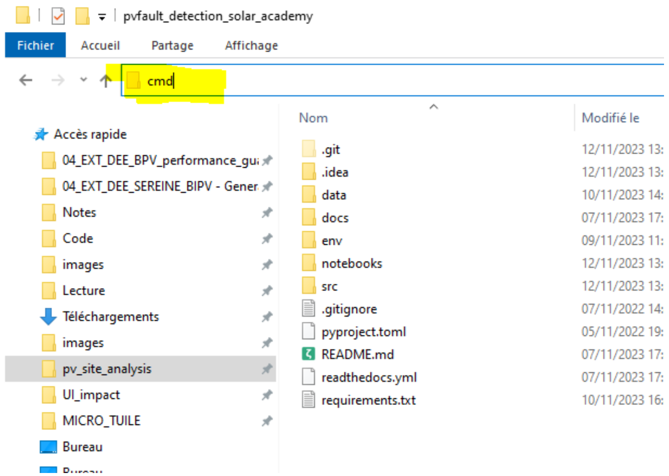
    1. Go in the folder and open the command line from that same folder by writing "cmd" in the path bar (with Windows)
    2. In the command bar: execute the following line to create the "solar_env" environnement that you will use in your notebooks
        1. "pip install virtualenv"
        2. "python –m virtualenv solar_env"
        3. "call solar_env\Scripts\activate" (you should have a 'solar_env' on the left of the command at this point)
        4. "pip install –r requirements.txt" (load all the libraries, take a little time, be patient)
        5. "python -m ipykernel install --name=solarkernel" (create a kernel for the notebooks)

It's ready !

Appendix

How to start a notebook

1. Go in the folder and open the command line from that same folder by writing “cmd” in the path bar (with Windows)



2. In the command bar, exexute:
   1. “call solar_env\Scripts\activate” (go in the virtual env)
   2. “jupyter notebook” (open the notebooks browser)

3. Browse to the notebooks folder, choose one and pick the solarkernel when asked.