Operational research for urban solar development

“PV failure detection based on operational time series”

07/12/2023
Alexandre Mathieu

Agenda

Curriculum

PV performance model steps

Curriculum

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

Today →

Project: groups of 2 for the project

Agenda

Curriculum

PV performance model steps

Modeling steps

27/11/2023 & 05/12/2023

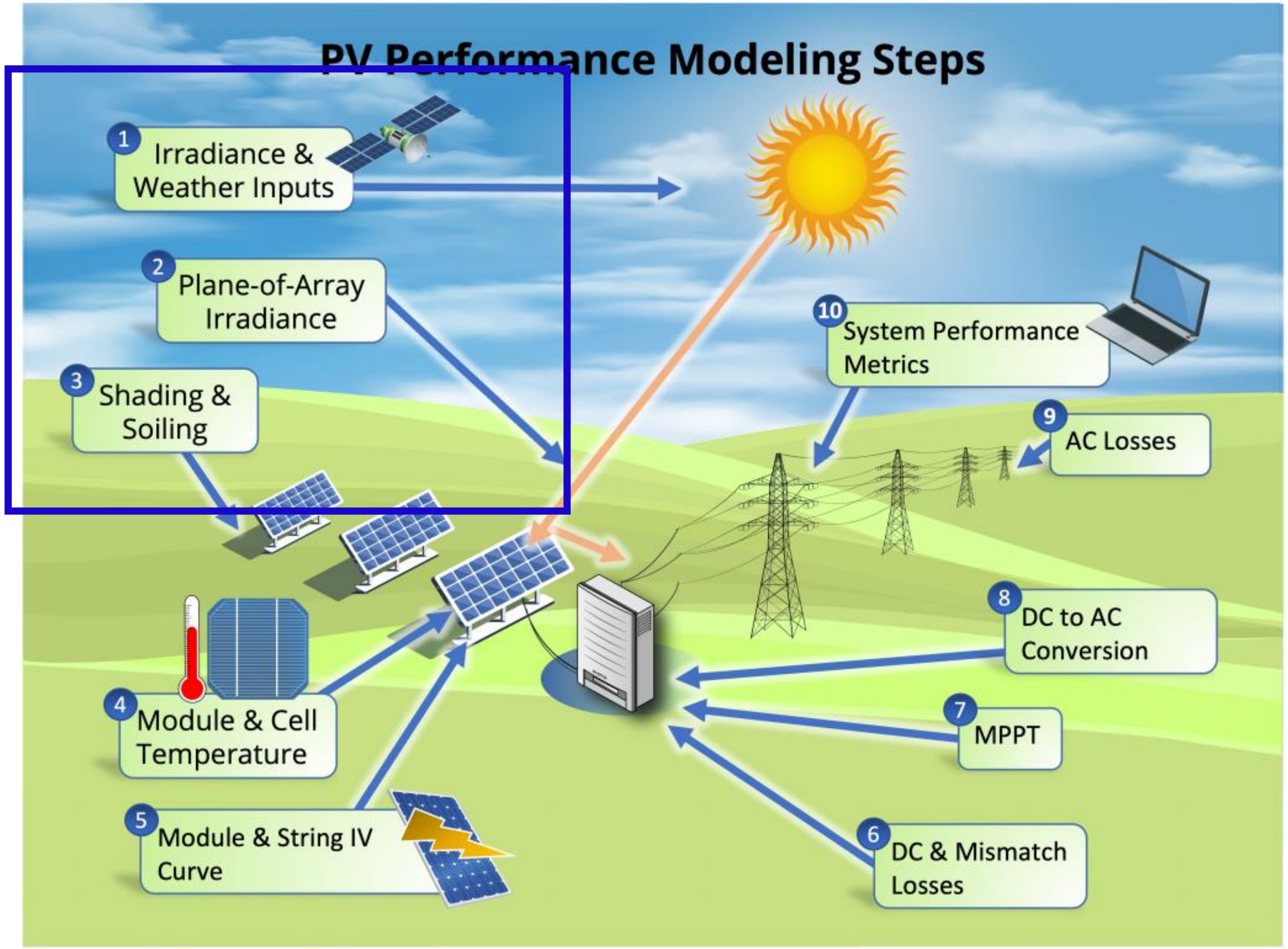


*image from: PVSC48 python tutorial

Modeling steps

27/11/2023
& 05/12/2023

Today

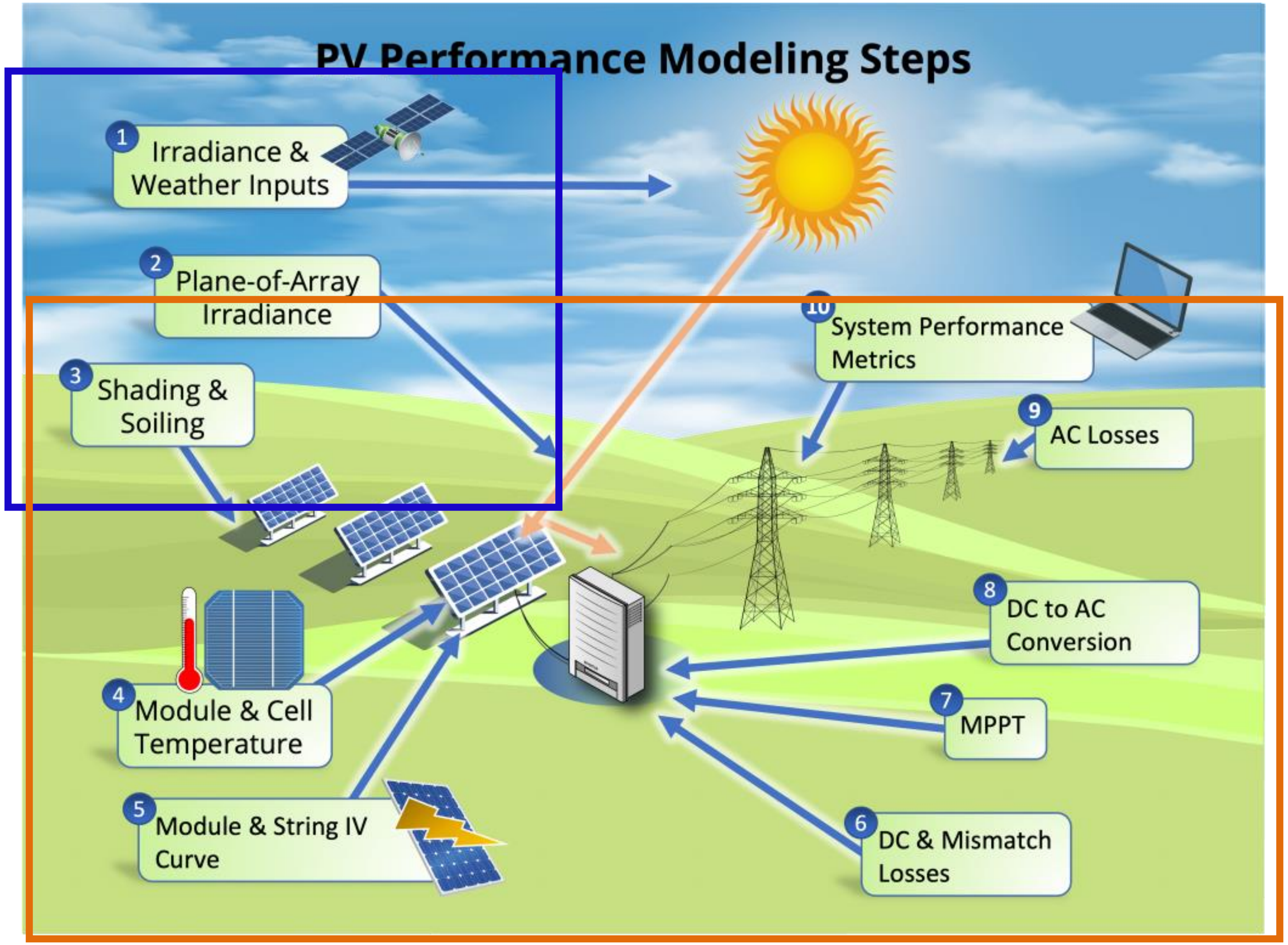


*image from: PVSC48 python tutorial

Modeling steps

Notebook recap 05/12/2023

The notebook is now corrected and can be read online:
https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy/blob/master/notebooks/python_intro2_horizon_mask.ipynb

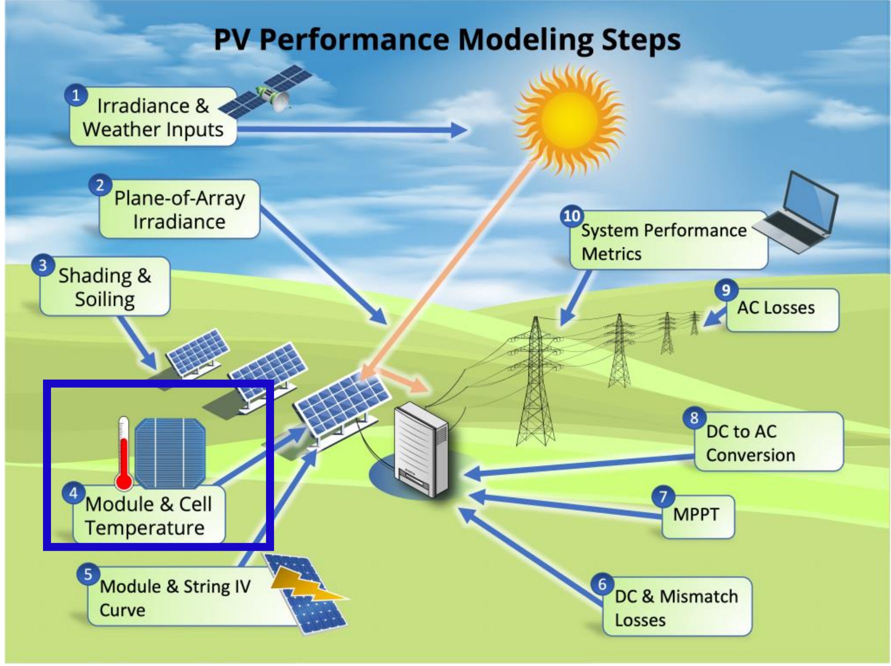
Modeling steps

Notebook recap 05/12/2023

Python commands

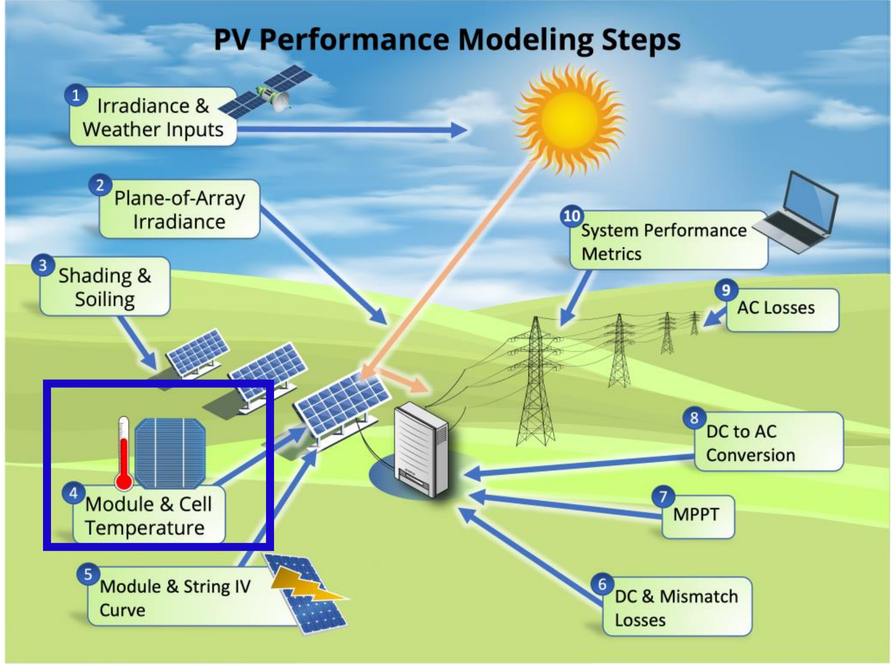
```
import matplotlib.pyplot as plt

# Apply filters
filter_1 = weather_data["ghi"] > 800
filter_2 = (weather_data.index > pd.to_datetime("20220701").tz_localize("CET"))
filter = filter_1 & filter_2 # Combine with a “and” condition
weather_data.loc[filter, "dhi"]

# If statement
a=1
if a<0: # assertion: is "a" under 0 ? Do not forget the “:” at the end of the line
	print("a is lower than 0") # Line non-executed since the assertion above is wrong, do not forget the “tab” indendation after a “if”

# Loop over all elements of a list or pd.Series which allow to perform task on each of the element
For element in [“a”,”b”]:
	print(element)

for index, row in df.iterrows(): # Loop over all rows and index of the dataframe one by one
	print(row["column1"] + row["column2"])

# Plot with matplotlib
plt.plot(x, y, linewidth=0, marker="o") # scatter plot with no line in that case

# Function, useful to store few lines of code you want to reuse and apply with different inputs
def my_func_name(argument1, argument2): # Define the function "" with the "def" command and a small increment tab to the right
	y = argument1 + argument2
	return y

my_func_name(1,2) # Apply the function with two arguments and return 3
my_func_name(1,3) # Return 4
```

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].

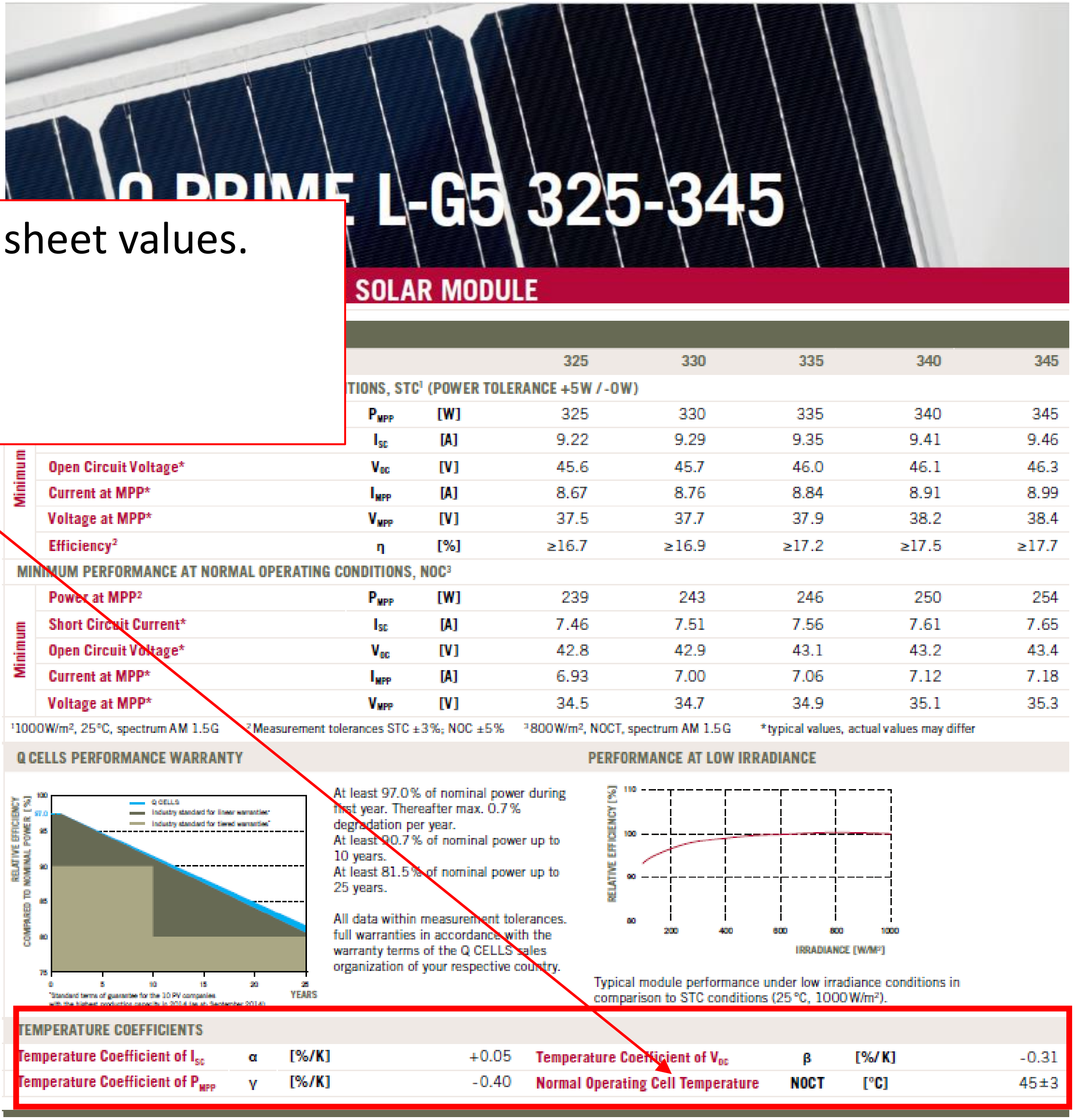
$$T_c = T_a + G_{POA} \cdot k_{Ross}$$

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



			325	330	335	340	345
	P_{MPP}	[W]	325	330	335	340	345
	I_{SC}	[A]	9.22	9.29	9.35	9.41	9.46
Minimum 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]							
Minimum 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] 1000W/m², 25°C, spectrum AM 1.5G [2] Measurement tolerances STC ±3%; NOC ±5% [3] 800W/m², NOCT, spectrum AM 1.5G *typical values, actual values may differ

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

4. Cell temperature

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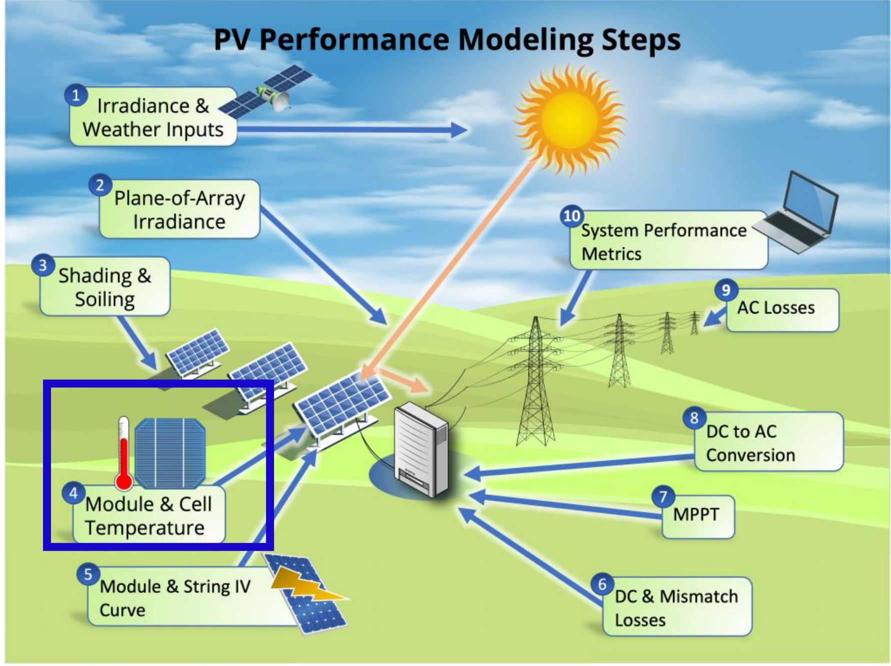
Modeling steps



4. Cell temperature

<u>Faiman model:</u>
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 $[\frac{m}{s}]$.

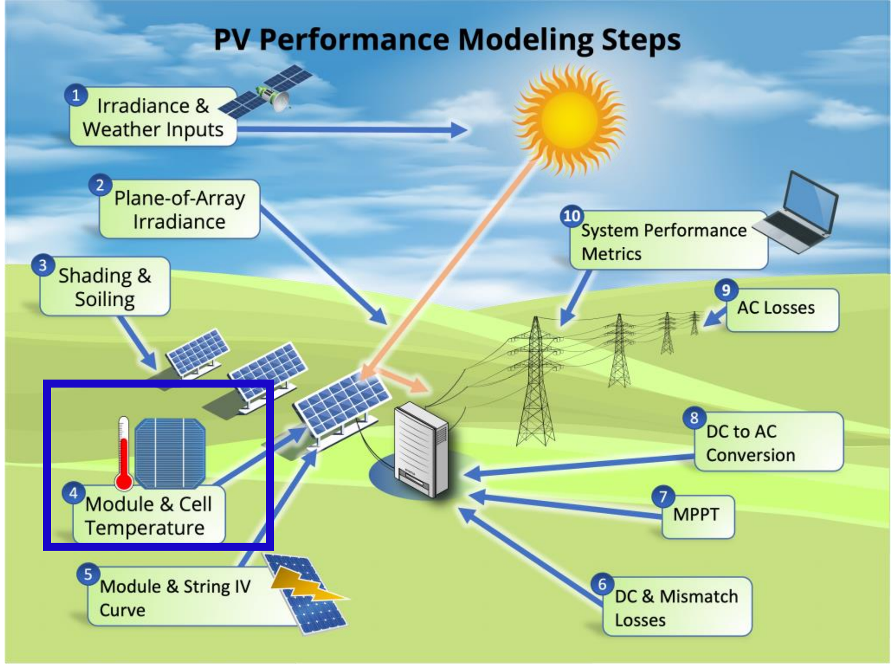
$$T_m = T_a + \frac{G_{POA}}{U_0 + U_1 \cdot WS}$$

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



4. Cell temperature

<u>Faiman model:</u>

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 $[\frac{m}{s}]$.

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

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

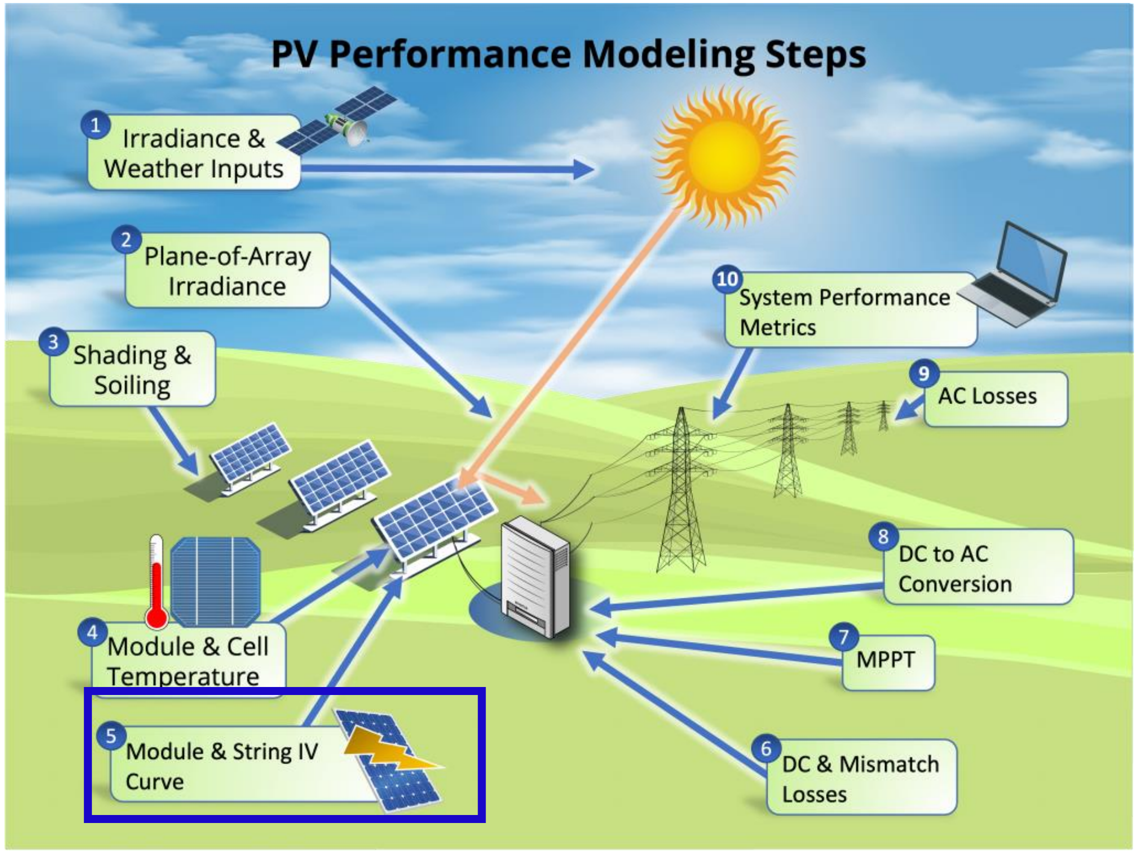
U_0 is the constant heat transfer component $[\frac{W}{Km^2}]$

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

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

Modeling steps

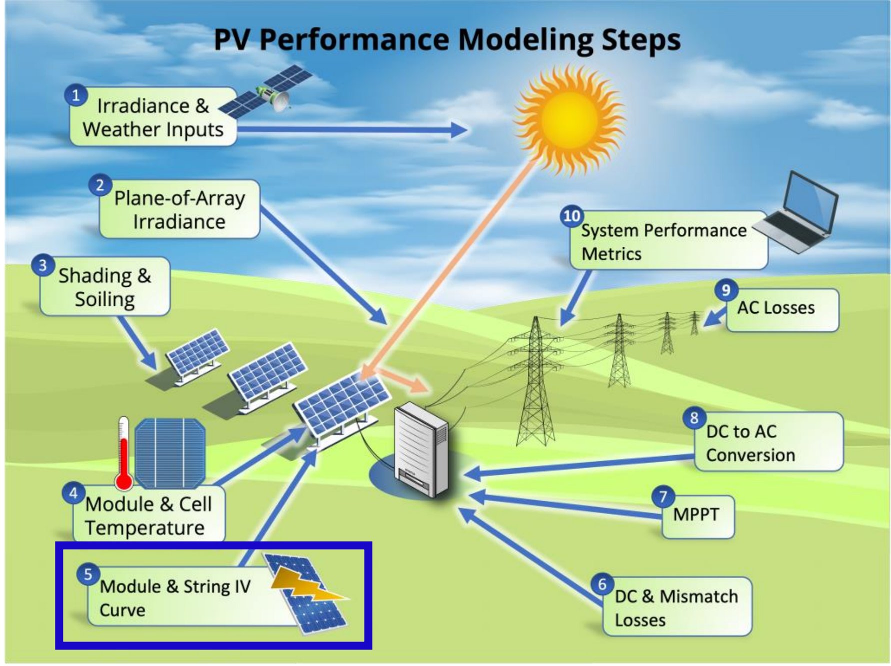
5. Module and String IV Curve

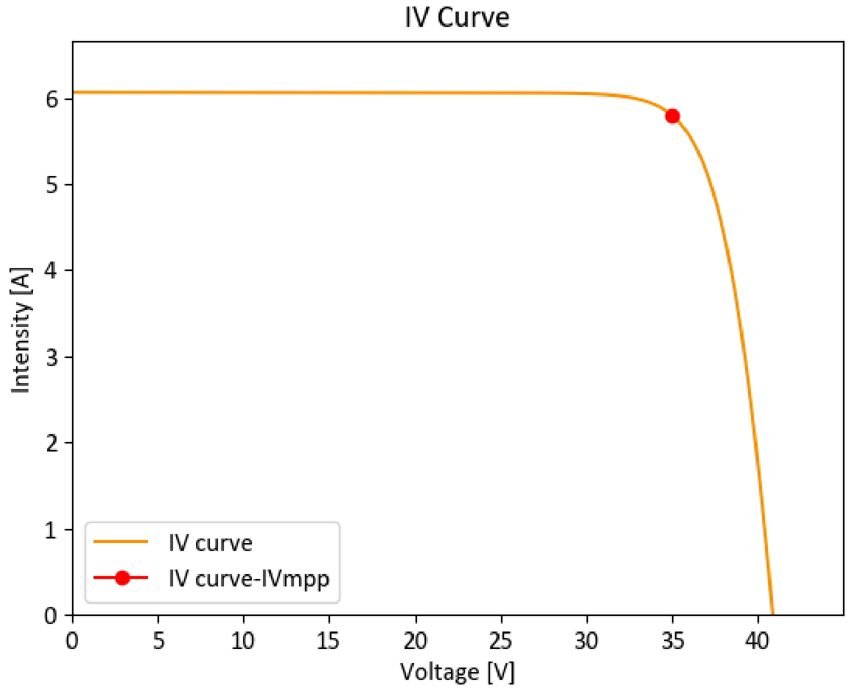


Modeling steps

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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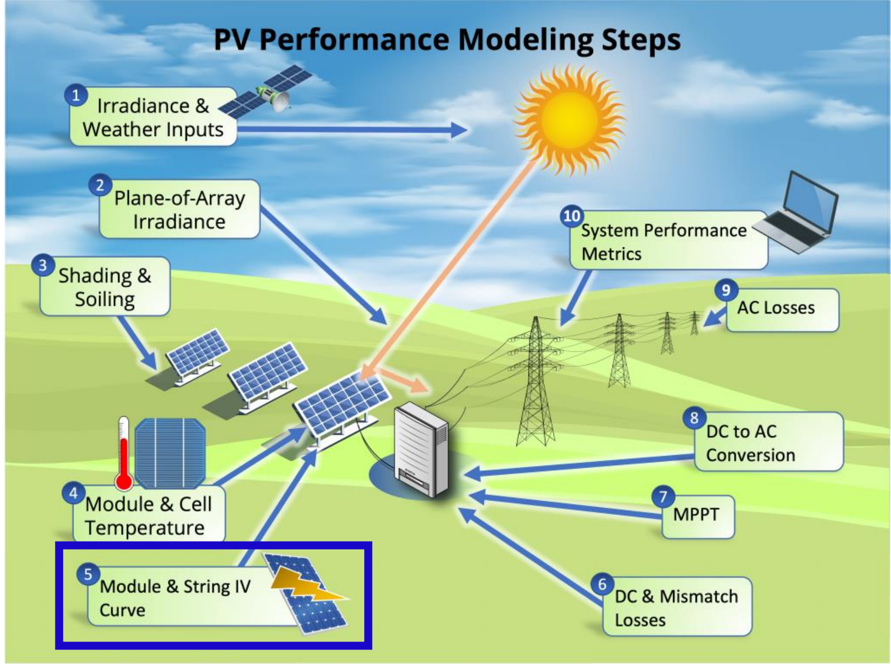
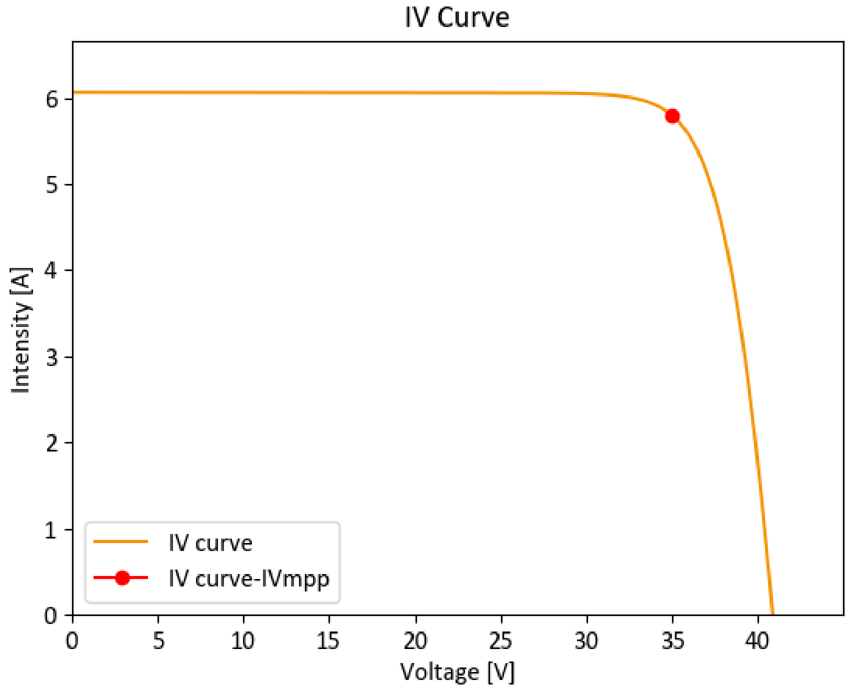
Modeling steps

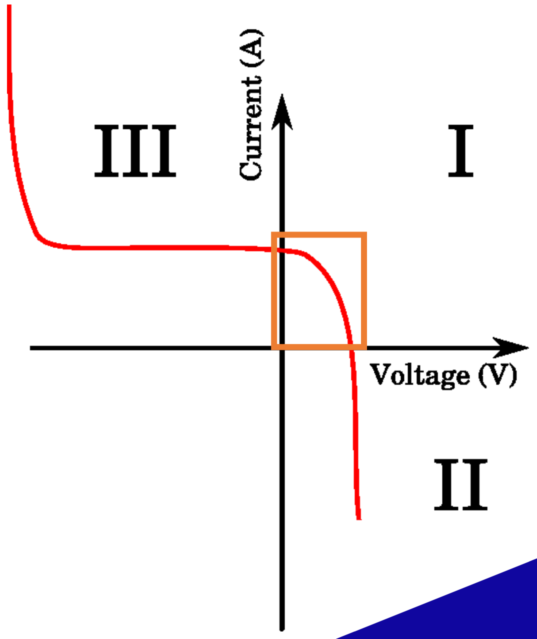


5. Module and String IV Curve

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.



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



Modeling steps

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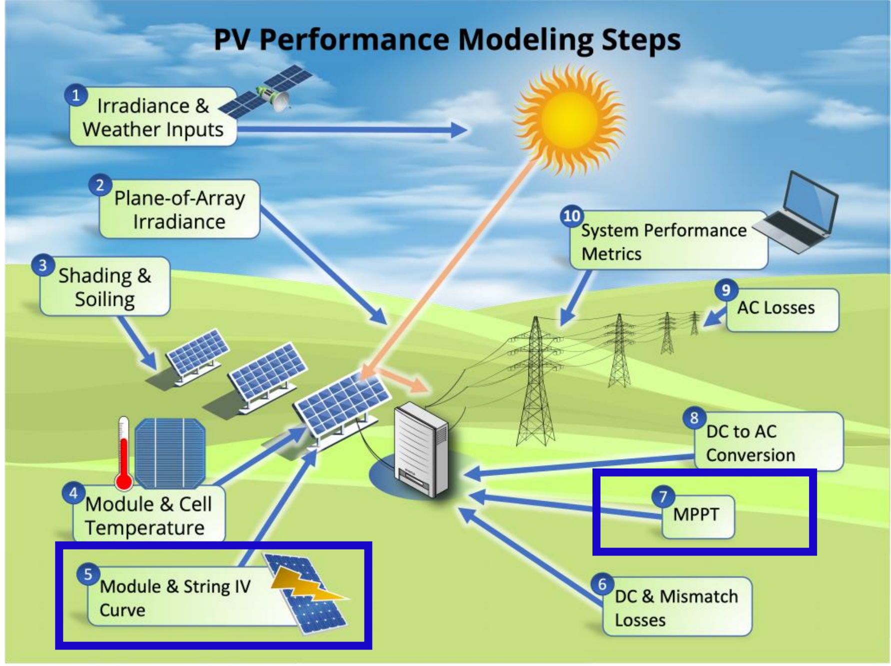

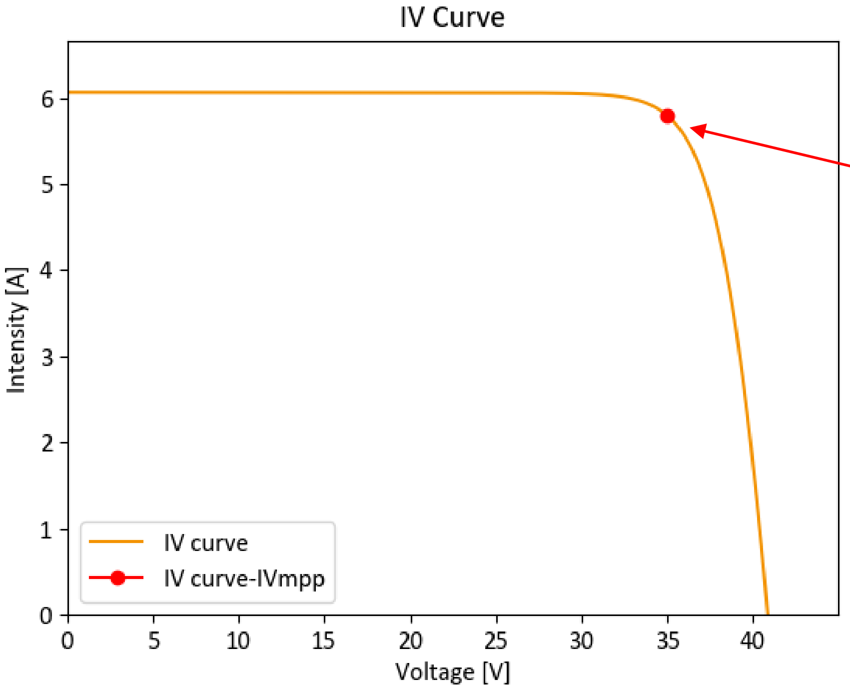

Then, the inverter is constantly searching for the operating point which maximizes the power MPP: Maximum Power Point.

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Modeling steps

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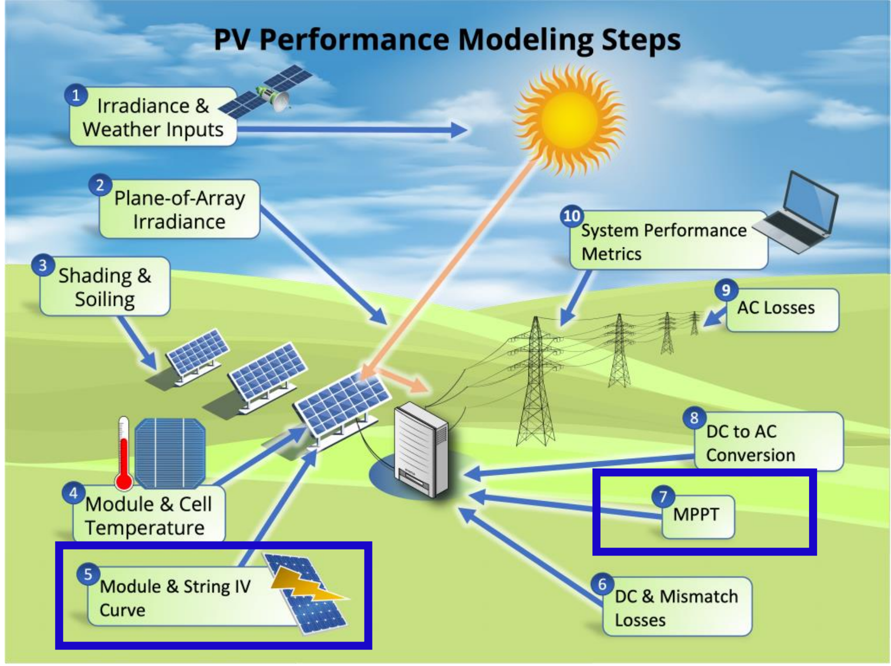
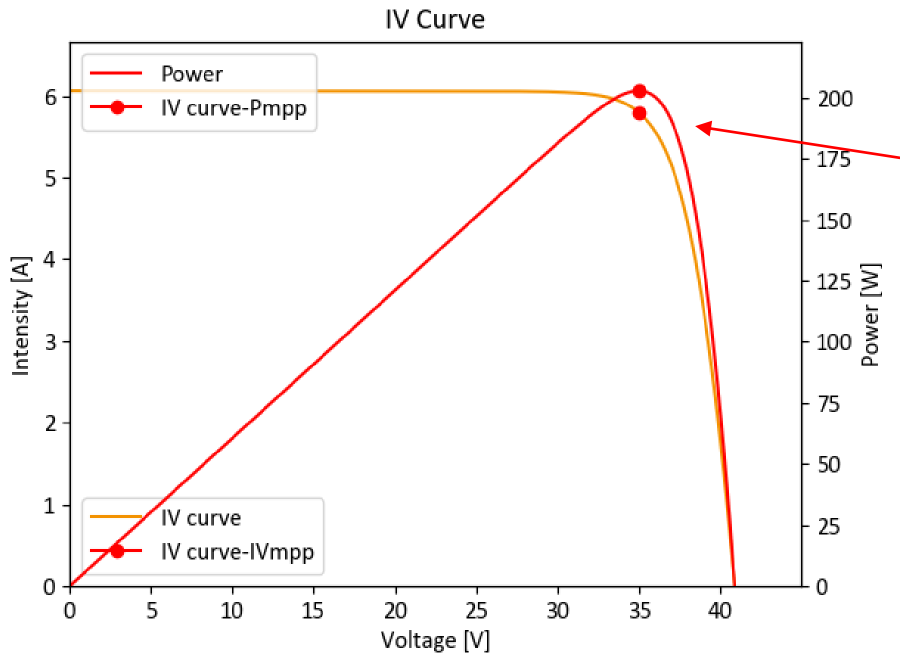




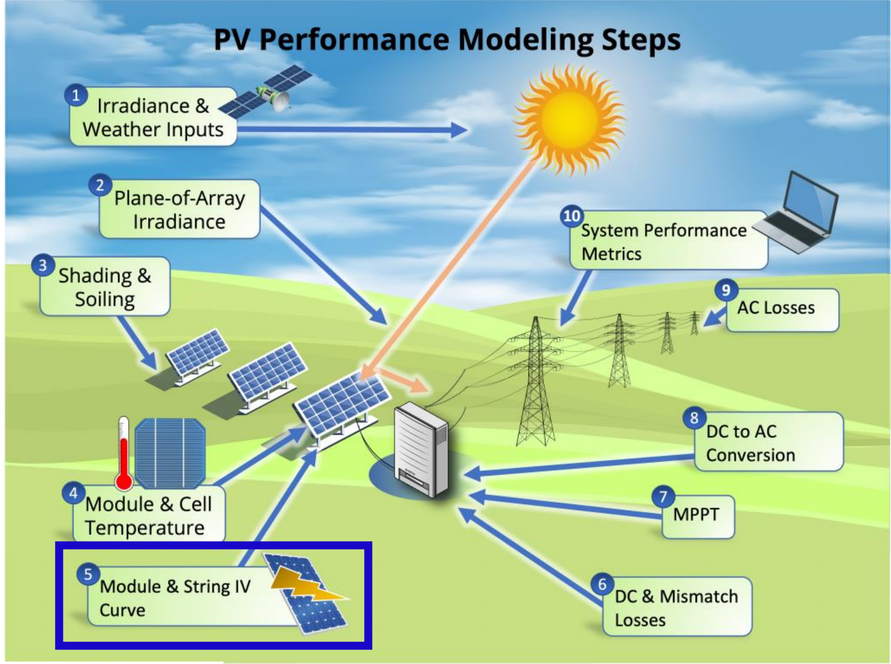
Then, the inverter is constantly searching for the operating point which maximizes the power MPP: Maximum Power Point.

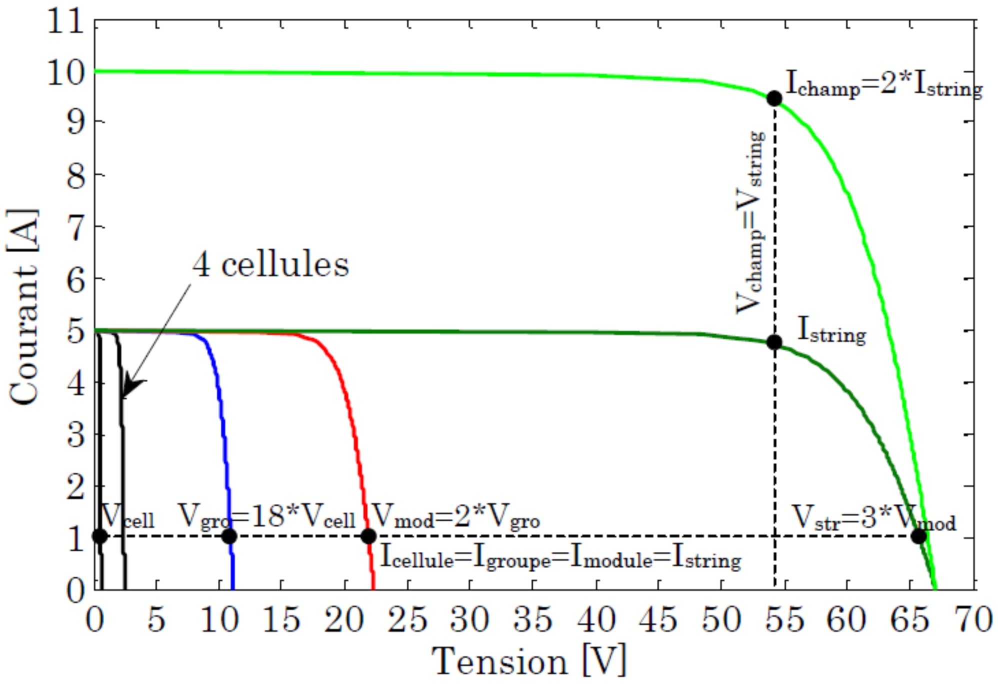
Especially, it changes the voltage with the MPP-Tracker (MPPT) to maximize power.

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).

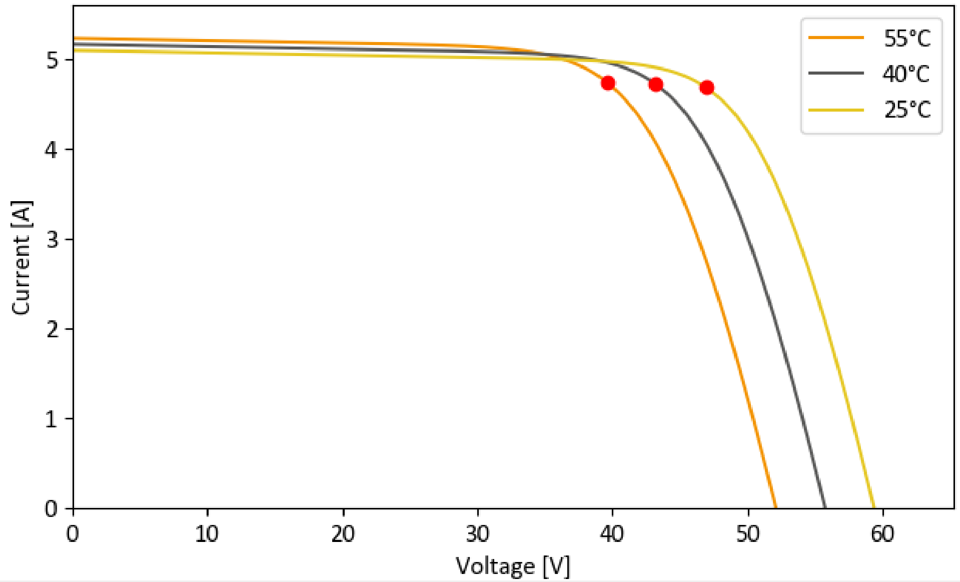
Modeling steps

5. Module and String IV Curve

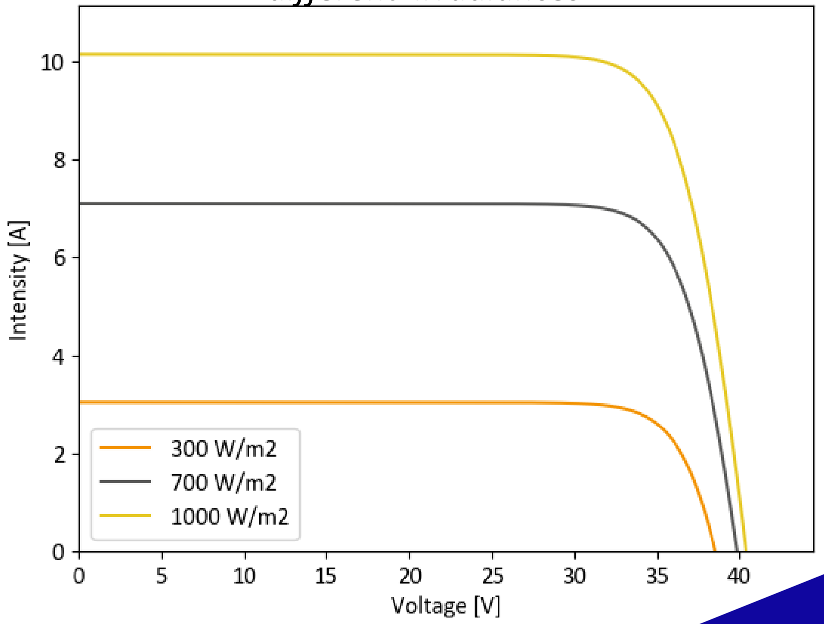
The IV curves' dependencies:

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

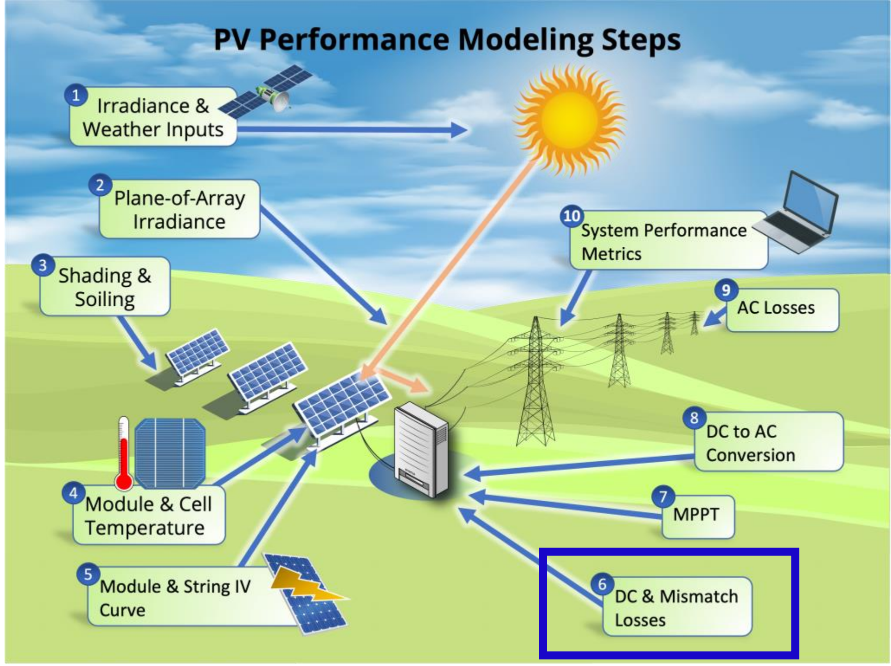
Example of I-V curves as function of different module temperature



Example of I-V curves as function of different irradiances



Modeling steps

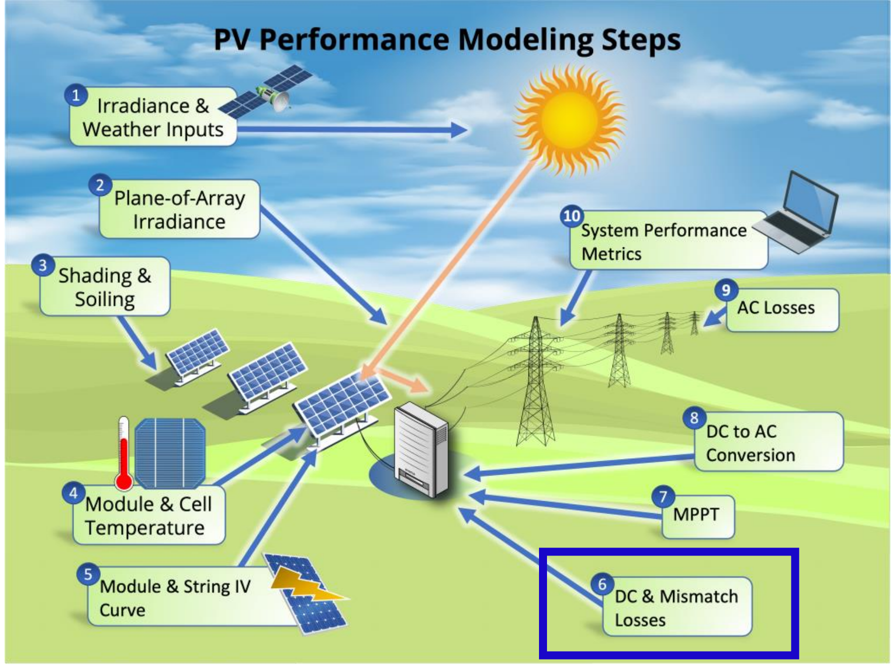


6. DC & Mismatch Losses

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

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

Modeling steps



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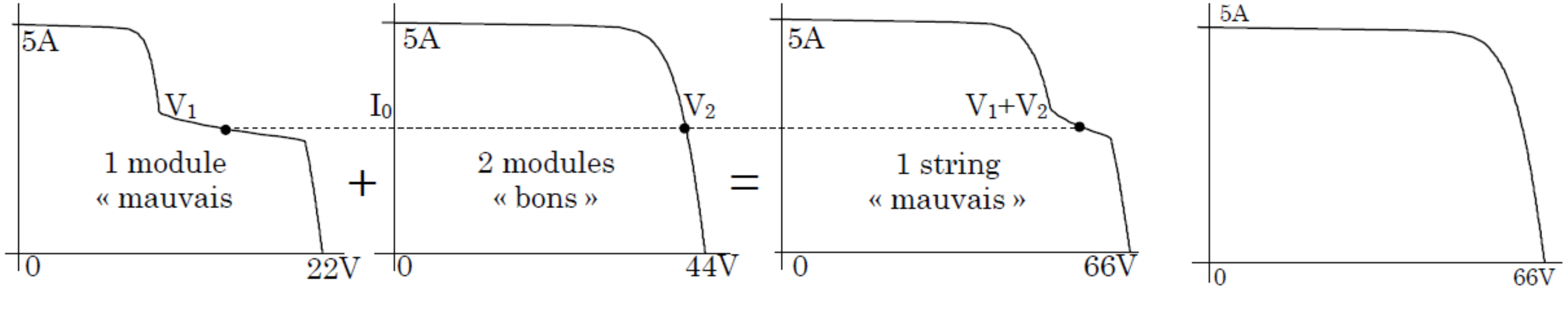
Not the focus of this class. However, keep in mind that:

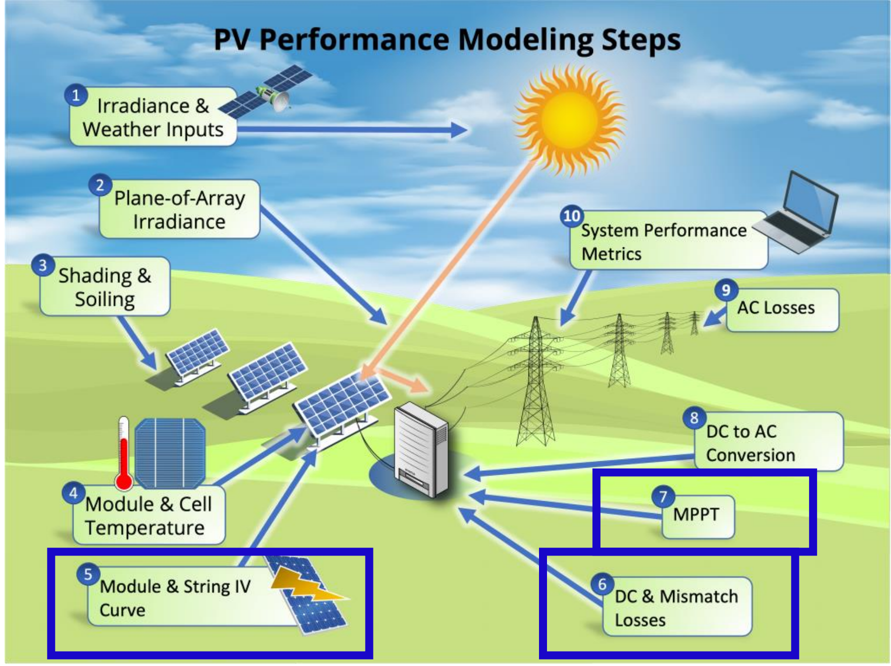
- **DC wiring losses** are around 0.5%-2%.
- **Mismatch losses** refers to the fact that PV modules have different IV curves and this can entail significant losses. For instance, if one of them has a very degraded IV curve (shading or other), it can significantly degrade the IV curve at the array level.



(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

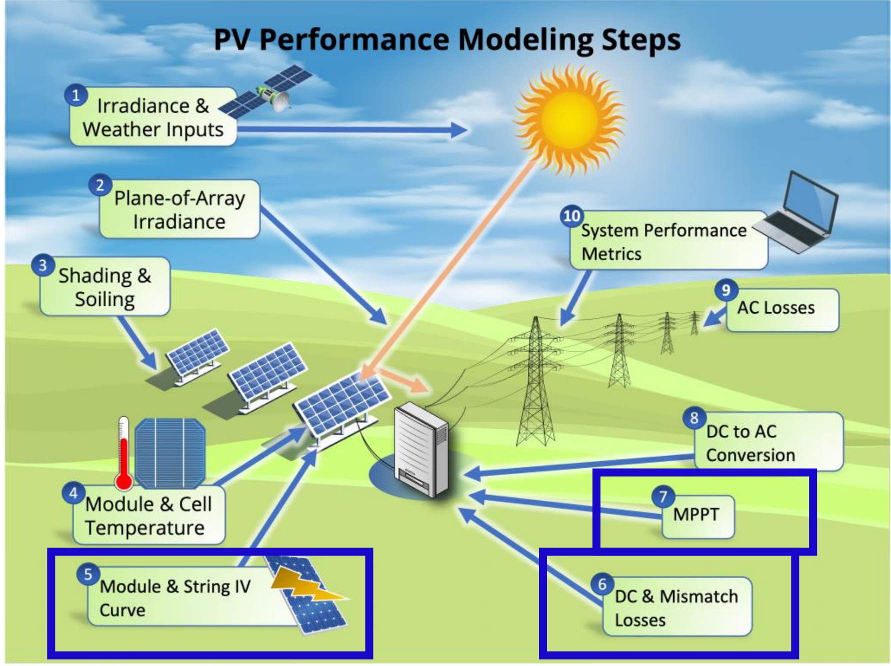
<u>Constant efficiency model:</u>

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

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]

Modeling steps



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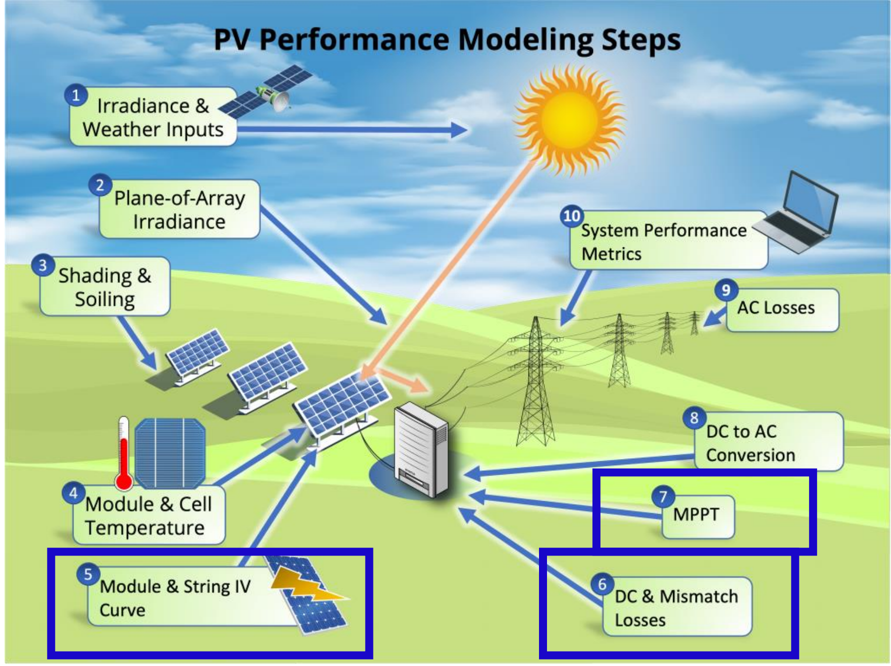
- A, the PV installation area [m2]

Not really precise for instantaneous values

Modeling steps



5./6./7. Power model

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

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

With:

- P_{dc0} Nominal DC power [Wp] (installed capacity)
- G_{POA} the irradiance in the plane of array [W/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).

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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.

$$P_{dc} = \eta_{Huld}(G, T_m) \cdot G' \cdot P_{dc0}$$

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

With:

- P_{dc0} Nominal DC power [Wp] (installed capacity)
- G_{POA} the irradiance in the plane of array [W/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,

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Modeling steps

5./6./7. Power model

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With:

- P_{dc0} Nominal DC power [Wp] (installed capacity)
- G_{POA} the irradiance in the plane of array [W/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

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

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

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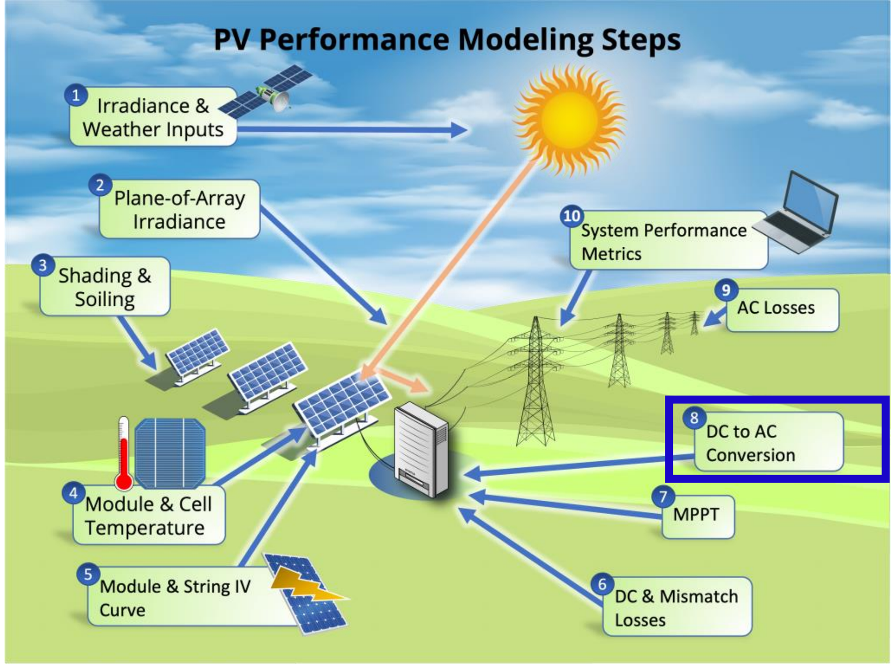
Modeling steps



8. Inverter model

The PVWatts inverter model enables to calculate a generic AC/DC efficiency

$$\eta = \frac{\eta_{nom}}{\eta_{ref}} \cdot \left(-0.0162 \cdot \frac{P_{dc}}{P_{dc0}} - \frac{0.0059}{\frac{P_{dc}}{P_{dc0}}} + 0.9858 \right)$$

With:

- η_{nom} The nominal inverter efficiency $[-]$, by default 96%
- η_{ref} The reference inverter efficiency $[-]$, by default 96.4%
- P_{dc} The DC power $\left[\frac{W}{m2}\right]$
- P_{dc0} The DC input power limit $[W/m2]$

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

Modeling steps

8. Inverter model

The Sandia inverter model enables to include the voltage and be more precise

$$P_{AC} = \left[\frac{P_{AC0}}{A - B} - C \cdot (A - B)\right] \cdot (P_{dc} - B) + C \cdot [P_{dc} - B]^2$$

Where:

- $A = P_{dc0} \cdot [1 + C1 \cdot (V_{dc} - V_{dc0})]$
- $B = P_{s0} \cdot [1 + C2 \cdot (V_{dc} - V_{dc0})]$
- $A = C_0 \cdot [1 + C3 \cdot (V_{dc} - V_{dc0})]$

Parameters:

- V_{dc}: DC input voltage (V).
- V_{dc0} : DC voltage level (V) at which the AC power rating is achieved
- P_{AC} : AC output power (W)
- P_{AC0} : Maximum AC power rating for inverter at reference conditions (W).
- P_{dc0} : DC power level (W) at which the AC power rating is achieved.
- P_{s0} : DC power required to start the inversion process (W)
- C_0,C_1, C_2, C_3: Empirical coefficients

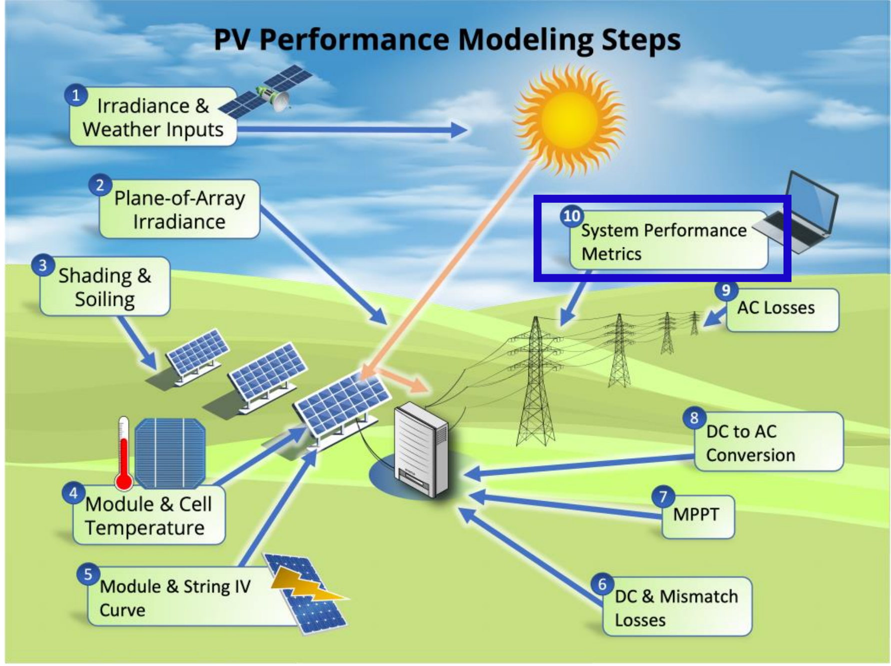
D. King, S. Gonzalez, G. Galbraith, W. Boyson, “Performance Model for Grid-Connected Photovoltaic Inverters”, SAND2007-5036, Sandia National Laboratories

Modeling steps

10. Performance Metrics

Performance Ratio PR (IEC 61724)**:**

$$PR = \frac{E_{out}}{E_{POA}} / \frac{P_0}{G_{ref}}$$



Real efficiency normalized by efficiency in STC conditions (1000 W/m2, cell temperature of 25 °C, and AM1.5 spectrum)

With:

- E_{out} : Energy produced [Wh] over the period of time T
- E_{POA} : Irradiation received [Wh/m²] over the period of time T
- P_0: Installation DC rated power [Wp]
- $G_{ref} = 1000\frac{W}{m^2}$, reference irradiation

Modeling steps

10. Performance Metrics

Performance Ratio PR (IEC 61724)**:**

$$\boldsymbol{PR} = \frac{E_{out}}{E_{POA}} / \frac{P_0}{G_{ref}}$$

Real efficiency normalized by efficiency in STC conditions (1000 W/m2, cell temperature of 25 °C, and AM1.5 spectrum)

With:

- E_{out} : Energy produced [Wh] over the period of time T
- E_{POA} : Irradiation received [Wh/m²] over the period of time T
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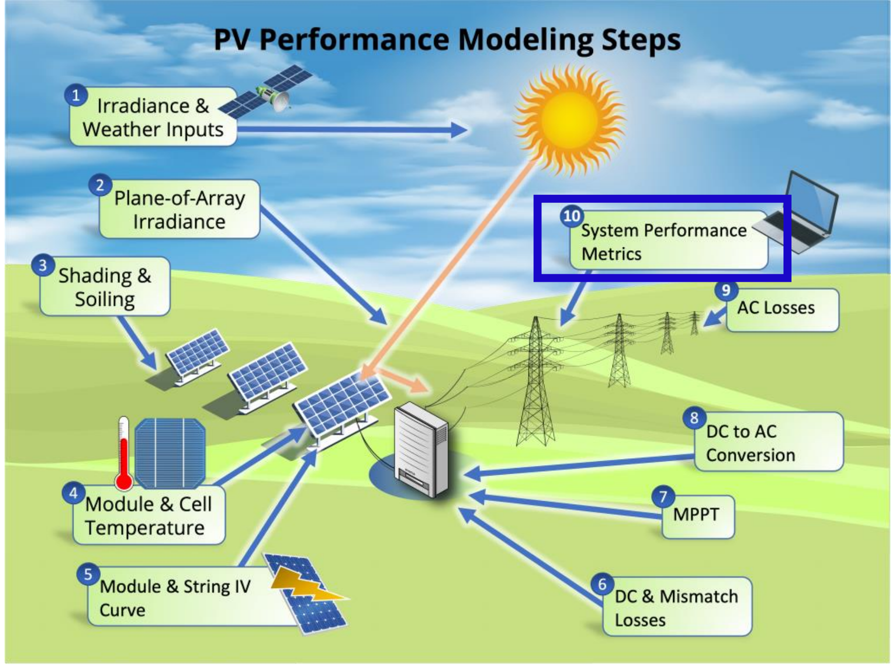

Energy Performance Index EPI:

$$EPI = \frac{\boldsymbol{PR}}{PR_{expected}}$$

$\boldsymbol{PR}$ divided by expected (modelled) $PR_{expected}$

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Modeling steps

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 AC power for one year.

Resources

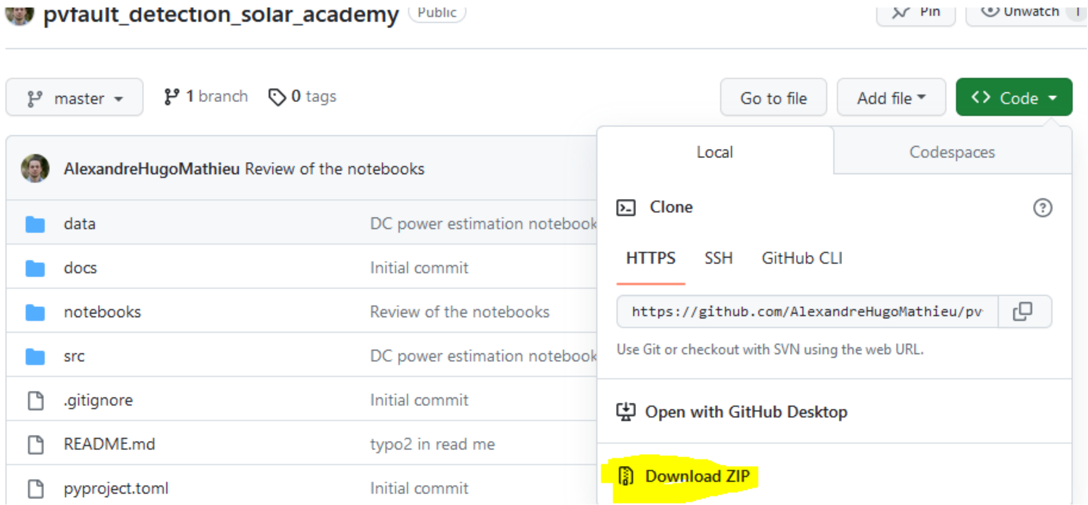
- Modeling guide PVPMC: https://pvpmc.sandia.gov/modeling-guide/
- Python / Pvlib tutorial: https://pvsc-python-tutorials.github.io/PVSC48-Python-Tutorial/
- To go further:
  - The Use of Advanced Algorithms in PV Failure Monitoring: https://iea-pvps.org/wp-content/uploads/2021/10/Final-Report-IEA-PVPS-T13-19_2021_PV-Failure-Monitoring.pdf

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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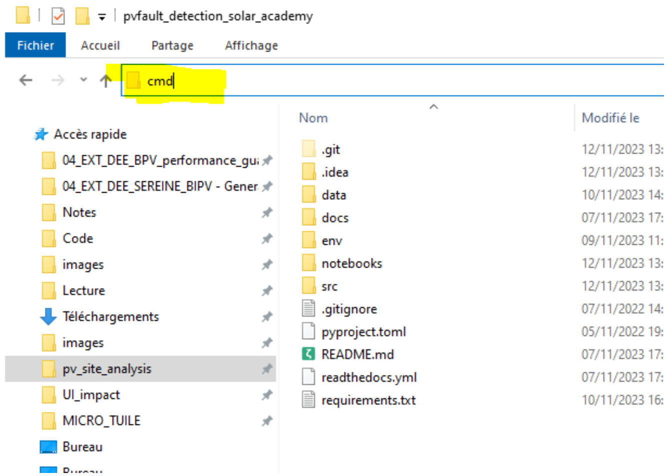
Appendix

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
3. Unzip it and put it in adequate location in your PC.
4. Let’s create a virtual environment where you will find all the functions for this course:
    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. Install python: www.python.org/downloads/, download and install the 3.9.13 “release”
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3. Unzip it and put it in adequate location in your PC.

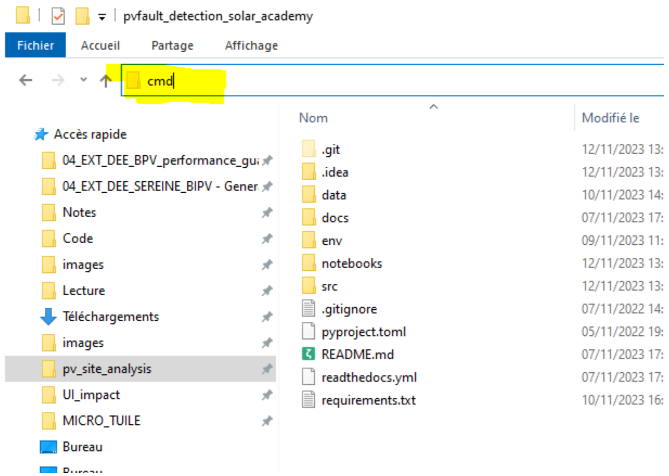
4. Let’s create a virtual environment where you will find all the functions for this course:
   1. Go in the folder and open the command line from that same folder by writing “cmd” in the path bar (with Windows)
   2. In the command bar: execute the following line to create the “solar_env” environnement 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.