

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

Today →

Project: groups
of 2 for the
project

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

Agenda

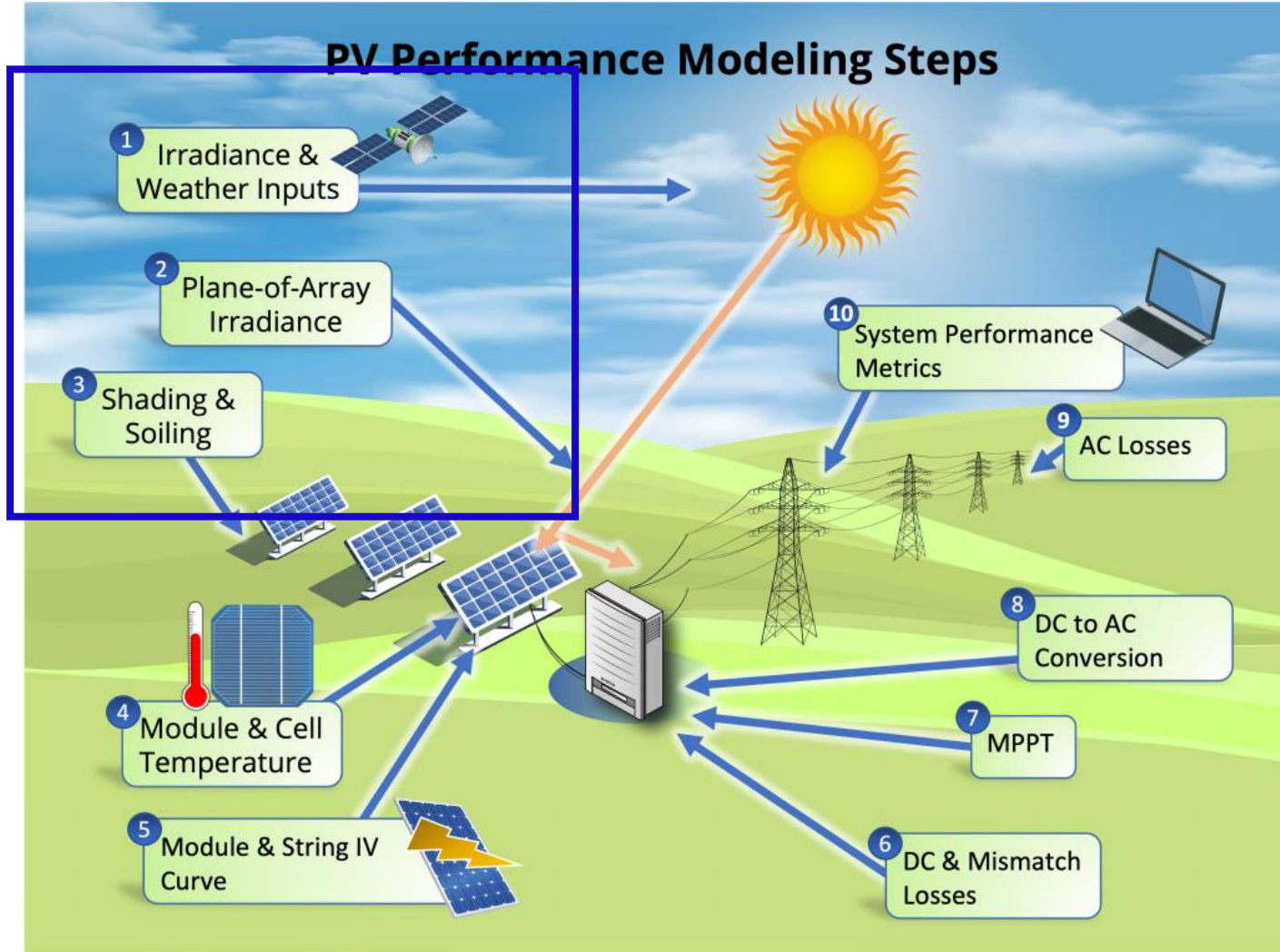


Curriculum

PV performance model steps

Modeling steps

27/11/2023
& 05/12/2023

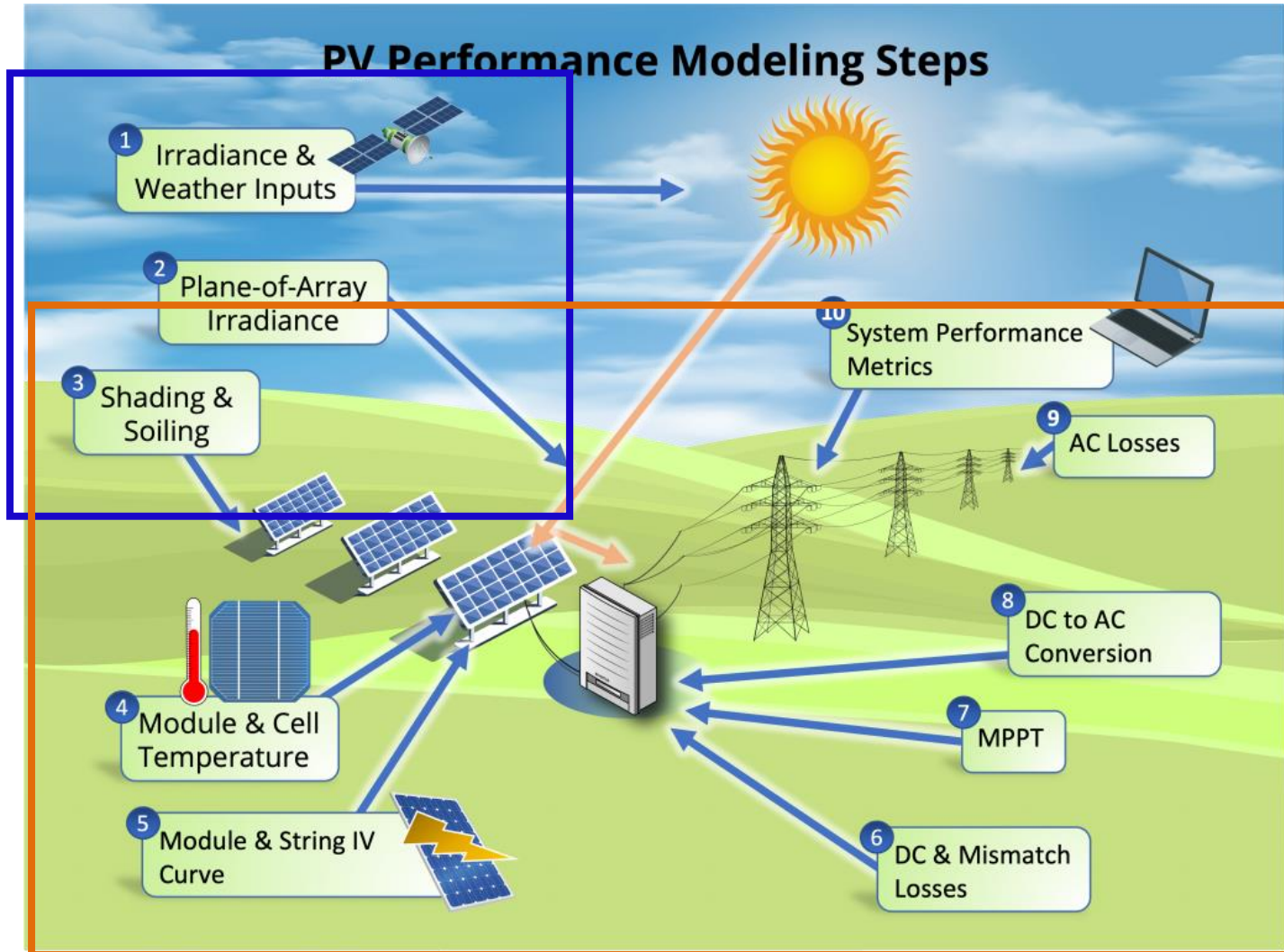


*image from: PVSC48 python tutorial

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"  
    # indentation 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
```

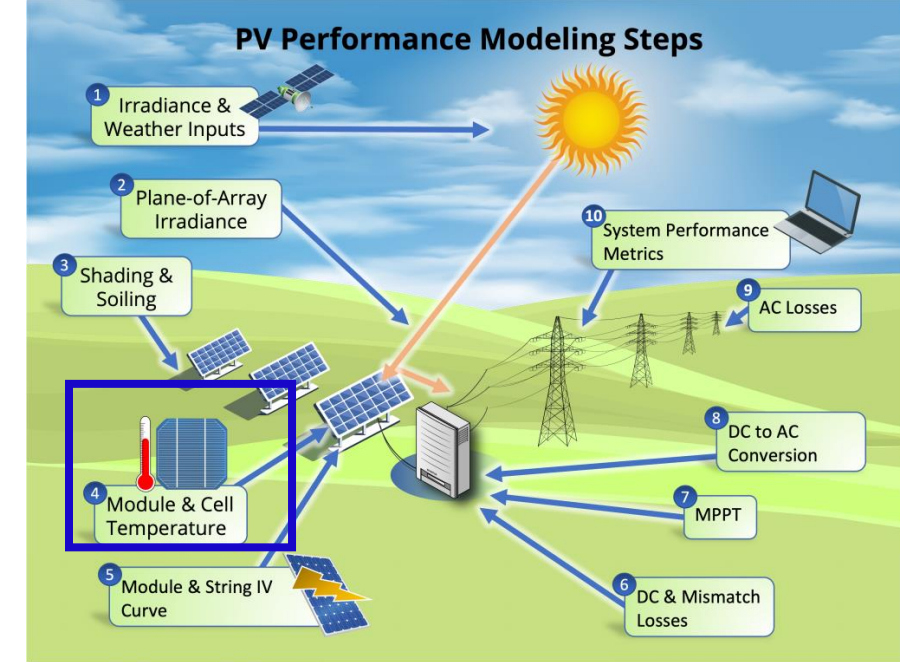
```
my_func_name(1,2) # Apply the function with two arguments and return 3
```

```
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

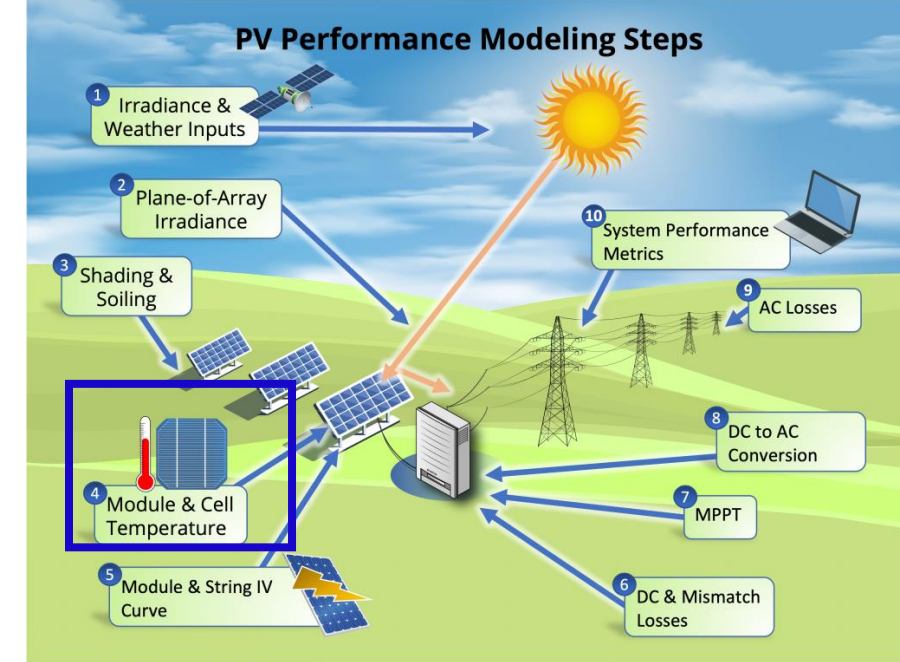
4. Cell temperature

Ross model:

Model to estimate the cell temperature T_c [°C] as function of ambient temperature and irradiance 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.



Modeling steps

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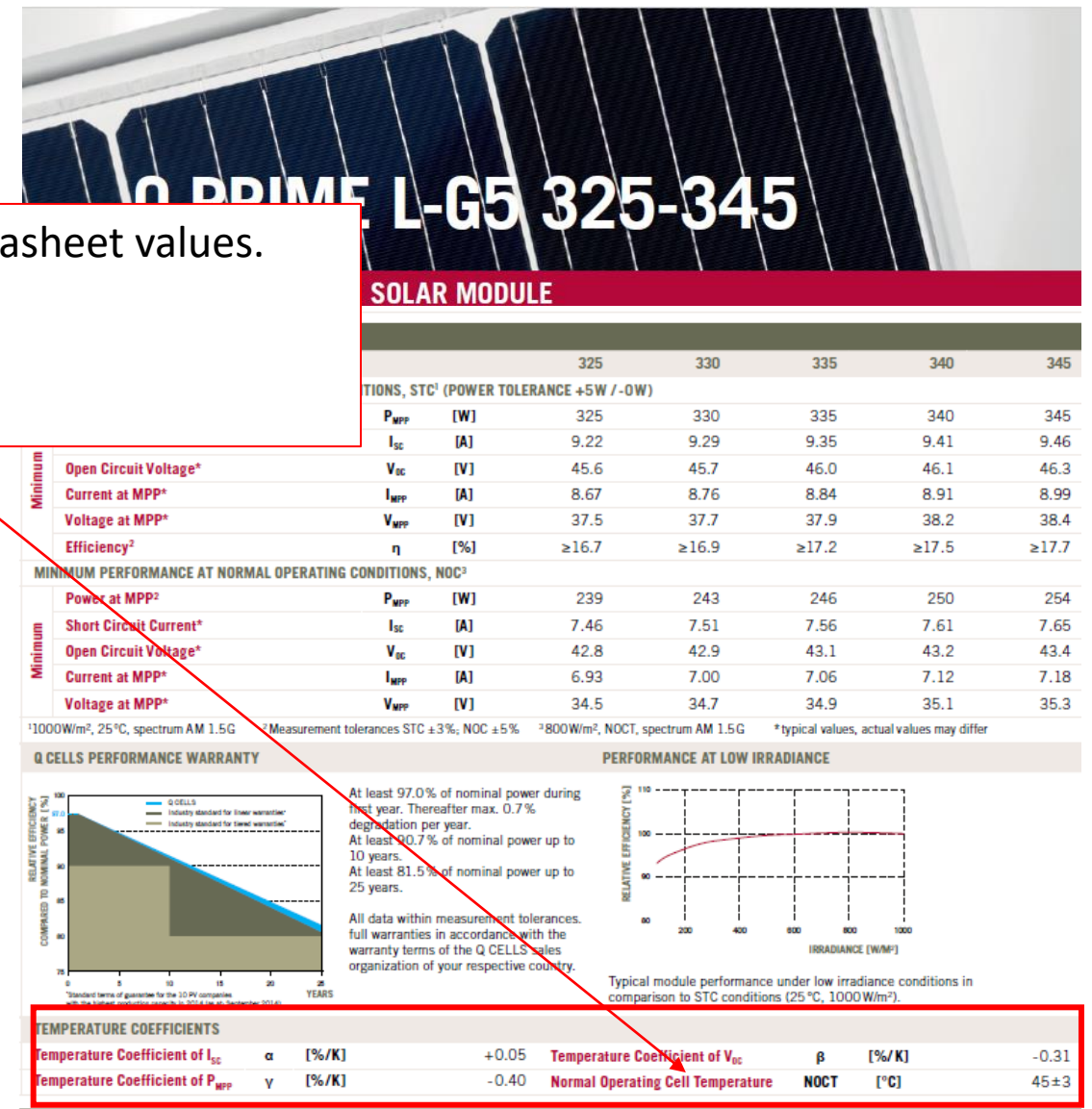
k_{Ross} , typically in the range 0.02-0.05 K/m²/W.

k_{Ross} can be fitted from datasheet values.

NOCT conditions:

$$G_{POA} = 800 \text{ W/m}^2$$

$$T_a = 20^\circ\text{C}$$



Modeling steps

4. Cell temperature

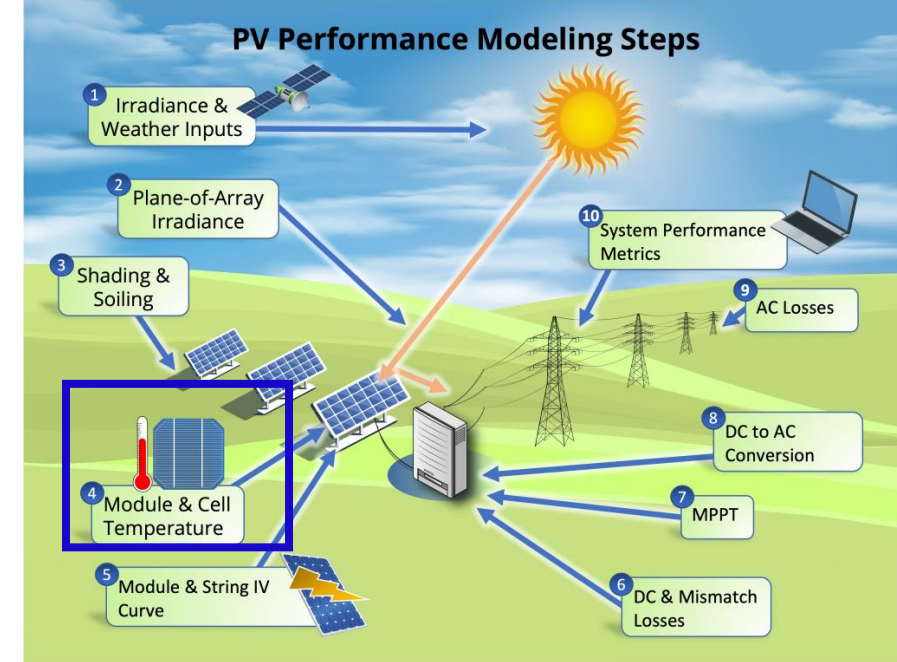
Faiman model:

Model to estimate the cell temperature T_c [°C] as function of ambient temperature and irradiance 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 [$\frac{W}{Km^2(\frac{m}{s})}$]



Modeling steps

4. Cell temperature

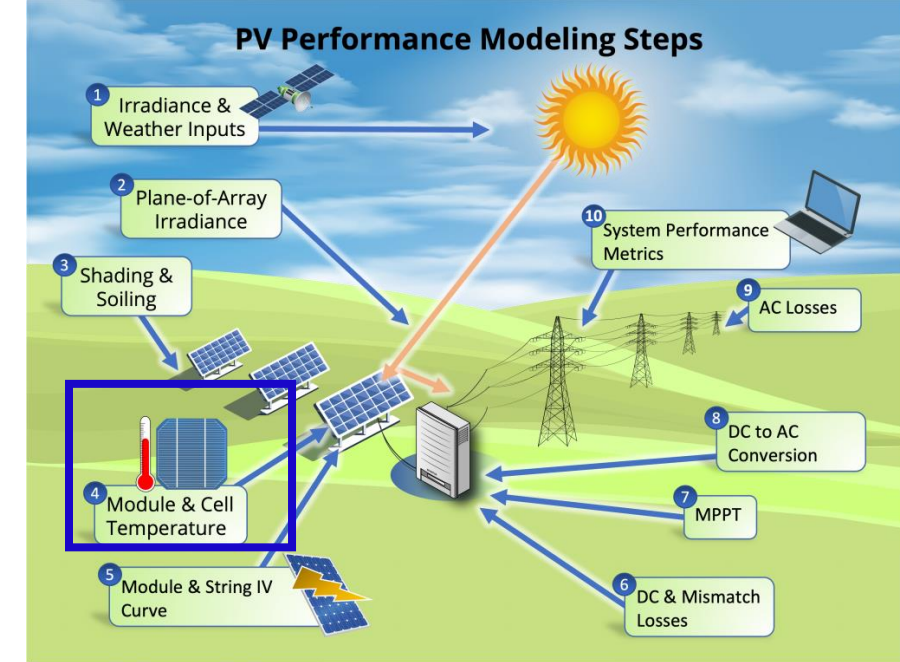
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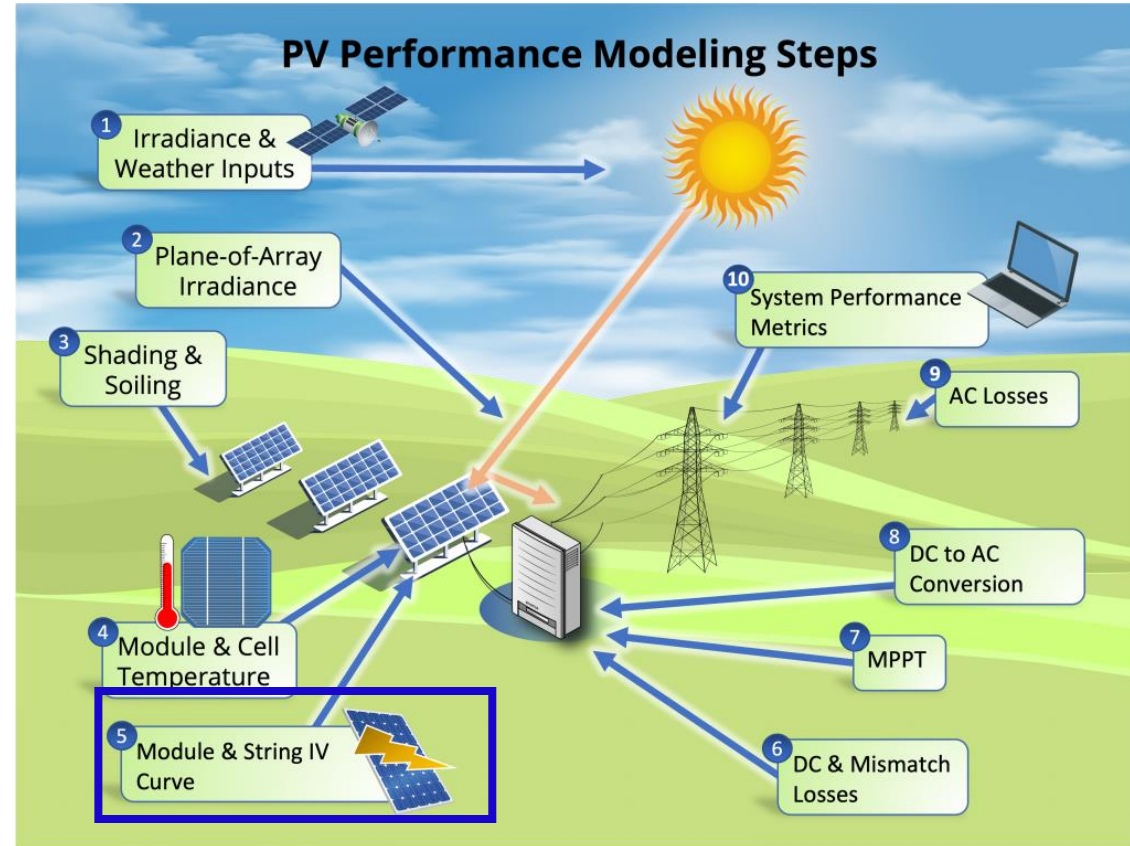
U_1 is the convective heat transfer component [$\frac{W}{Km^2(\frac{m}{s})}$]



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

Modeling steps

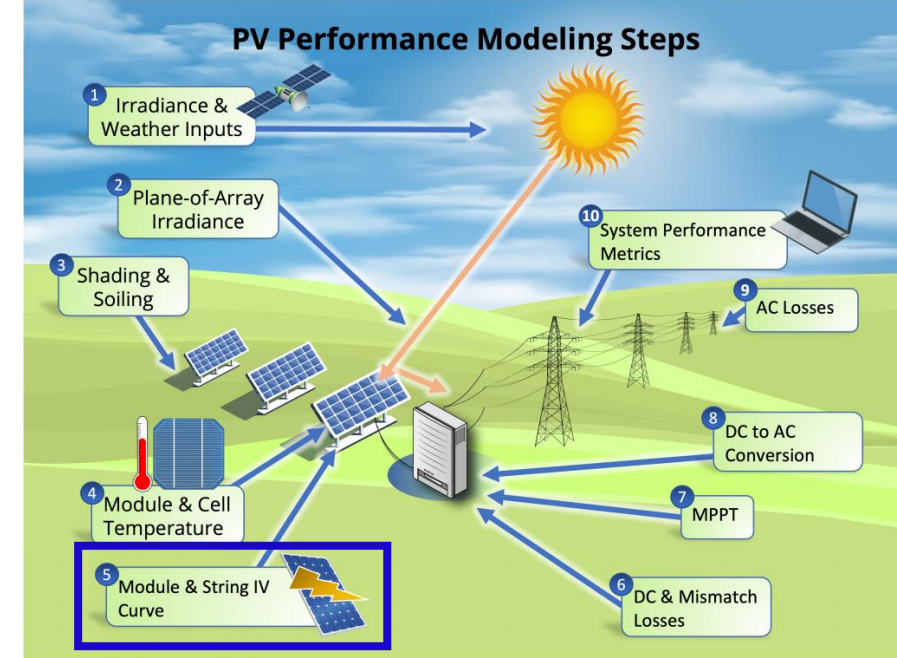
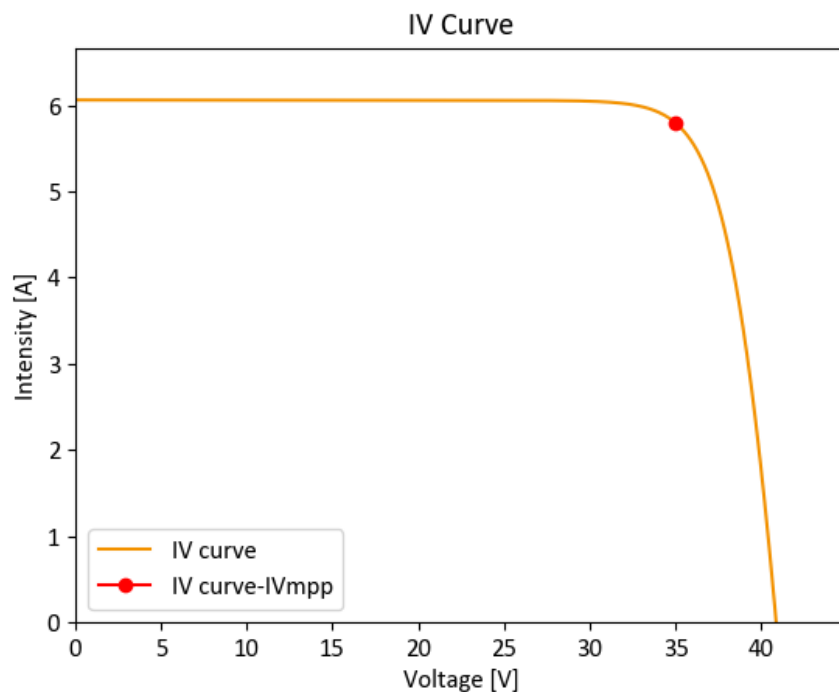
5. Module and String IV Curve



Modeling steps

5. Module and String IV Curve

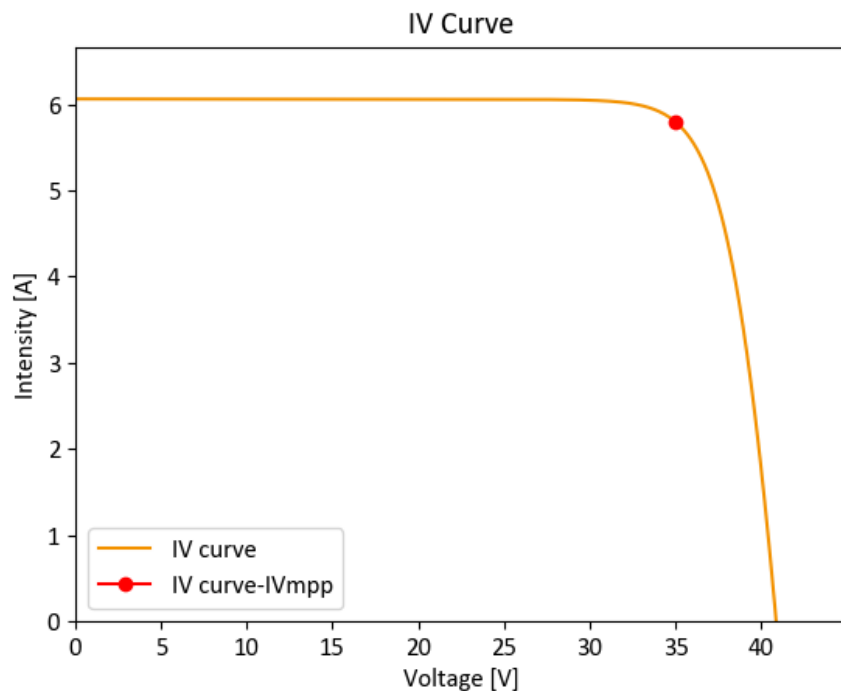
For a fixed irradiance and module temperature, the PV module has its I , current which depends on V , voltage and it can take many operating points.



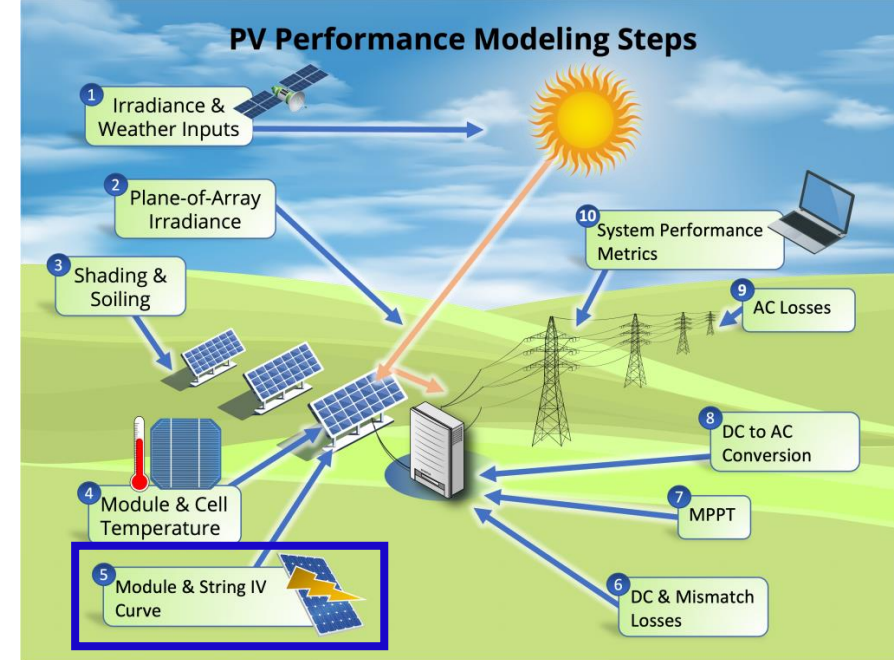
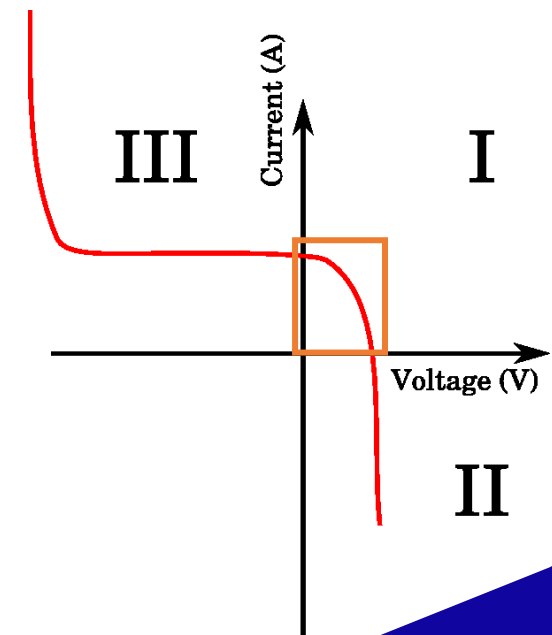
Modeling steps

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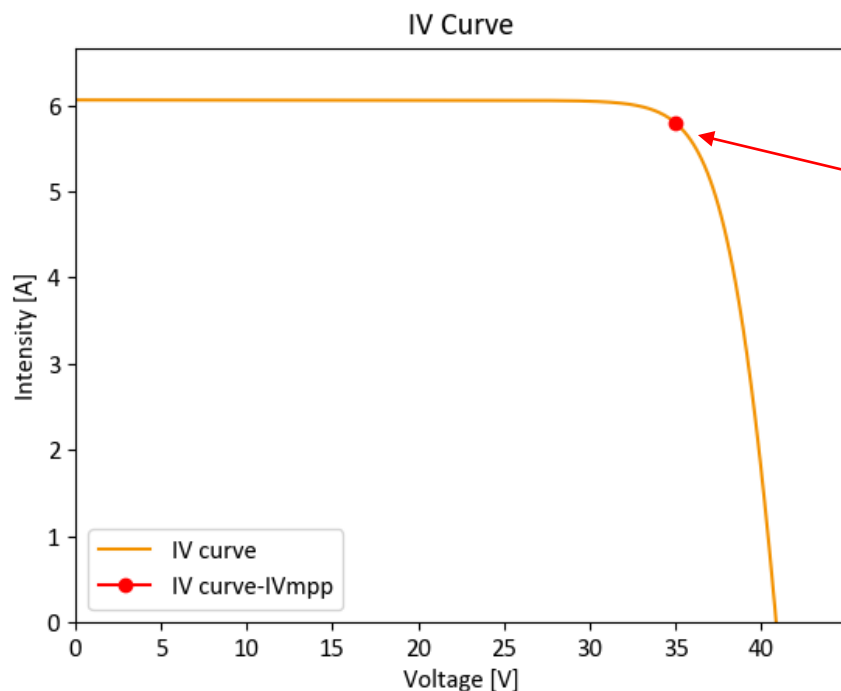
In reality, the IV characteristics go out of the 1st quadrant and the module can potentially consume power.



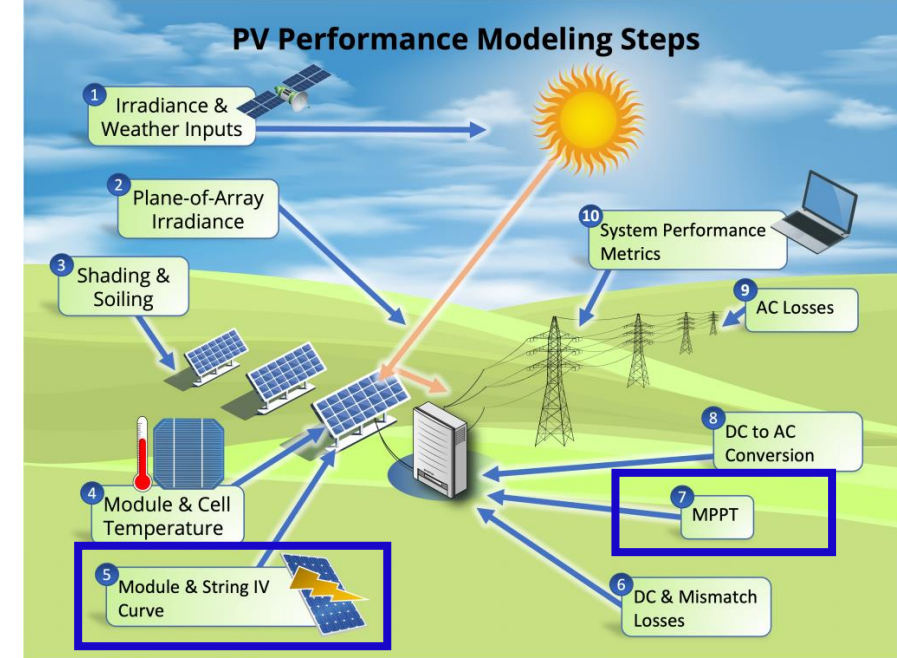
Modeling steps

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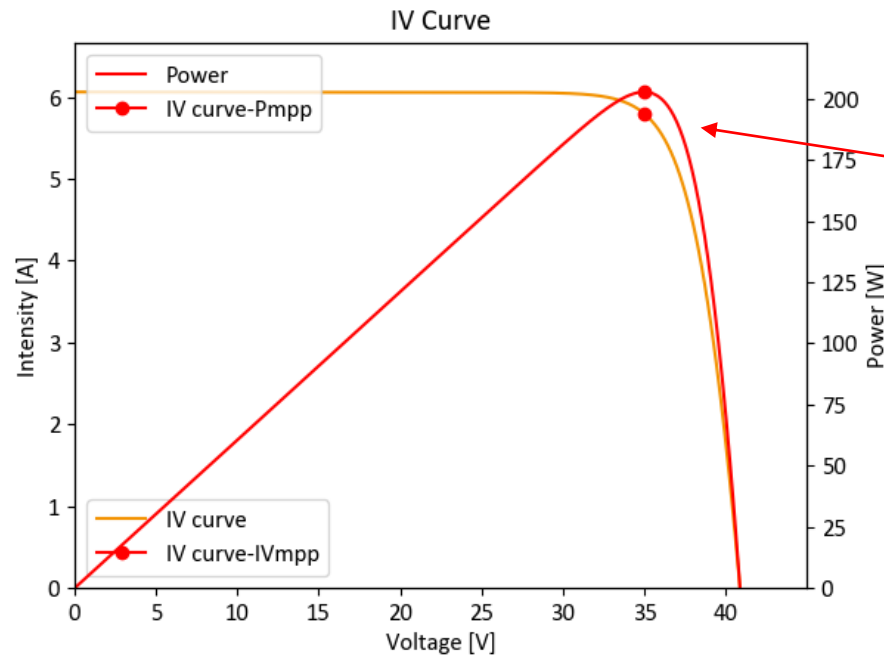
Then, the inverter is constantly searching for the operating point which maximizes the power MPP: Maximum Power Point.



Modeling steps

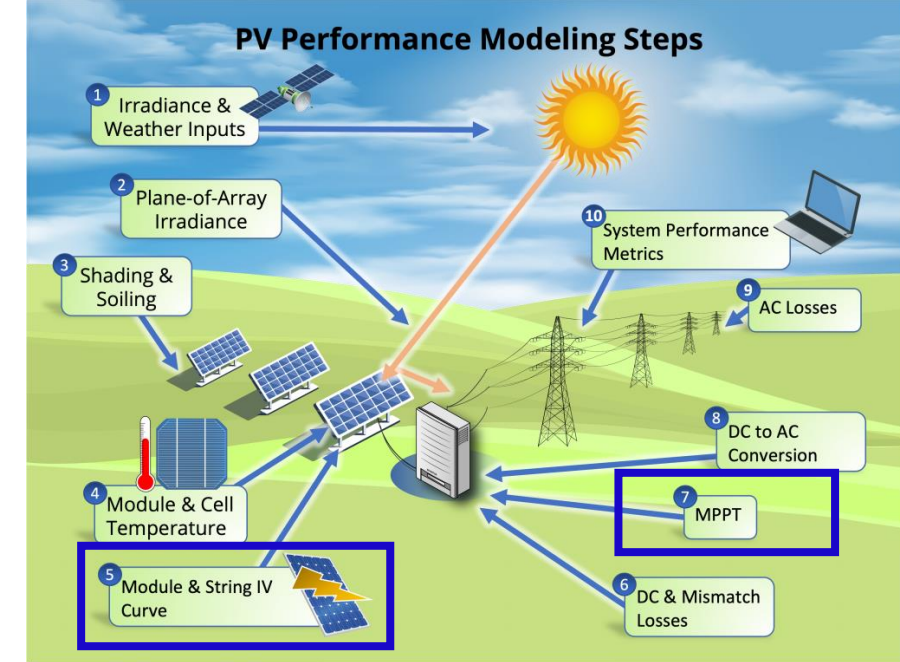
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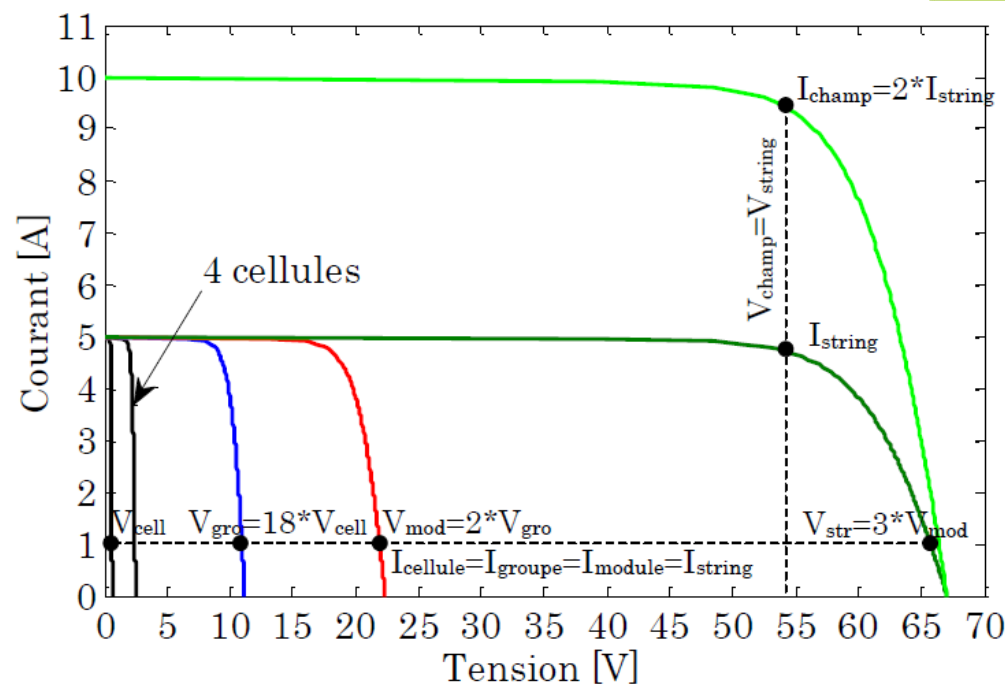
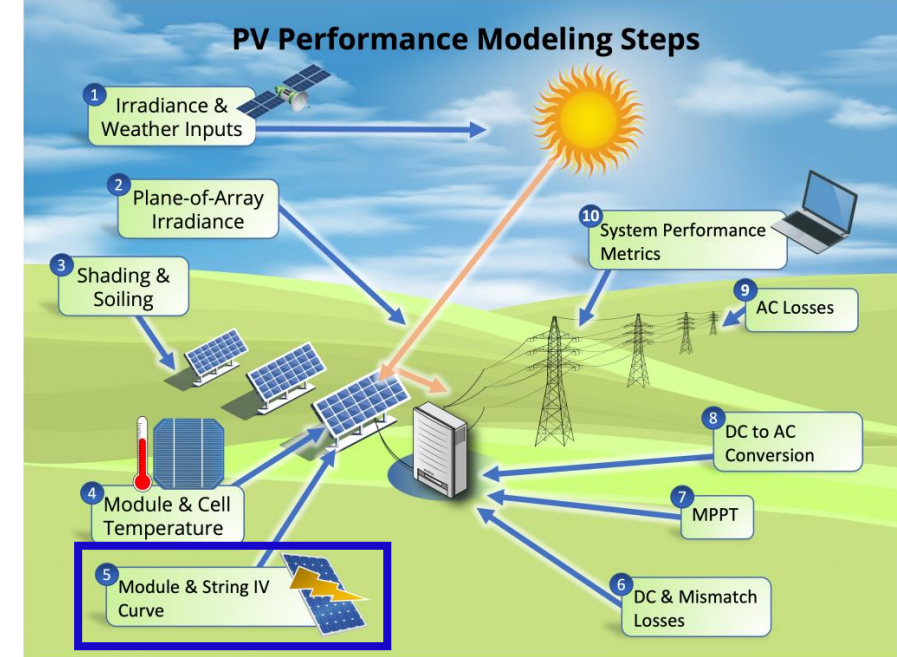
Especially, it changes the voltage with the MPP-Tracker (MPPT) to maximize power.



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.



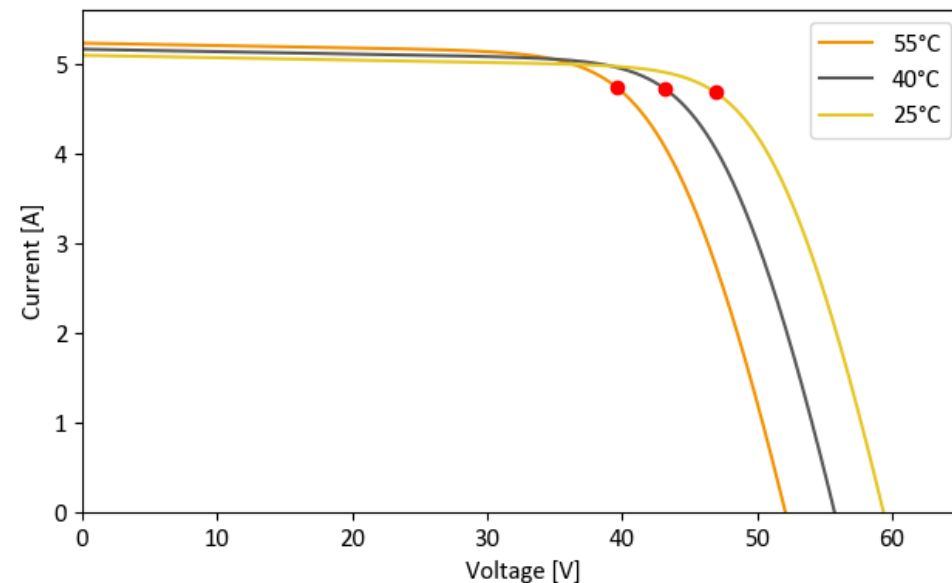
Modeling steps

5. Module and String IV Curve

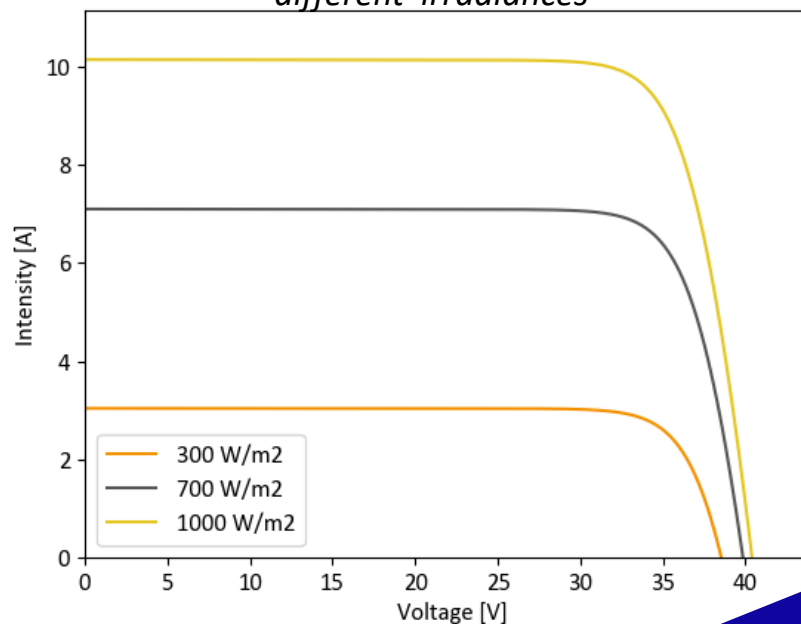
The IV curves' dependencies:

- 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

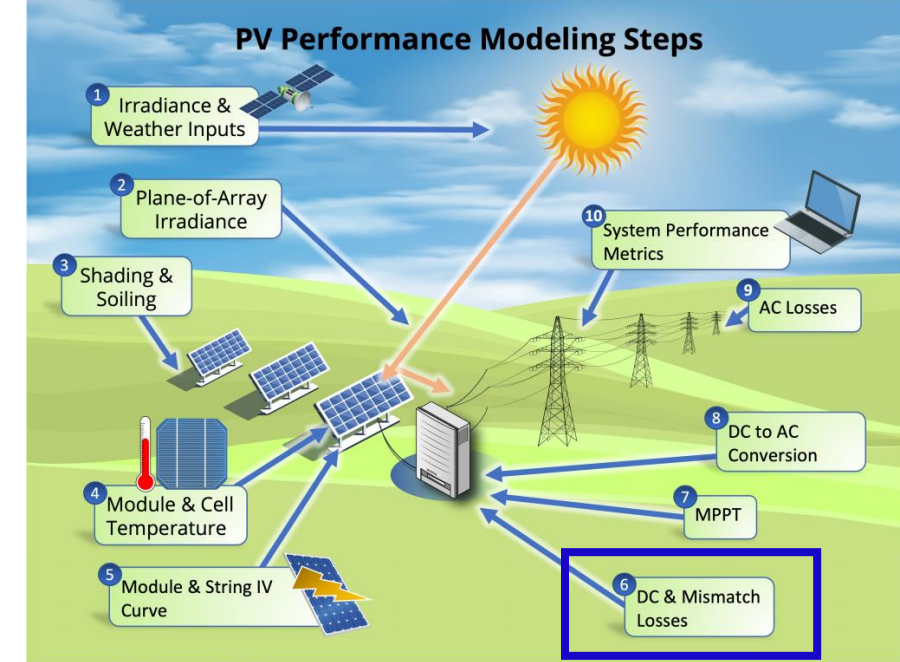


Modeling steps

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.

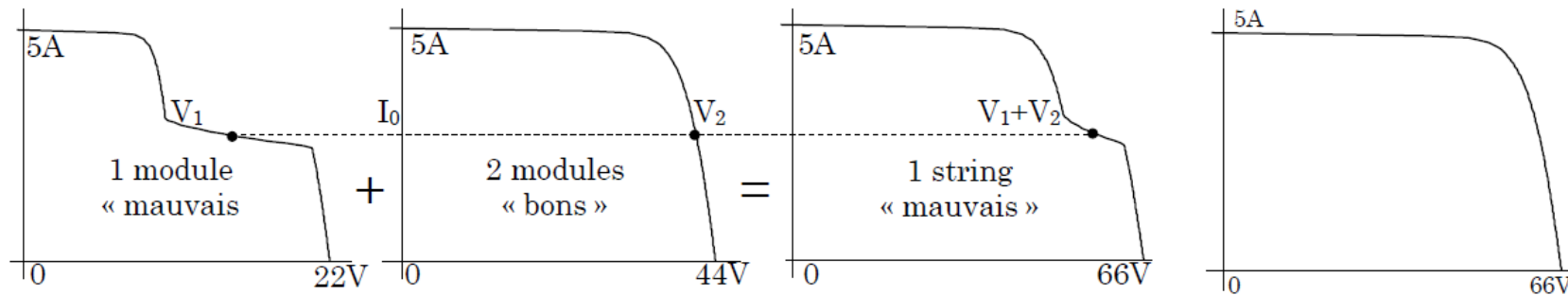
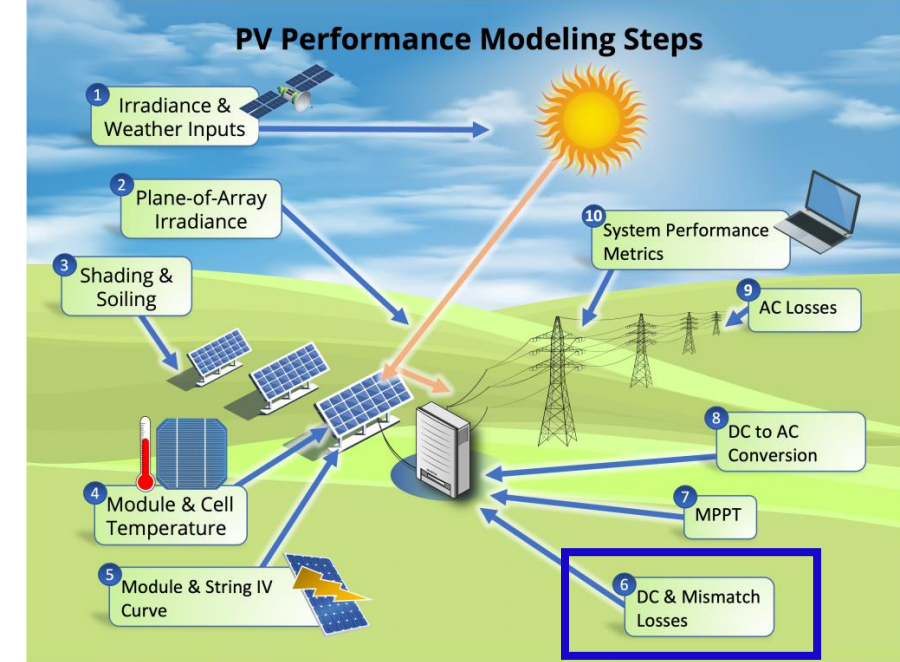


Modeling steps

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- **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 »

Modeling steps

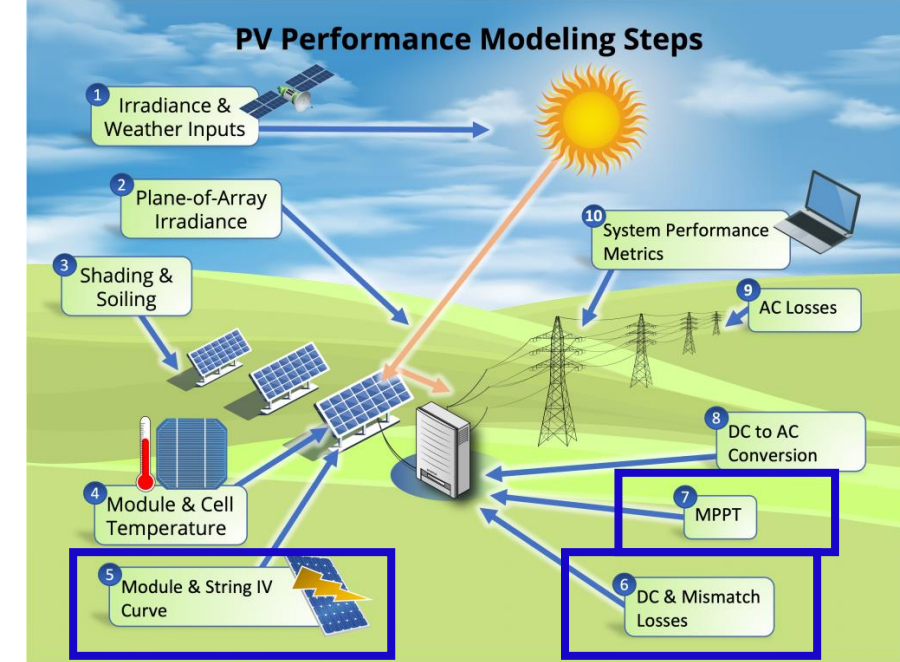
5./6./7. Power model

Constant efficiency model:

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

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

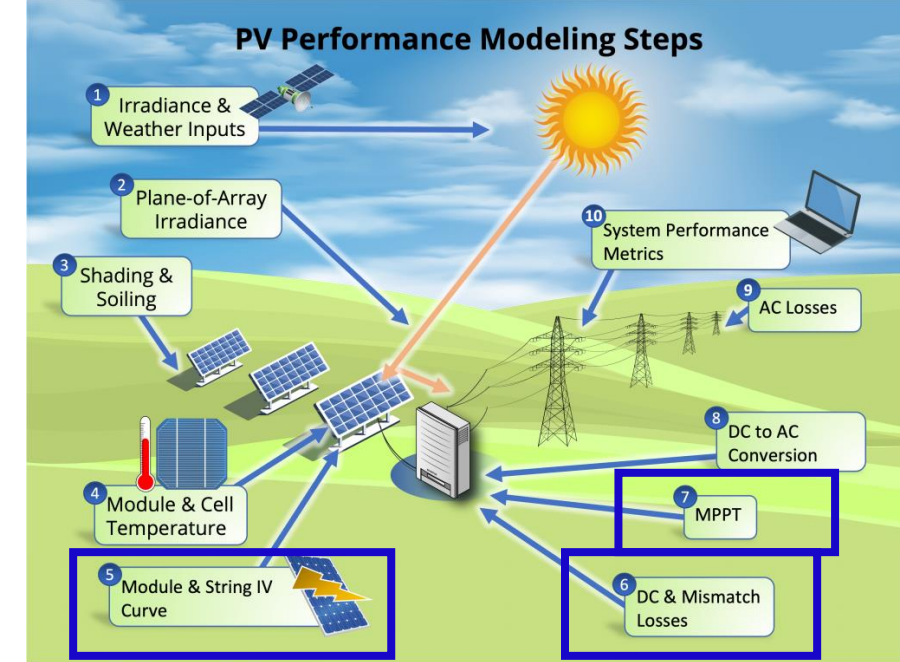
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Not really precise for instantaneous values

Modeling steps

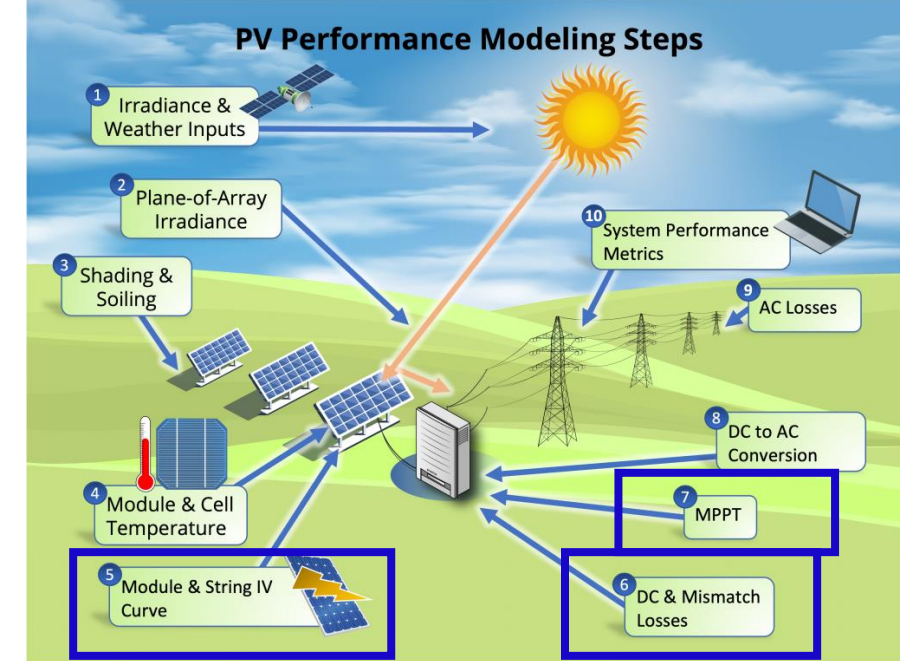
5./6./7. Power model

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

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

With:

- P_{dc0} Nominal DC power [Wp] (installed capacity)
- G_{POA} the irradiance in the plane of array [W/m^2]
- γ_{pdc} , the temperature coefficient (negative, usually between -0.2 – -0.5 %/°C)
- T_{cell} , the cell temperature [°C]



Modeling steps

5./6./7. Power model

The Huld model (used in PVGIS) enables to take into account the module temperature and non-linearity 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/m^2]
- $G' = \frac{G_{POA}}{1000 \text{ W/m}^2}$ the normalized irradiance
- $T_m' = T_m - 25^\circ C$, the module temperature delta [$^\circ C$]
- $k_1 \dots k_6$, the model coefficients

Modeling steps

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- $k_1 \dots k_6$, 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

Modeling steps

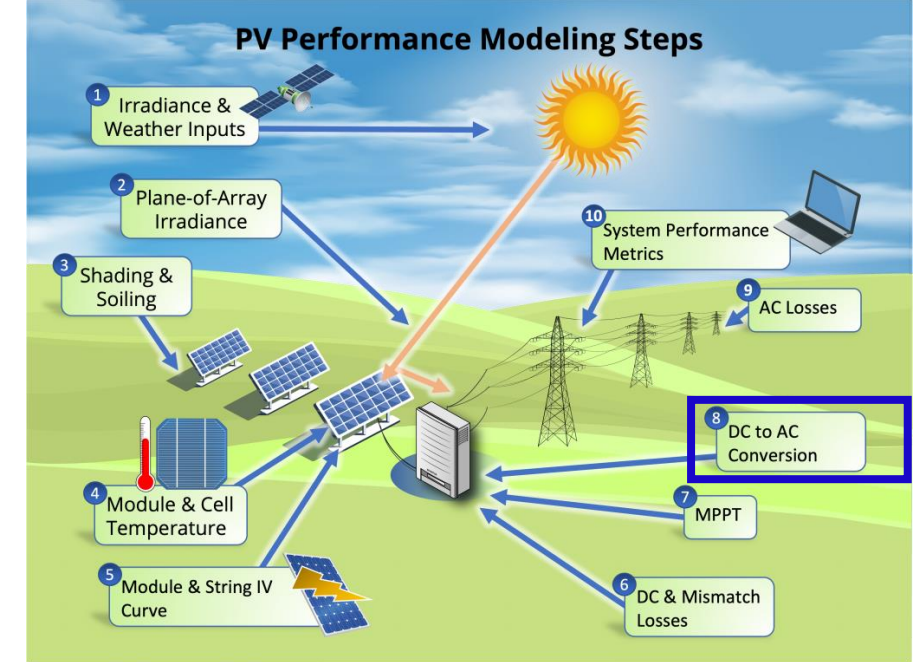
8. Inverter model

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 $\left[\frac{W}{m^2} \right]$
- P_{dc0} The DC input power limit $[W/m^2]$



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

Modeling steps

10. Performance Metrics

Performance Ratio PR (IEC 61724):
To calculate real performance

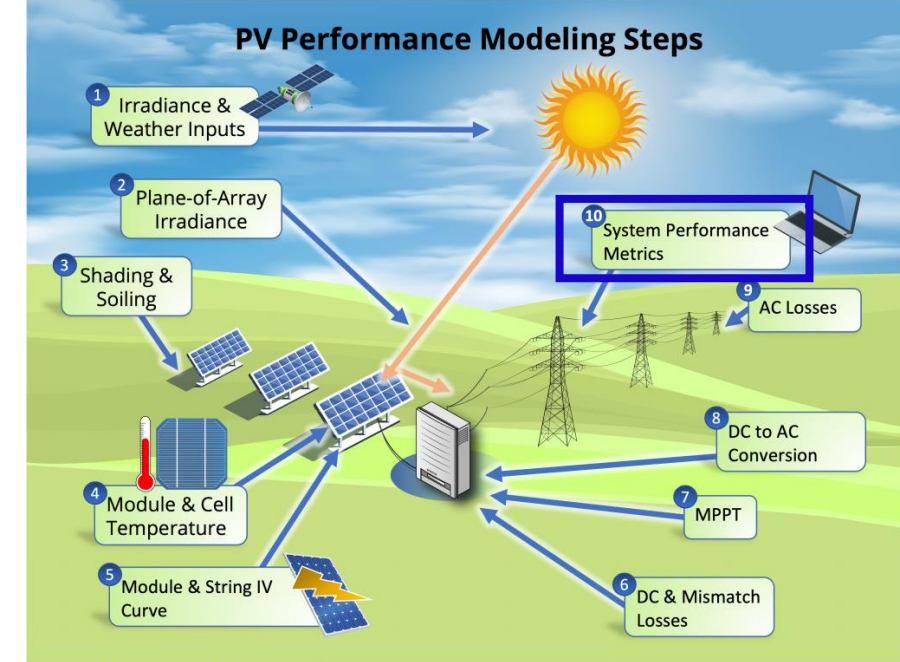
$$PR = \frac{E_{out}}{E_{POA}} / \frac{P_0}{G_{ref}}$$

Real efficiency normalized by the efficiency in STC conditions

STC: Standard Test 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

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To calculate real performance

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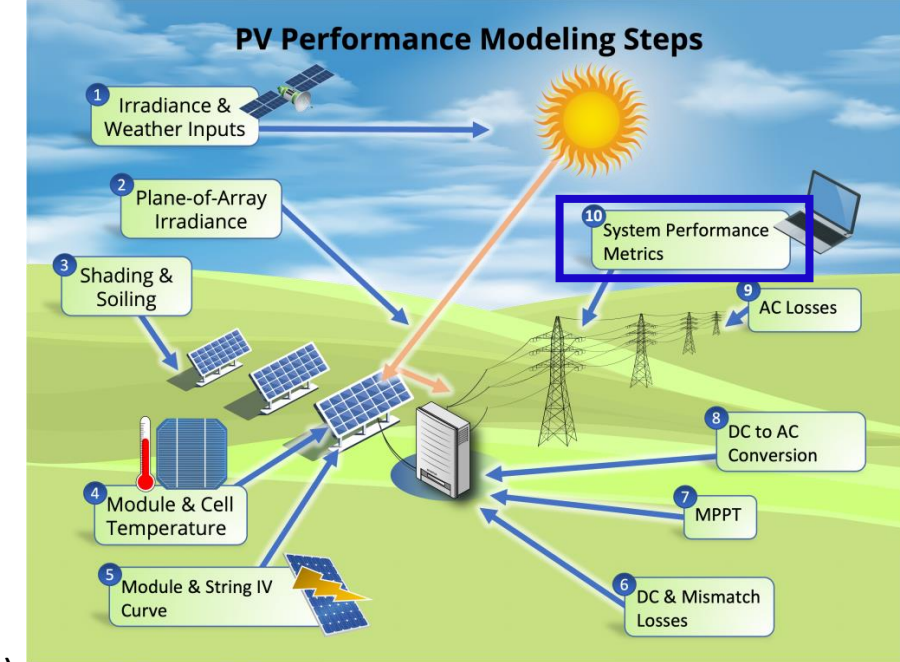
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Energy Performance Index EPI:

To monitor performance

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

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



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.

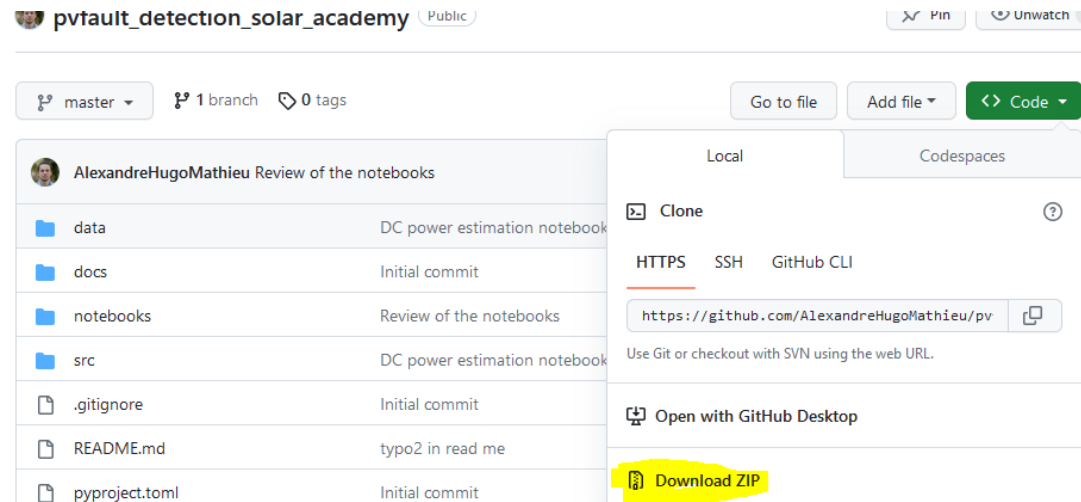
Resources

- Modeling guide PVPMC: <https://pvpmc.sandia.gov/modeling-guide/>
- Python / Pvlb 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.

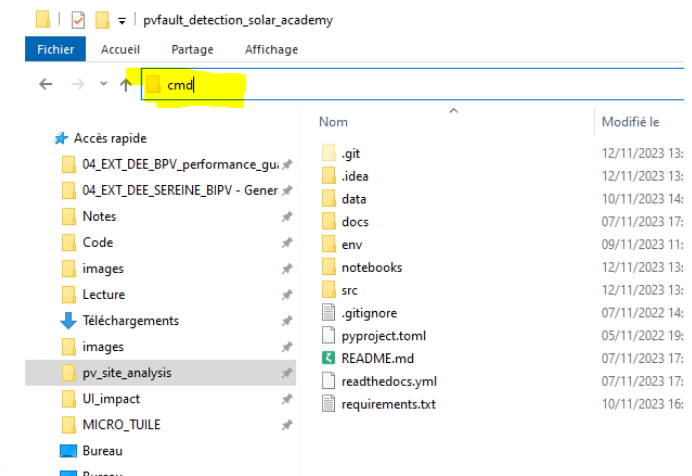
1. Install python: www.python.org/downloads/, download and install the 3.9.13 “release”
(Add python to your Path)
2. Go to https://github.com/AlexandreHugoMathieu/pvfault_detection_solar_academy, click on the green “Code” button and then download the folder as the zip



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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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)

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, execute:
 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.

