Enseignement PV au SIRTA

Anne, Jordi, Moira, Vincent,
Bouchra, Johan, Sylvain,
Mahery, Sandra, Hiba, Maximilien.
Louis, Valentin
Florian, Aurélie, Thibault, Marion, Baptiste, David

JSS, 4 juin 2026

Installations sur l'énergie solaire PV au SIRTA

GT EnR

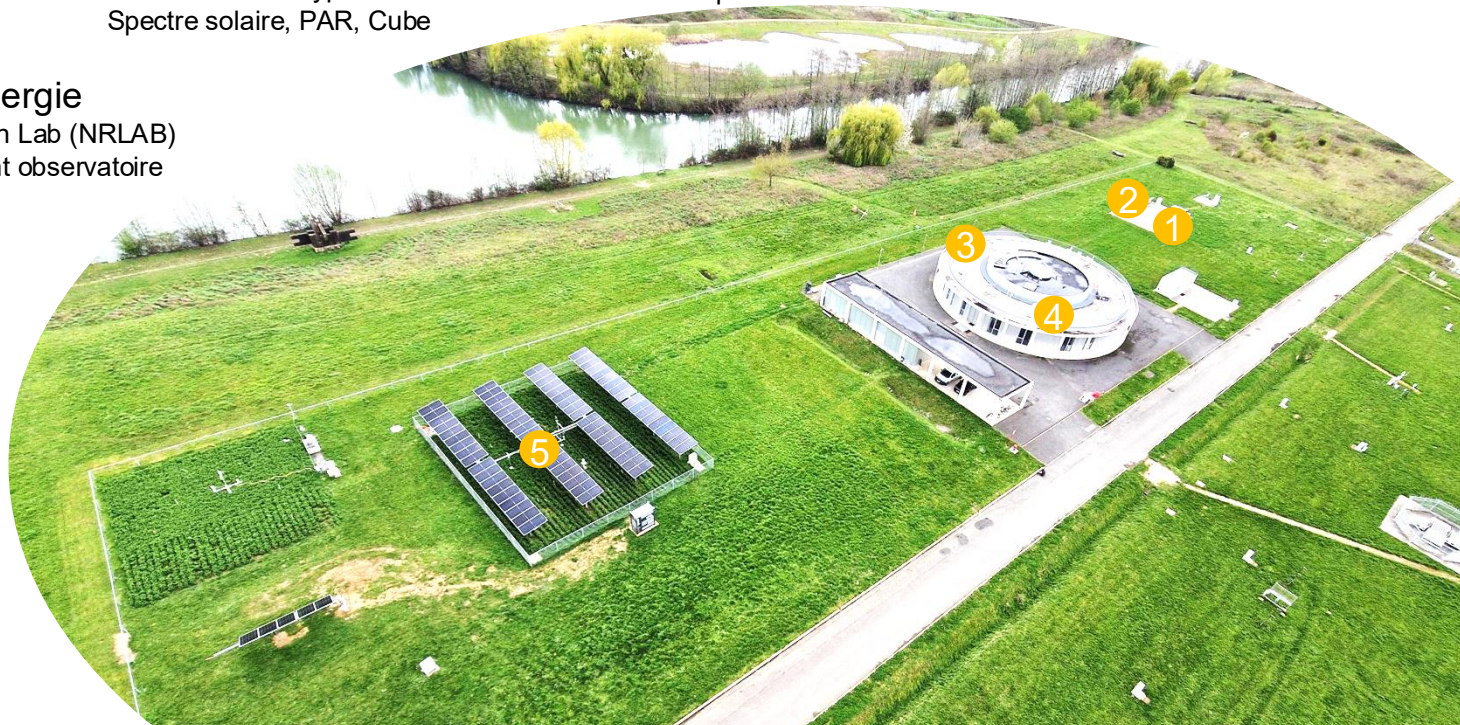
2 Caractérisation et diagnostic PV
Bancs de test de modules commerciaux et pérovskites

1 Enseignement pratique
Plateformes PV pédagogiques

3 Ressource EnR
Station radiative type BSRN
Spectre solaire, PAR, Cube

4 Gestion d'énergie
Nanogrid research Lab (NRLAB)
Microgrid bâtiment observatoire

5 Optimisation et évaluation d'impact
Pilotage tracker solaire
Agrivoltaïsme



Deux plateformes TP PV principales

TP PV SIRTA

TPs allant de L2 à Executive Education

Suiveur solaire (x2)

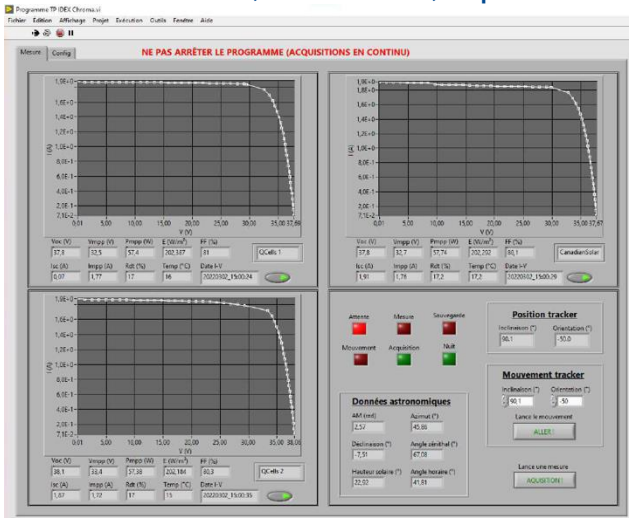
Impact du positionnement des modules PV par rapport au Soleil
- Étude de performance PV (courbe I-V, rendement)
- Diverses inclinaisons et orientations

Système PV (x2)

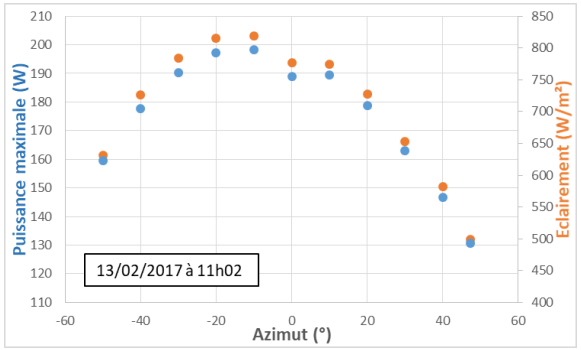
Comprendre l'association de modules PV
- Connexions série, parallèle et série-parallèle
- Étude d'impact de l'ombrage
- Courbe I-V

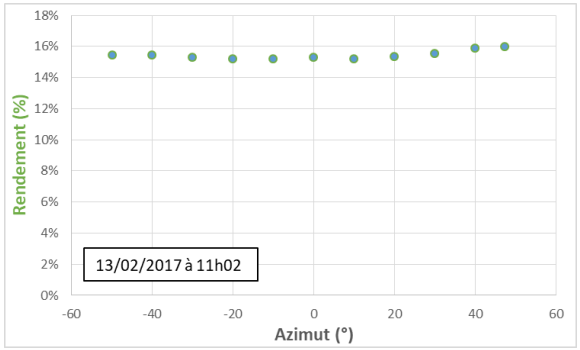
Plateforme « suiveur solaire »

Courbes I-V, Tracker 1, 3 panneaux



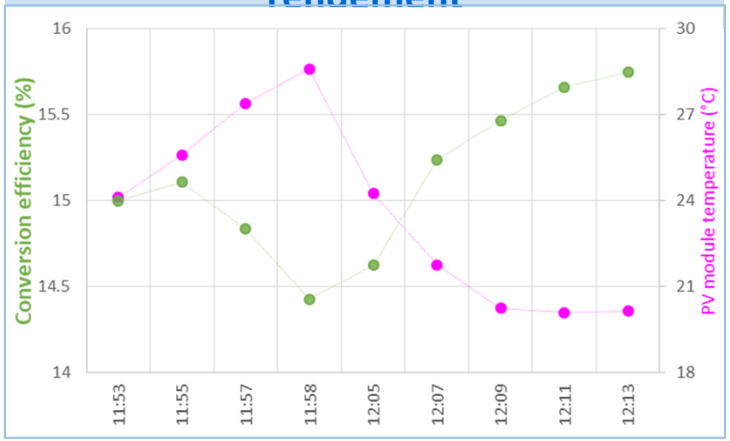
Quel est l'impact de l'azimut des modules sur les performances PV ?



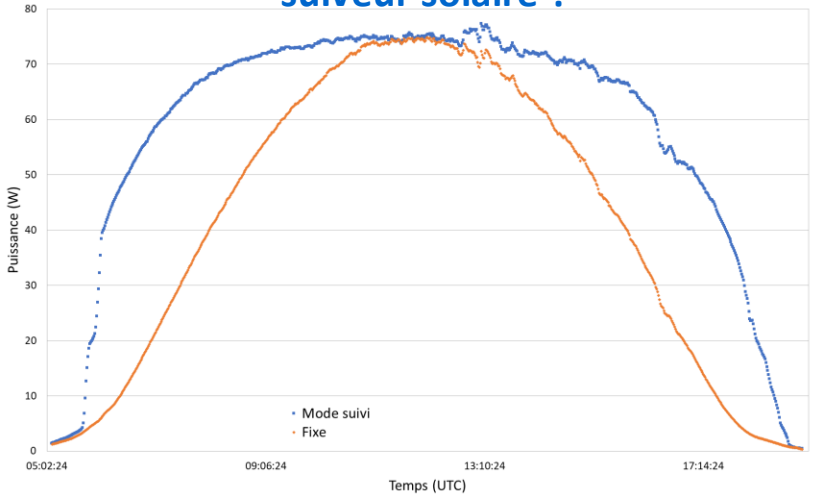


Plateforme « suiveur solaire »

Effet de la température sur le rendement

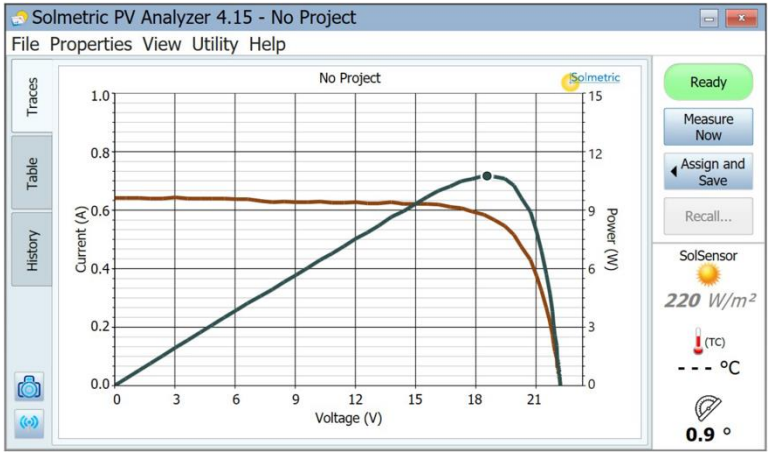


Quelle amélioration peut-on attendre d'un suiveur solaire ?



Plateforme « Système PV »

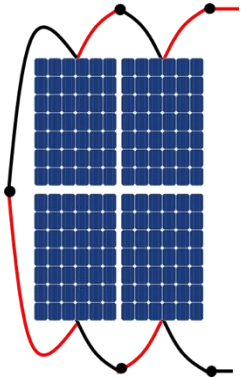
TP PV SIRTA



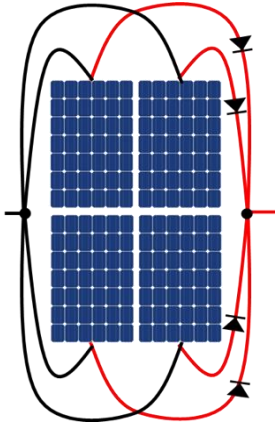
Plateforme « Système PV »

TP PV SIRTA

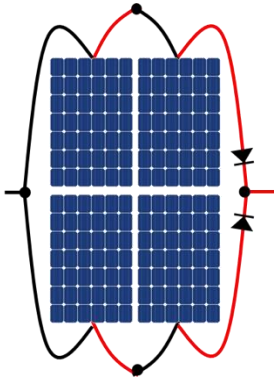
Association série, parallèle, série-parallèle : Quelles conséquences sur les caractéristiques courant-tension et puissance-tension ?



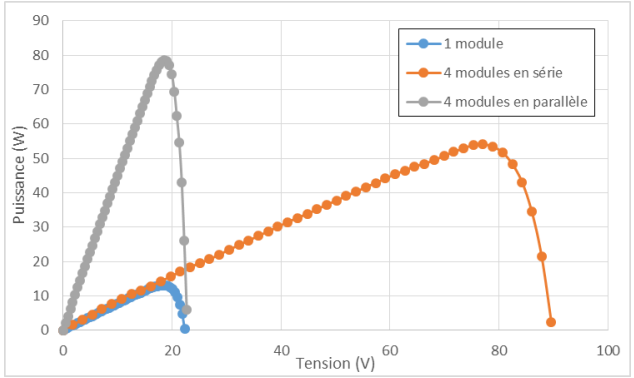
Série

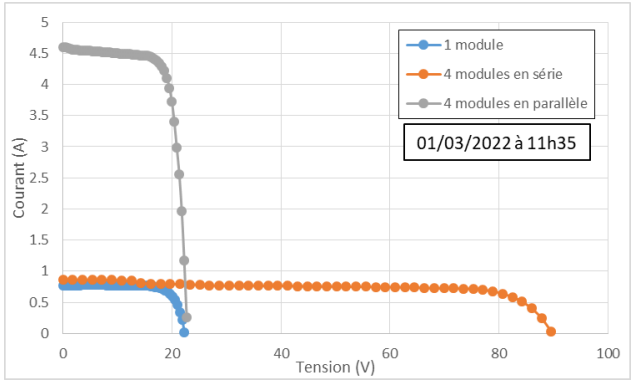


Parallèle



Série-Parallèle

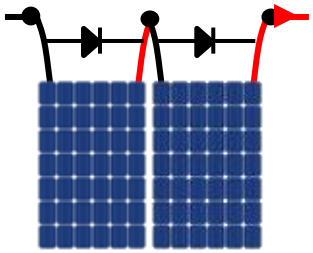




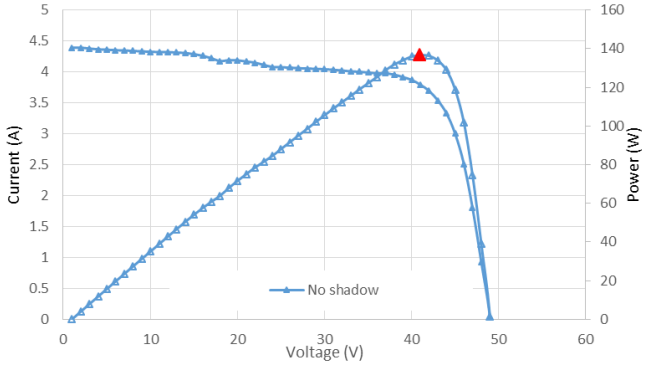
Plateforme « Système PV »

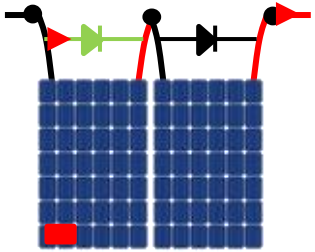
TP PV SIRTA

Quel est l'effet d'un ombrage ?

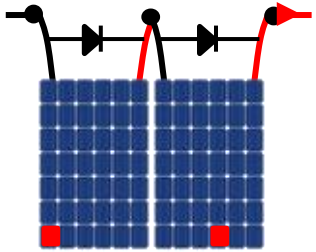


Sans ombrage

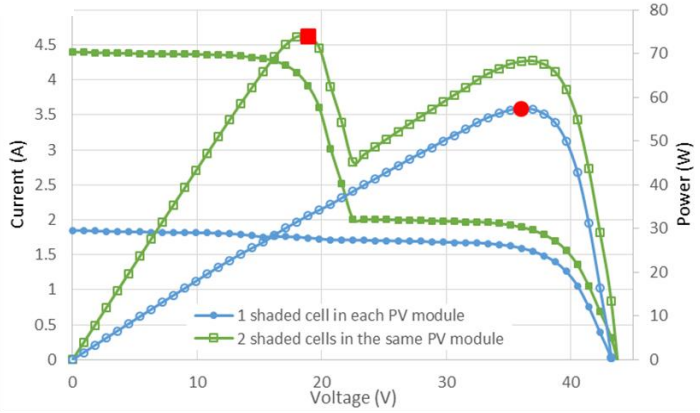




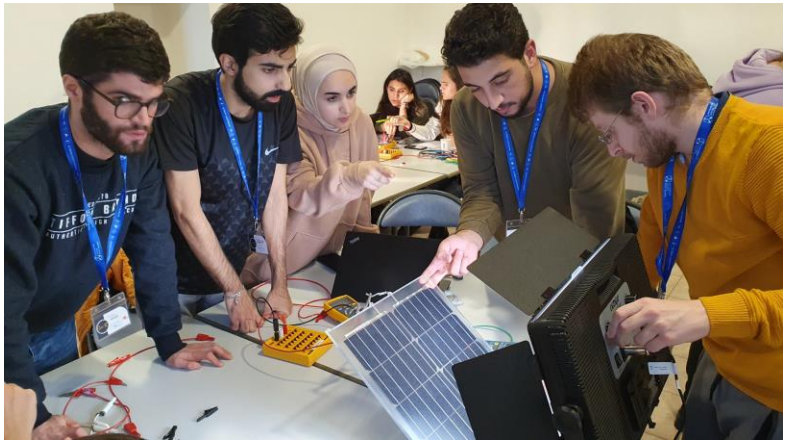
2 ombrages sur le même module PV



1 ombrage sur chaque module PV



Plateforme « Indoor »



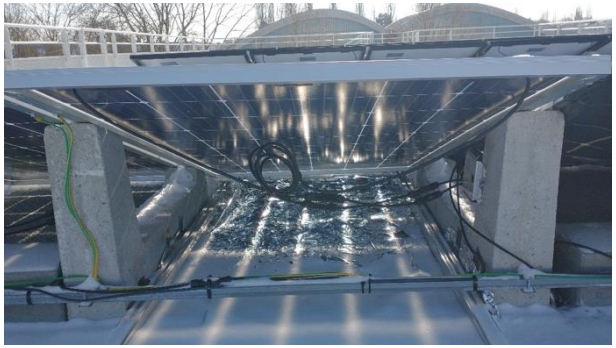
- Association série, parallèle, série-parallèle :
- Quelles conséquences sur les caractéristiques courant-tension et puissance-tension ?
- Quel est l'effet d'un ombrage ?

Plein d'autres exemples de TP PV

TP PV SIRTA

Étude de la température

Étude de l'albédo

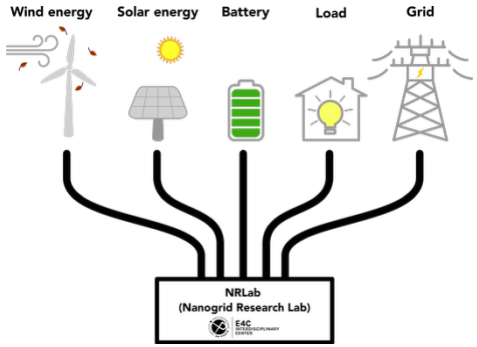


Étude de la bifacialité

Plateforme NRLAB (Nanogrid Research and Teachning Lab)

TP PV SIRTA

Démonstration du fonctionnement d'un nanoréseau en conditions réelles



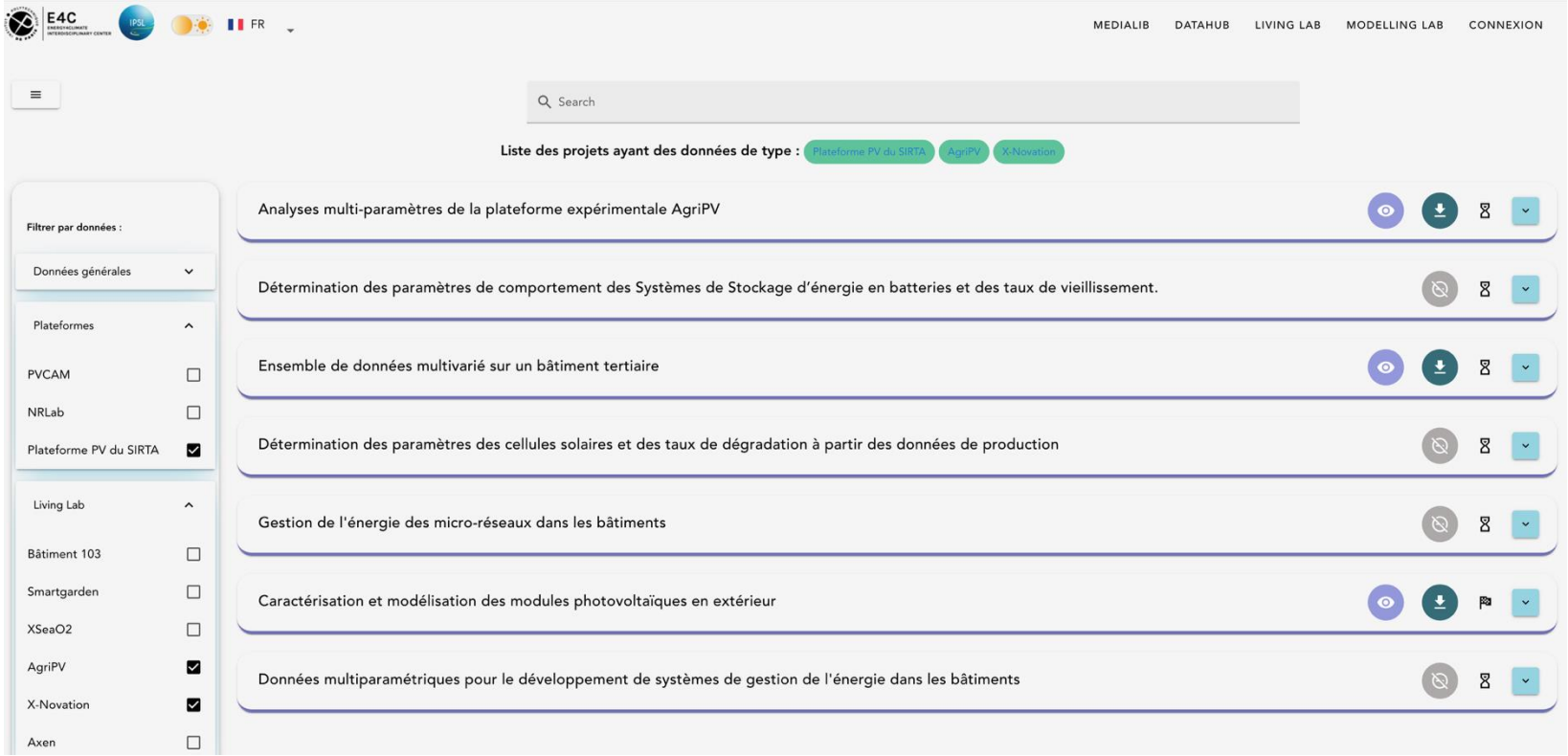
Et beaucoup de visites

Photos des Ateliers CLE 28 Avril 2026

Données pour des analyses TP PV
Site de services Energie-Climat E4C-IPSL

TP PV SIRTA

https://**e4c-ipsl.ip-paris.fr**/#/fr/datahub/projects/



Enseignements concernés : +400 étudiants / an

TP PV SIRTA

Niveau	Formation	Etablissement	Nb étudiants	Responsable	Depuis	Format
M1	MEC52183	Ecole polytechnique	25	Jordi Badosa, Simone Kotthaus	2012	Projets
M2	PIE - Énergie renouvelables et efficacité énergétique.	Université Paris-Saclay	60	Vincent Bourdin	2013	CM -TD
M1	MEC573	Ecole polytechnique	25	Simone Kotthaus	2013	Projets
Ingé5	Polytech	Université Paris-Saclay	42	Sylvain Le Gall	2015	TP
M2	PIE	Université Paris-Saclay	24	Sylvain Le Gall	2015	TP
L3	LP TPEBC	Université Paris-Saclay	12	Sylvain Le Gall	2015	TP
Ingé5	Polytech	Université Paris-Saclay	42	Sylvain Le Gall	2015	TP
L3 pro BUT	IUT Génie-Thermique et Énergie (énergie solaire thermique et PV)	Université d'Évry- val-d'Essonne	32	Vincent Bourdin	2015	CM – TD - TP
ExEd	EnR (Solaire, Eolien, microgrids)	Executive Education X	40	Vincent Bourdin, Imma Bastida, Jordi Badosa	2017	TP
M2	PHY54402	Ecole polytechnique	25	Eric Johnson	2018	Projets
M2	ECE54402	Ecole polytechnique	20	Jordi Badosa, Yvan Bonnassieux	2018	Projets
M2	MATEC	UVSQ	12	Zakaria Djebbour	2018	TP
L2	IUT Mesures-Physiques	Université Paris-Saclay	48	Anne Migan	2019	TP
M2	PEE - Efficacité et flexibilité énergétique	Université Paris-Saclay	12	Vincent Bourdin	2020	CM -TD

Focus sur un TP PV avec Jupyter notebook sur le cours PRACTICAL PHOTOVOLTAICS

TP PV SIRTA

Git Tabs Settings Help

Markdown git Notebook pangeo 2025

Practical PV 2026

This Jupyter Notebook has been created for the **Practical PV** course which is part of the MScT program taught in Ecole Polytechnique.
The Notebook is oriented towards introducing the p

All module and functions utilized in this notebook ar

This cell contains the necessary modules and functi

```
[1]: from matplotlib.dates import DateFormatter
     from matplotlib.dates import MO, TU, WE, TH
     from IPython.display import Video, Image, H
     from IPython.core.interactiveshell import I
     InteractiveShell.ast_node_interactivity = "

     import ipywidgets as widgets
     import pandas as pd
     import matplotlib.pyplot as plt
```

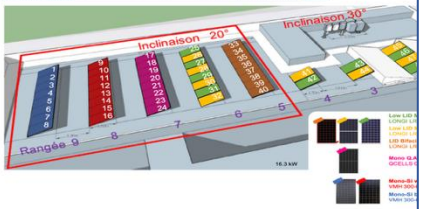
Presentation of each installation

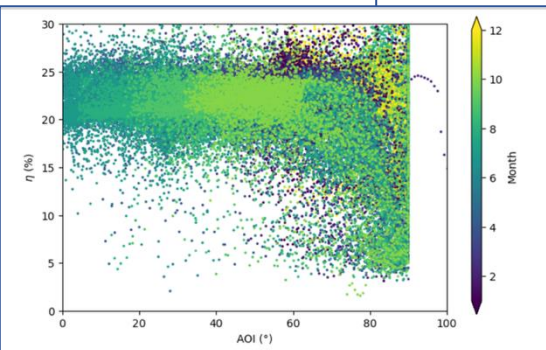
Agripv

- There are 72 c-Si TOPCon based **bifacial** modules.
  - They are divided in 4 strings each of **18** panels connected in series
  - Each string is connected to an inverter
  - Modules of rows 2 and 3 are equipped with optimizers
- South is towards the lake

X-Novation

For a description of the variables available for this installation please read the file 'PV_DrahiX_modules_Meteo_SIRTA_conso_temp_v5_readme.csv' in the 'Data' folder.





It can be seen that, in general, efficiency decreases when the angle of incidence is larger. As efficiency also depends on other variables, such as temperature, low irradiance or even in partial shading due to obstacles, we can see some values that differ from the bulk of points.
Some values overcome the 25% efficiency and approach to 30%, due to the bifacial gain from the modules. On the other hand, we see some points where the efficiency oscillates between 0 - 5%, a value that indicates us that we are on the prescence of very low irradiance or even night-time.
Another very noticeable feature observed is the vertical line at AOI = 90°. This position only occurs twice a day: sunrise and sunset. When this happens, as trackers tend to only be able to reach 60 - 70° with the horizontal, the AOI increases rapidly towards 90° with varying and rapidly changing values of irradiance, which end up causing the almost vertical spread of efficiency values at this AOI.

jupyter

Jupyter Notebooks

TP PV SIRTA

Practical PV
STEEM
2 année

Objectifs

1. Apprentissage de coder en Python
   - Utilisation Jupyter Notebooks
   - Faire des calculs
   - Création des figures

2. Traitement des données
   - Calcul des indicateurs de performance
   - Analyse de performance des installations PV
   - Interpretation des résultats

Jupyter Notebooks

Structure:

1. Introduction
   - Functions utilisés dans le Notebook (créées par moi)
   - Définition des listes et variables
   - Présentation des installations
   - Calculs supplémentaires
2. Exploration des données
   - Incohérence entre les mesures
     - Jours de neige
     - Nuages
     - Ombrages
   - Nettoyage de données
     - Angle d'incidence
     - Mesures erronées
     - Problèmes de connexion

Jupyter Notebooks

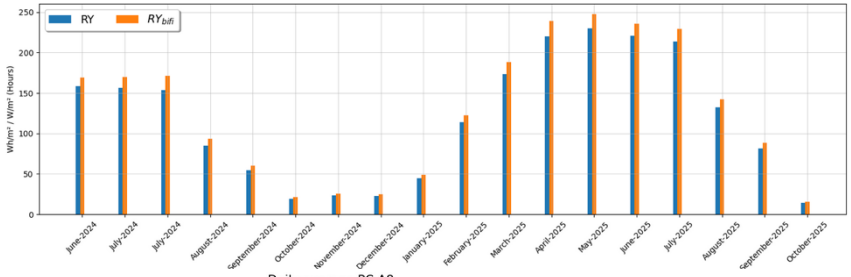
3. Calculs
   - Indicateurs de performance (gain bifacial, ratio de performance, efficacité, etc.)
   - Agrégation temporelle (journalière, mensuel, annuel)

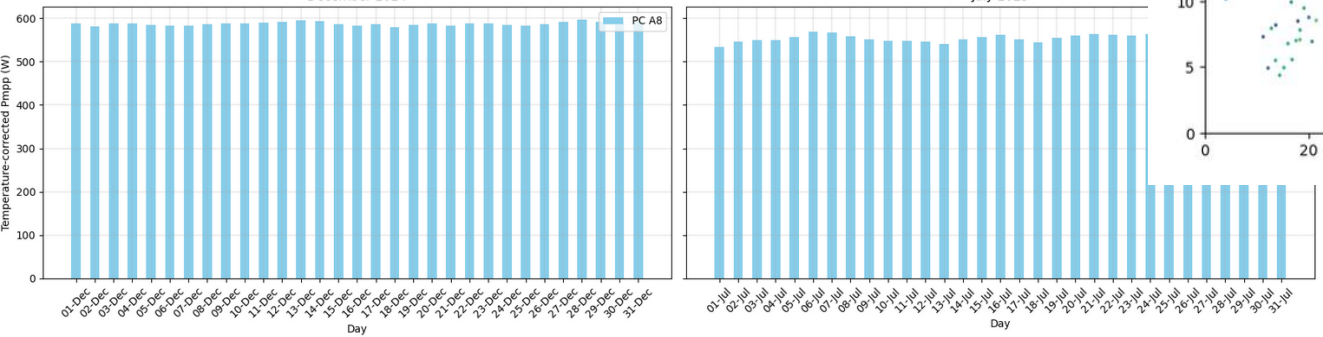
4. Interpretation des résultats

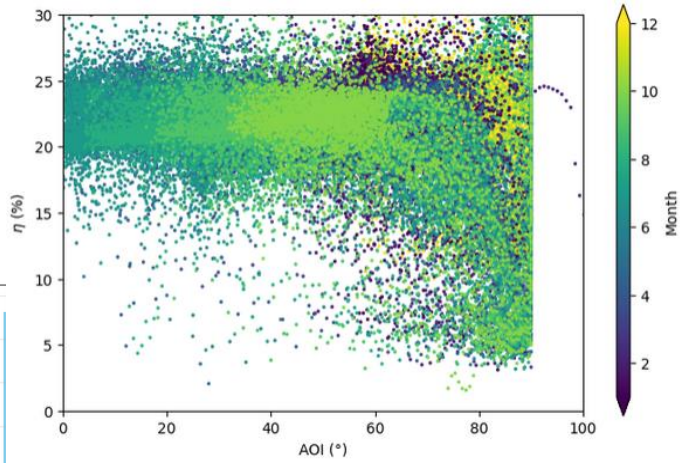
Jupyter Notebooks

TP PV SIRTA

Déliverable:
Notebook avec des figures et réponses aux questions ouvertes ou ponctuelles







Jupyter Notebooks

TP PV SIRTA

```
Task:
- Explain briefly the reason for the shading observed in the figure.
- During which months is there shading on the modules? Explain the reason.
- Are all modules affected by shading? Say which ones and justify your answer.
```

To answer the questions, start by choosing sunny days in a given month to be able to clearly visualize the impact of shading.
To do this, plot the 'Global_Solar_Flux' of several days to select a sunny day.

The occurrence of shadows will vary in causation according on the season. During summer, the sun traverses a higher trajectory in the sky, resulting in diminished shadowing throughout the day. The railing of the building and the trees ought to produce diminished shadows when the sun ascends higher in the sky. Nevertheless, the light traverses a more extended trajectory (resulting in longer days), therefore shadows may still manifest between sunrise and dusk. In the morning, the building's railing may temporarily influence the modules, however in the afternoon, the avenue trees serve as the primary source of shading. Conversely, during winter, the sun traverses a lower trajectory across the horizon, resulting in reduced daylight hours. The lower route results in a more pronounced shade impact of the railing on the building's modules, especially during the morning and afternoon; nevertheless, the avenue trees become less significant with reduced sunlight hours.

This is evident in the graphed days. On the August day, the shading effect is less, resulting in analogous behavior among the three depicted modules. The diminished power output of modules 25 and 32 during midday may result from a localized shadow created by an instrument.

The January day graph distinctly illustrates diminished output in module 1 during the morning and afternoon, attributable to the shadow cast by the building's railing at those times. Module 32, conversely, succeeds in regaining some production and adheres to a trajectory akin to that of an unshaded module.

The modules most impacted will consistently be those next to the railing.

To address the inquiries, begin by selecting bright days within a specific month to effectively illustrate the effects of shading. To accomplish this, graph the 'Global_Solar_Flux' over multiple days to identify a sunny day.

Jupyter Notebooks

(Ratio de performance, efficacité, rendement de référence, rendement du module, gain bifacial, effet de la témperature, salissure)

Calcul des indicateurs

Données PV

AgriPV

DrahiX

Données SIRTA

Irradiance

Angles solaires

Temp, précipitation, etc.

Librairie PVlib

Puissance

masse d'air

Angle d'incidence

GHI du ciel clair

Jupyter Notebooks

Difficultés:

1. Aucune connaissance préalable de Python
2. Aucune expérience avec traitement des données "réelles"
3. Manque de compréhension d'une application du traitement des données

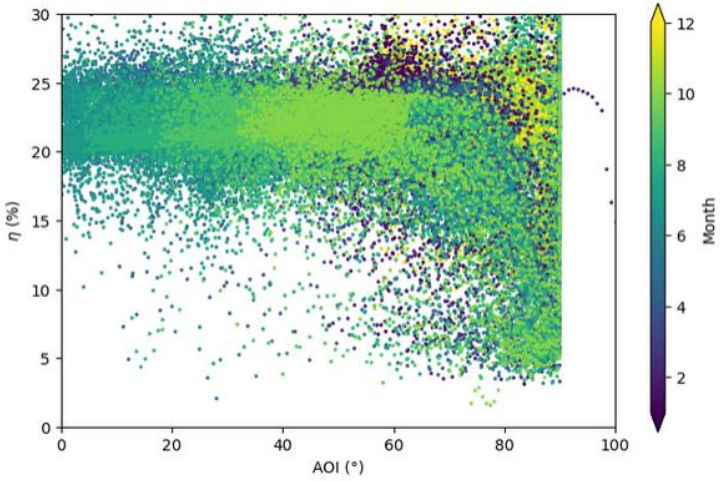
Stratégies:

1. Documenter chaque cellule au début du Notebook
2. Utilisation des widgets pour rendre l'expérience plus dynamique
3. Donner un code prêt à utiliser pour l'analyse des données ou création d'une figure
4. Expliquer a chaque pas l'utilisation et l'importance du résultat obtenu
5. Poser questions assez souvent à différentes personnes

Angle-of-Incidence (AOI)

In this section you will explore the need the to filter your original dataset in order to be bale to conduct analyses.
First, plot the efficiency of module A8 ('Eff_a8') vs the angle-of-incidence ('AOI') and observe the figure.
Can you infer anything from this plot? Try to explain it in your own words.

```
]: # Write the lower and upper limits for the X and Y axisinside the parenthesis
x_lim = (0,60)
y_lim = (0,30)

# We create our own figure witn one axis to be able to modify it in an easier manner.
fig, ax = plt.subplots()

# The 'c' parameter indicates a third variable that will correspond to the color of the points.
# The 's' parameters affects the size of the points. Only when using a scatterplot.
im = ax.scatter(data_agripv.AOI,data_agripv.Eff_a8, c = data_agripv.index.month, s = 2)

#The labels and title of the figure can be adjusted manually
ax.set(xlim = (0,100), ylim = (0,30), xlabel = 'AOI (°)', ylabel = '$\\eta$ (%)')#, title = '')

# The lines below allow the colorbar to be adjusted.
# Remember to label it accordingly.

# The line below adjusts the location of the colorbar
cbar_ax = fig.add_axes([0.95, 0.1, 0.02, 0.8])
fig.colorbar(im, cax=cbar_ax, label = 'Month', extend = 'both', orientation = 'vertical');
```



Jupyt

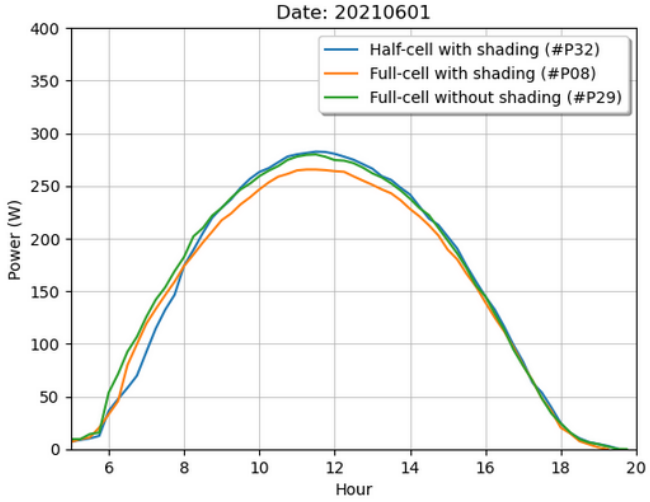
Date: 20210601

Half-cell with shading P32

Full-cell with shading P08

Full-cell without shading P29

```
# We again create a new variable dataset
df = data_drahi.loc[date.value]

fig, ax = plt.subplots()

# Change the labels of the shaded modules accordingly if needed
ax.plot(df.index.hour+df.index.minute/60, df[var.value], label = 'Half-cell with shading (#'+var.value+')')
ax.plot(df.index.hour+df.index.minute/60, df[var2.value], label = 'Full-cell with shading (#'+var2.value+')')
ax.plot(df.index.hour+df.index.minute/60, df[var3.value], label = 'Full-cell without shading (#'+var3.value+')')

# Set the range of hours you want to plot in xlim between the parethesis
# Set the range of values of ylim between parenthesis
ax.set(xlim = (5,20), ylim = (0,400), xlabel = 'Hour', ylabel = 'Power (W)', title = 'Date: '+date.value)

# Show the labels of the curves in the figure
ax.legend(shadow = True)

# Show a thin-lined grid on the figure
ax.grid(True, lw = 0.5);
```



Bifaciality

One advantage of bifacial modules is that they produce energy from both sides. This is evident on snowy days when their frontral face is completely covered but the back still produces due to the reflected irradiance that is absorbed.

Task:

- On the snow day mentioned in the Snow section, compare the energy produced by the A8 module in the agripv installation and a bifacial module (your choice) from the DrahiX installation. Which one produced more energy? Can you explain the reason?
- Compare the energy produced by the bifacial modules from the DrahiX installation with the monofacial in front of them (full- and half-cell). How much more energy did the bifacial modules produced?

Bifacial Gain

As mentioned, one of the advantages of having bifacial modules is the ability to absorb irradiance from both sides of the panel. However, it is important to know how much more energy it produces with respect to a monofacial module.

To calculate it, the bifacial yield ('Y_b') and monofacial yield ('Y_m') must be used in the following equation:

$$BC = \frac{Y_b - Ym}{Ym} * 100$$

Task:

- Calculate the bifacial gain for a sunny and overcast day. What are the differences in value? **Remember:** The yield must be in Wh/W
- Plot the monthly BG (already calculated with the other performance indicators). How do these range of values compare to the literature? Compare with one source and cite it.

Jupyter Notebooks

<u>À améliorer:</u>

1. Élimination des widgets
2. Rendre les questions plus claires et plus visibles
3. Limiter le nombre de caractères dans les questions ouvertes
4. Être plus spécifique avec le format des résultats

Merci pour votre attention

Ces plateformes ont été construites conjointement par le centre E4C d'IP Paris et par l'Université Paris-Saclay et ont bénéficié et bénéficieront de financements divers dont la Chaire DTER et la Région Île-de-France.