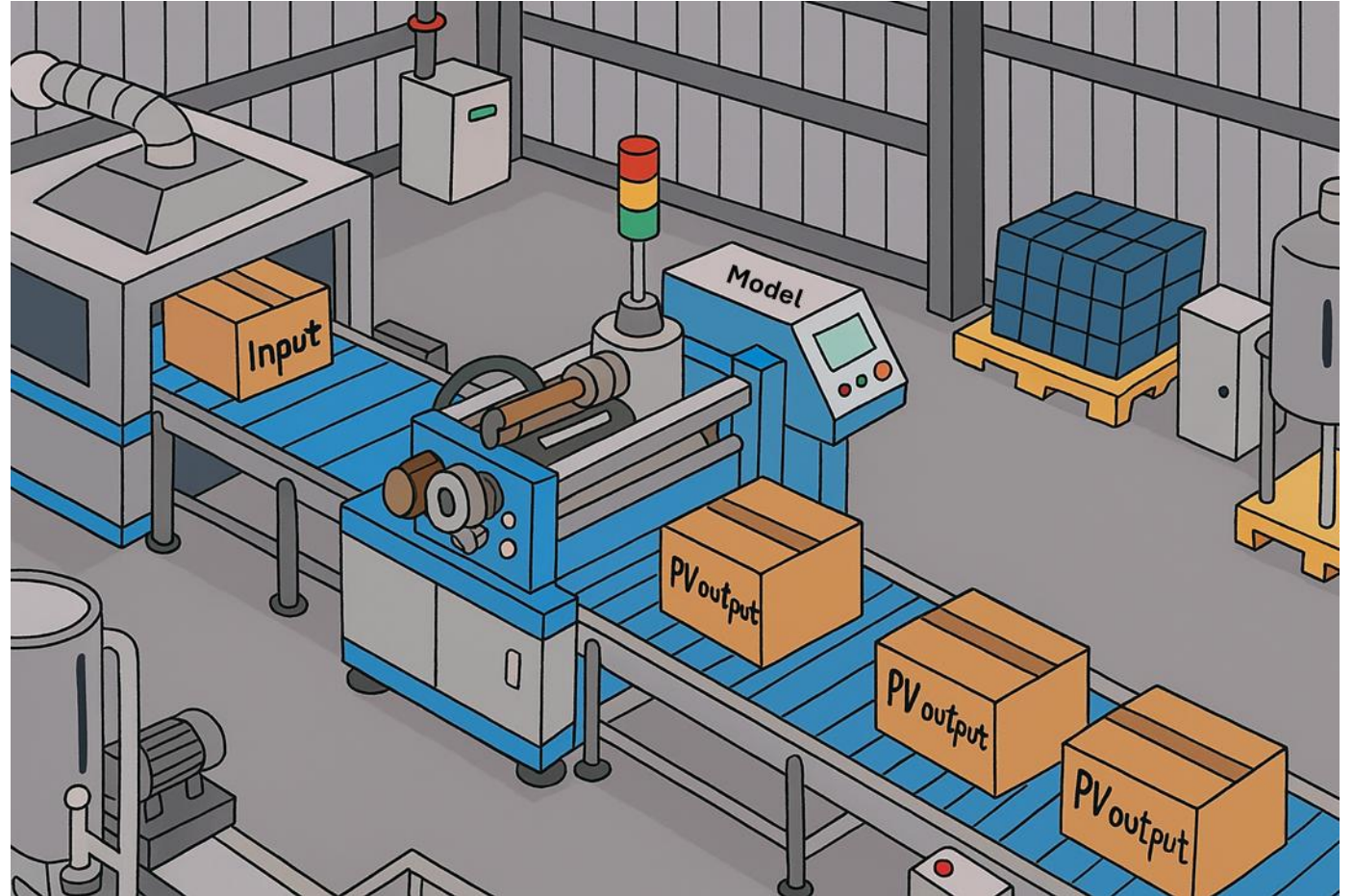


# PV modelling an overview (#1)

Rodrigo Amaro e Silva

[rasilva@ciencias.ulisboa.pt](mailto:rasilva@ciencias.ulisboa.pt)

26/10/2026



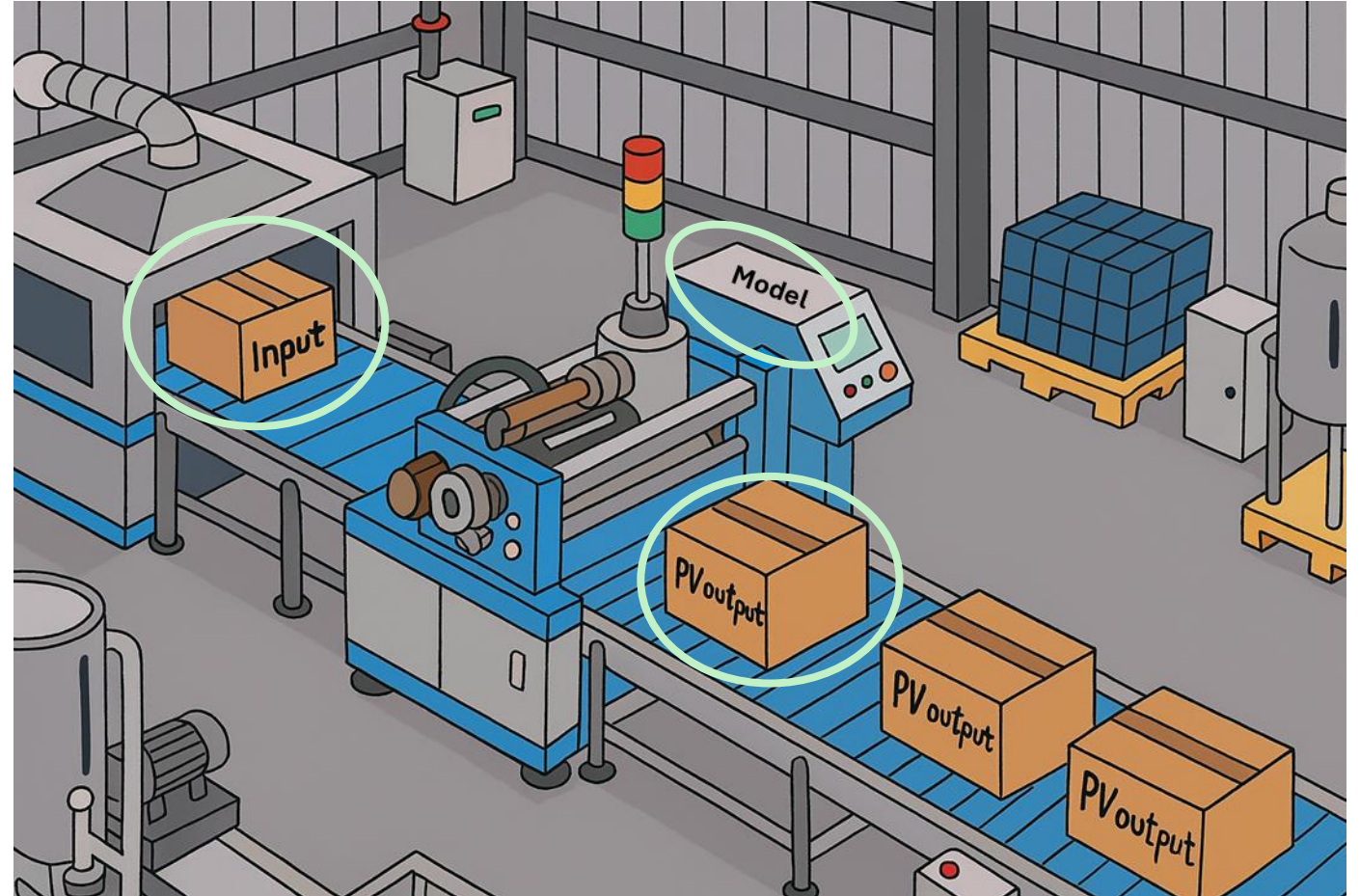
A few words about myself

# Goals for today

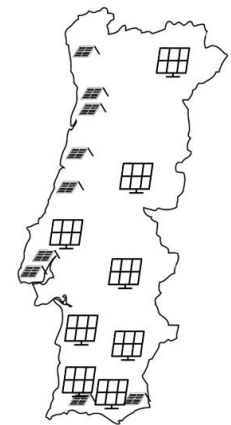
- 🎯 What does “PV modelling” mean and what it is used for?
- 🎯 How is PV modelling actually done?
- 🎯 What loss factors impact PV generation?

# Context

What it means:



# A variety of scales: space



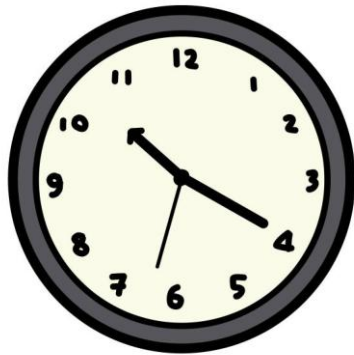
Rooftop

Power plant

Neighborhood/City

Country

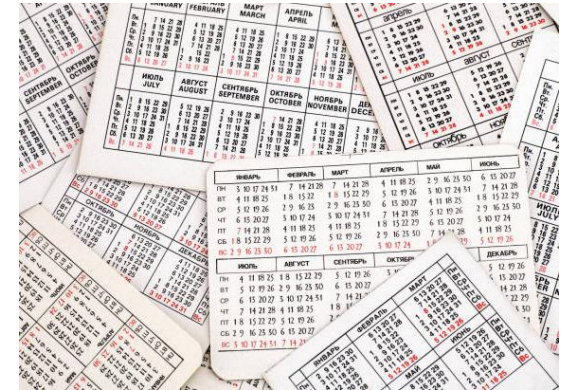
# A variety of scales: time



From minutes to days



From days to weeks



From months to years

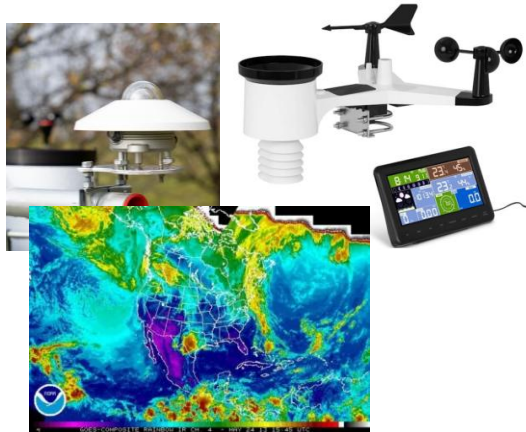
# A variety of scales: time

But also...



Often, terms like “estimation” or “forecast” are used to different if a model addresses the past, present or future.

# A variety of inputs



Weather



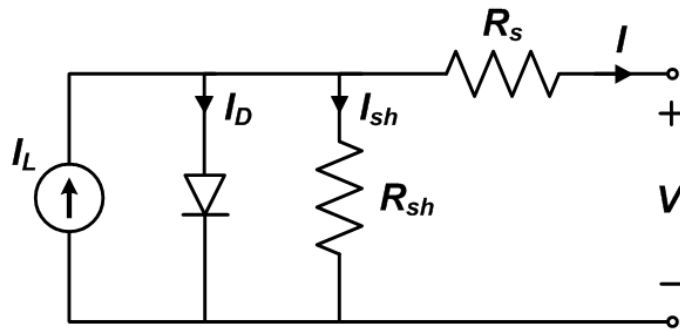
Own PV system



Portfolio and  
neighboring systems

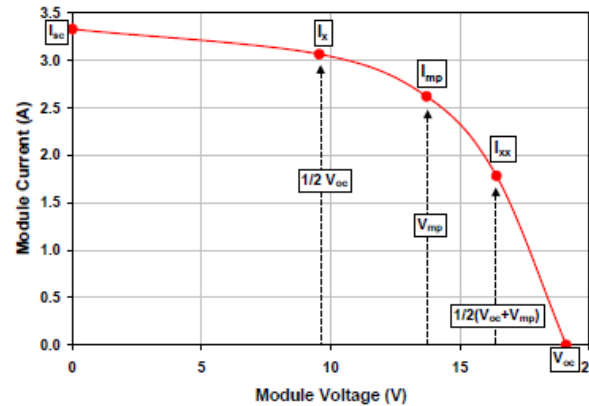
Note: in small setups (weather station, small PV systems) data collection is done mostly through dataloggers.  
However, large PV plants implement a more comprehensive Supervisory Control and Data Acquisition (SCADA) system.  
More on this [here](#), [here](#), [here](#), and [here](#).

# A variety of approaches



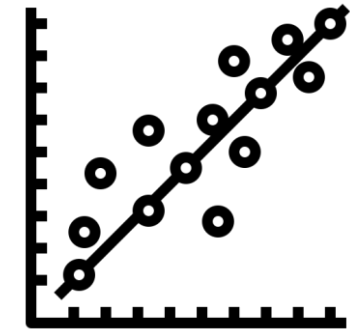
Diode-equivalent models

(provide I-V curves)



Point-value models

(provide only 1+ points in the I-V curve)

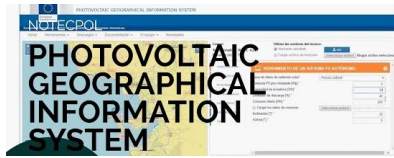


Statistical models

(returns the variable we want, as long as we measure it\*)

\* Could also be used to post-process another model to overcome certain limitations

# A variety of softwares



What it is used for

# Conceptual uses for PV modelling

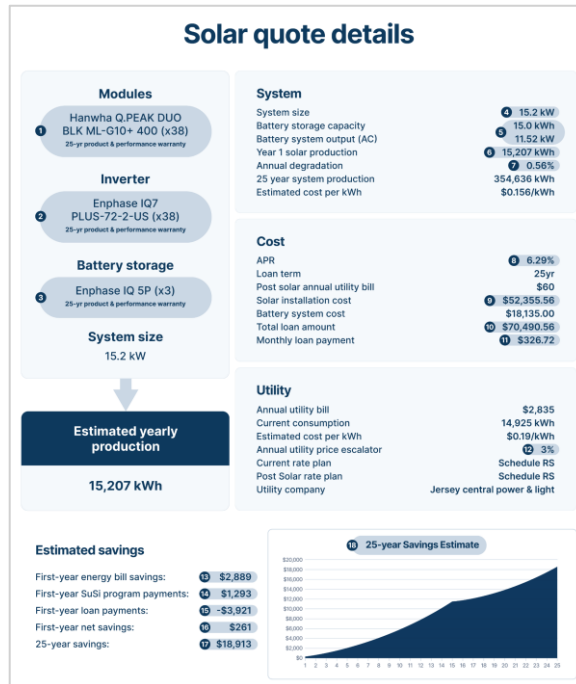
## **Prospection** (a project-to-be)

- what would be the best PV setup in a given context?
- how much would it generate over 30 years?
- how much can generation vary from one year to the other?

## **Operation** (a project already installed)

- how much should it have produced yesterday / last month?
- how much will it produce tomorrow / in 20 years?

# Prospection: what for?



Project design & quoting

**Project Proposal For Bank Loan**

**Date:** [Insert Date]  
**Prepared by:** [Your Name/Your Company Name]  
**Address:** [Your Address]  
**Contact information:** [Your Phone Number/Email]

**1. Executive Summary**  
Provide a brief overview of the project and the purpose of the loan.  
Summarize the following:

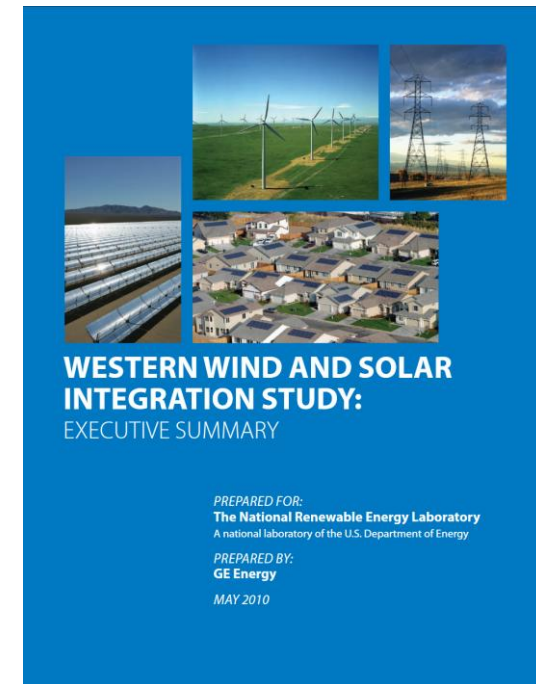
- Project name
- Purpose of the project
- Amount requested for the loan
- Duration of the loan and repayment plan
- Expected outcomes or benefits from the project

**2. Project Description**  
Give a detailed description of the project for which the loan is requested.  
Include:

- Background of the project
- Business objectives and goals
- Products or services involved

Copyright © EXAMPLES.COM

Project financing  
& insurance



Grid integration studies

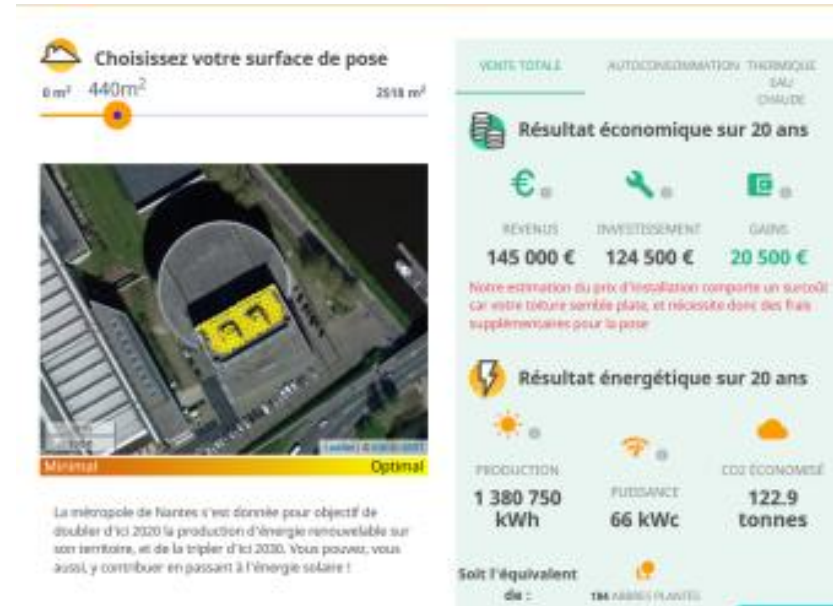
On project design: links from [pvcase](#), [detrasolar](#), and [glintsolar](#)

On project financing: links from [TrinaSolar](#), [borrego](#), [skyspecs](#); and insurance: links from [kWh Analytics](#), [PV Tech](#), [Sinovoltaics](#)

On grid integration: links from [Power and Energy Magazine](#), [Greening the Grid](#), [NREL](#)

# Prospection: what for?

But can also be used as a passive tool for raising awareness / customer engagement:



You may also want to take a look at Google's [Project Sunroof](#) and IRENA's [SolarCity Simulator](#).

# Prospection: what for?

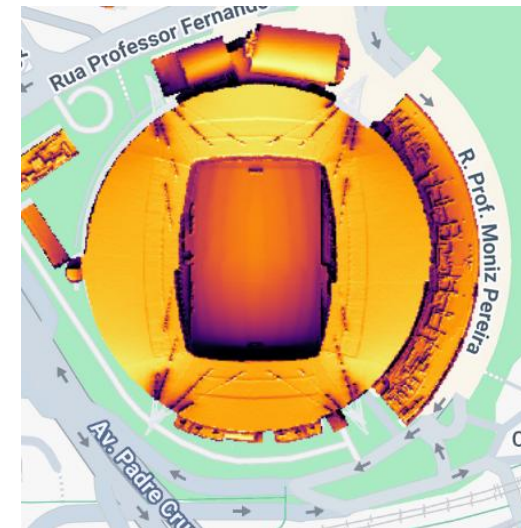
But can also be used as a passive tool for raising awareness / customer engagement:



Find [here](#) the Solis website



The FCUL campus



The best stadium  
in Lisbon

# Operation: what for?



Maintenance  
and insurance claims



Market bidding



Better time matching  
PV and demand

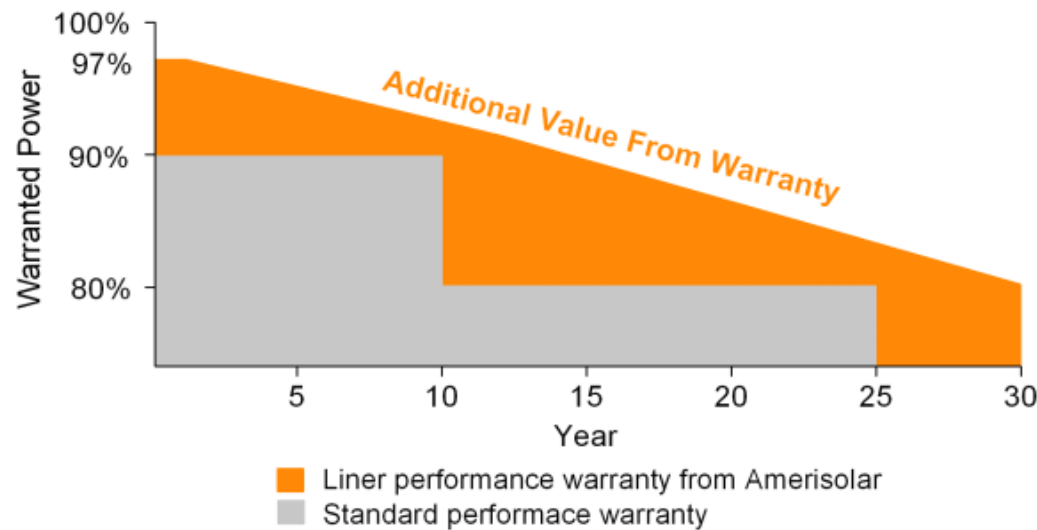
On project maintenance: links from [Oviedo Hernandez \(2022\)](#), [Micheli \(2021\)](#)

Market bidding: example from Iberian day-ahead market from [Antonanzas \(2017\)](#)

On grid integration: links from [Power and Energy Magazine](#), [Greening the Grid](#), NREL

# Operation: what for?

Performance warranties, the case of the module fabricant:



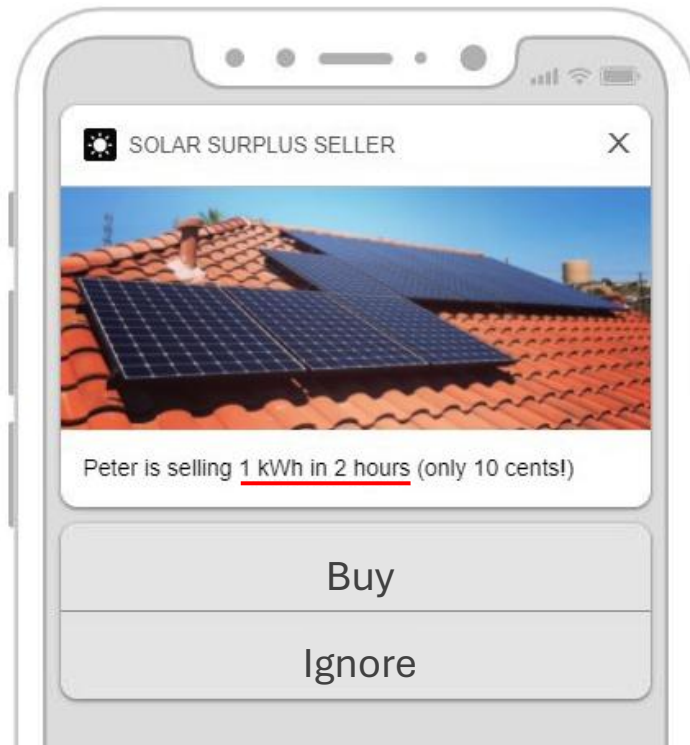
Verifying this requires accurate and credible generation estimates under “normal working conditions”

More on module warranties [here](#)

Read [Hsi et al. \(2024\)](#) introduction to know more about warranty fund reserves in PV industry

# Operation: what for?

It can also enable peer-to-peer trading



You might want to take a look at IRENA's [Peer-to-peer electricity trading](#) or [Neves \(2020\)](#).

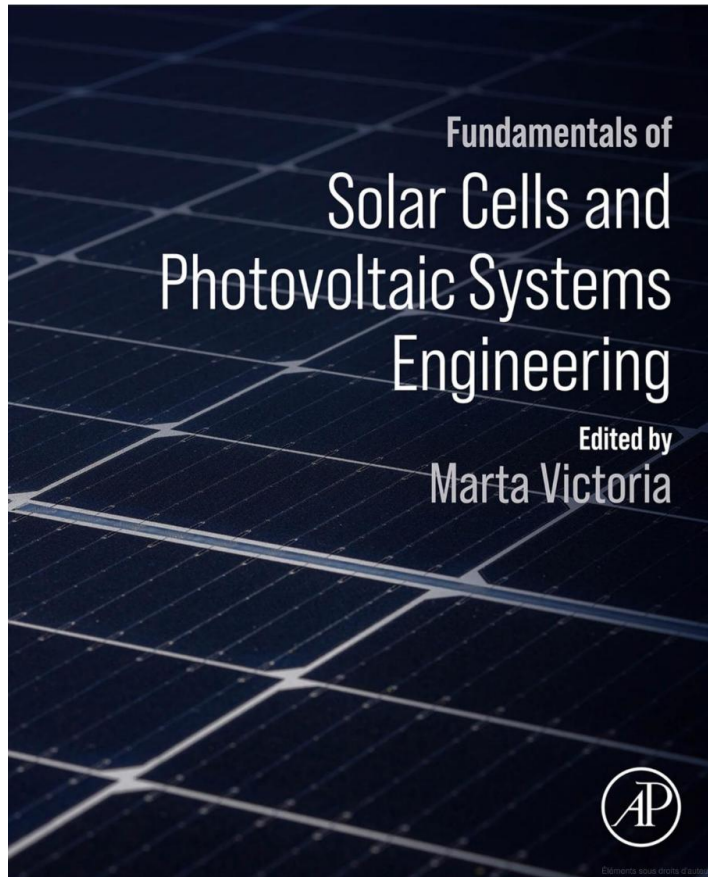
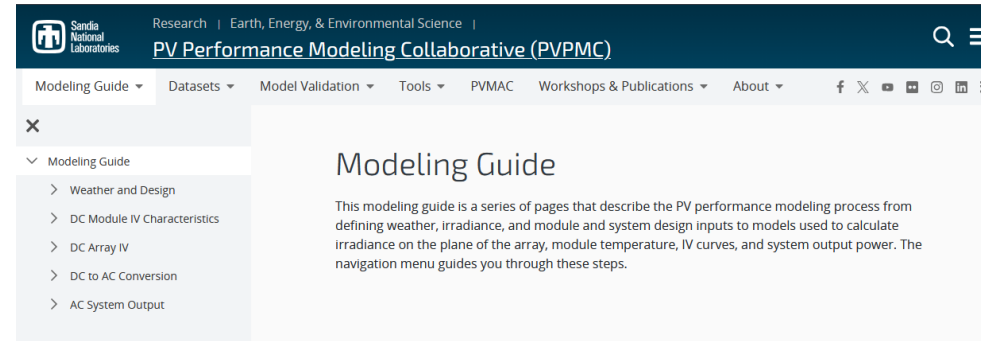
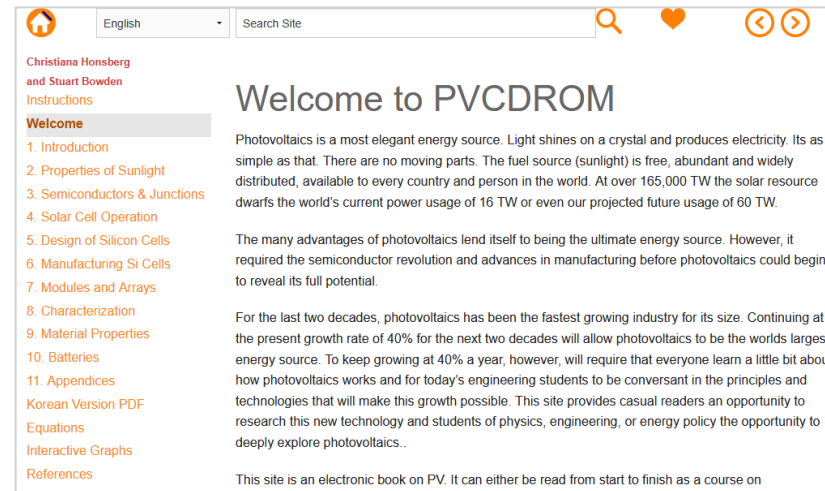
# Time for a mini-mini-pause

Any questions?



# How it is done

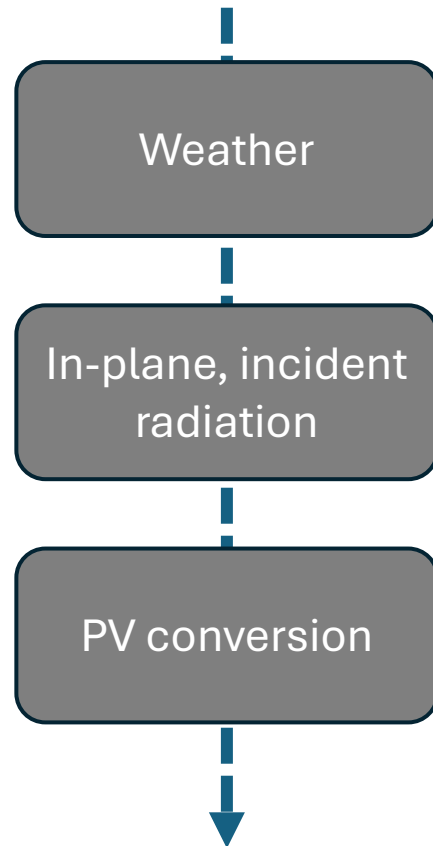
# Suggested materials



<https://pvpmc.sandia.gov/modeling-guide/>

<https://www.pveducation.org/pvcdrom/welcome-to-pvcdrom>

# High-level workflow

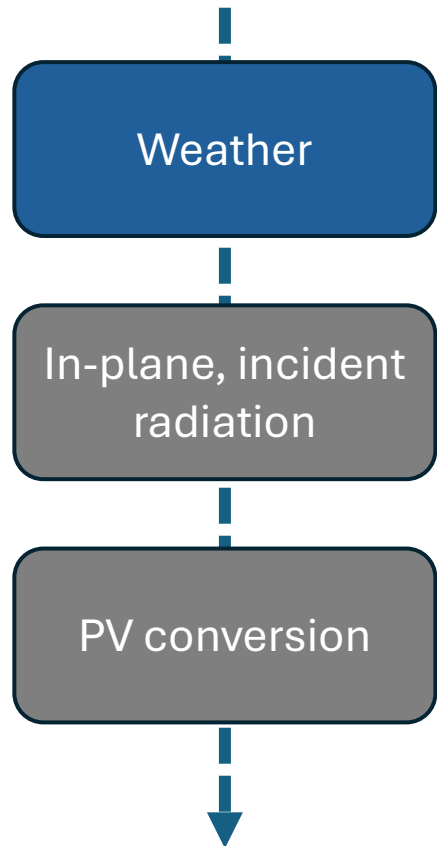
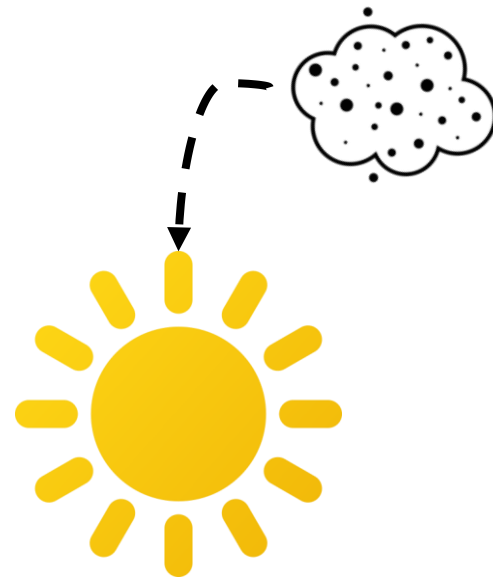


“Modelling” could include all of this

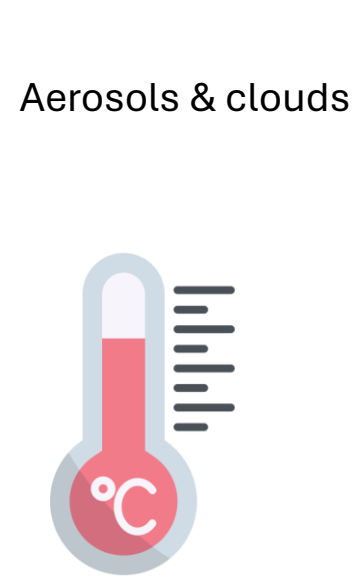


But just this last layer already comprises several modelling steps

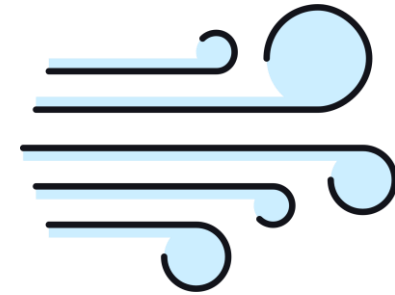
# Several variables of interest



Solar radiation



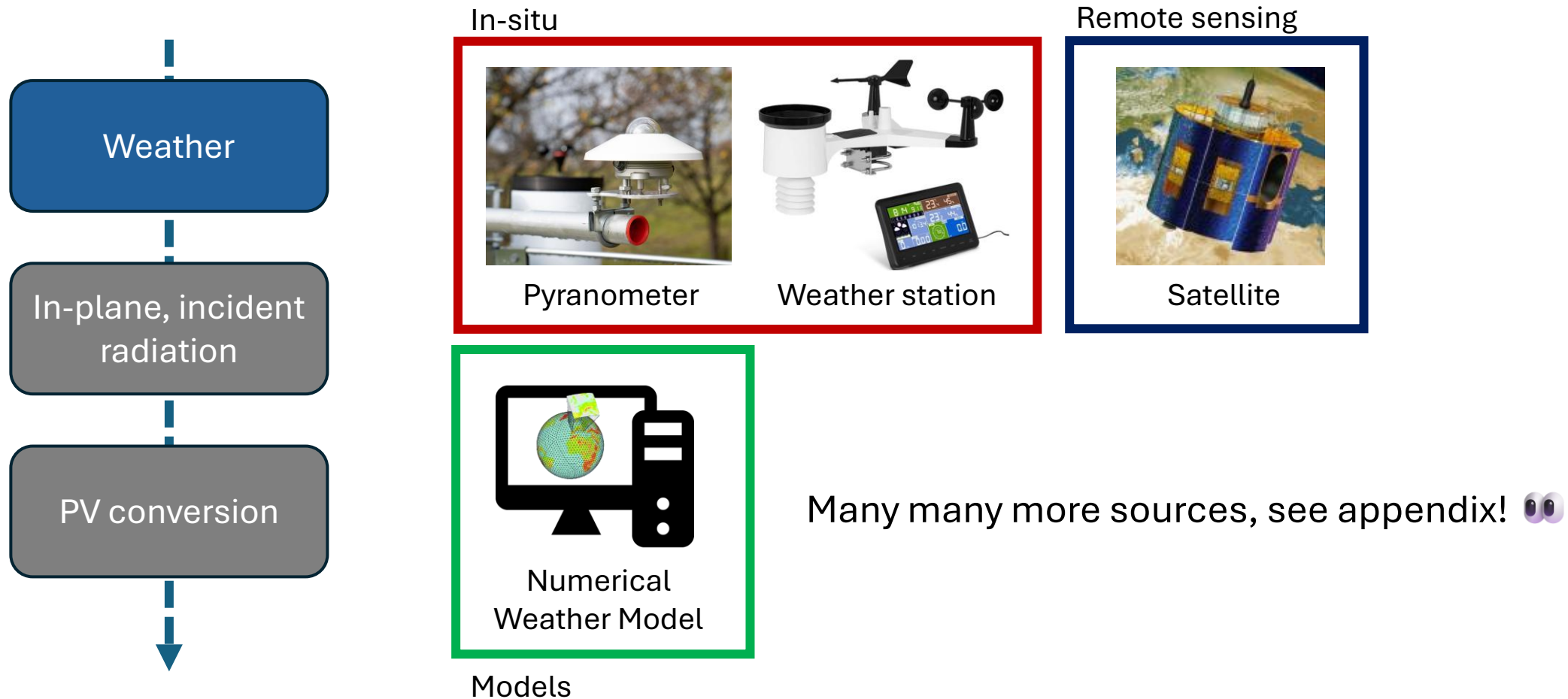
Air temperature



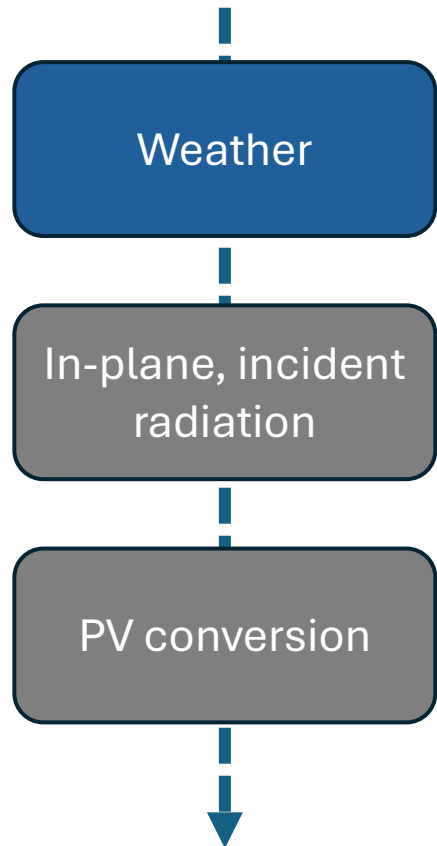
Wind speed

Other variables like relative humidity may be used, but less common

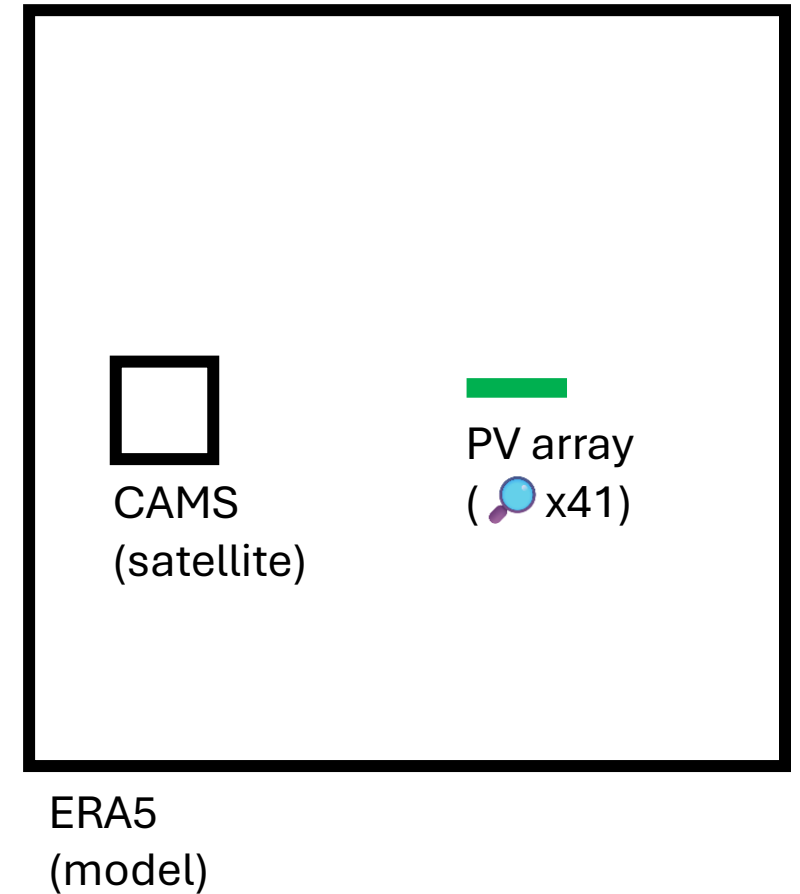
# Weather: several sources of data



# Weather: spatial scales



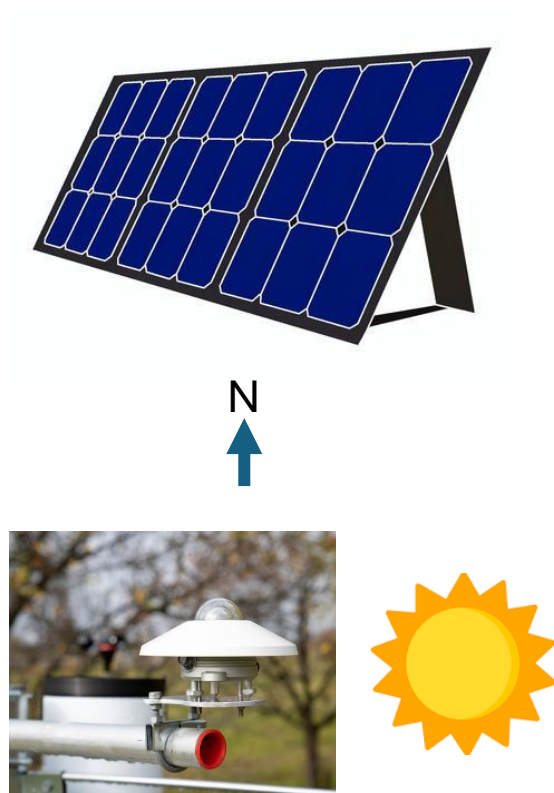
- FCUL C1 PV array
- FCUL weather station



# Weather: reading some data

Notebook time! Brief intro + reading some weather data.

# Question time

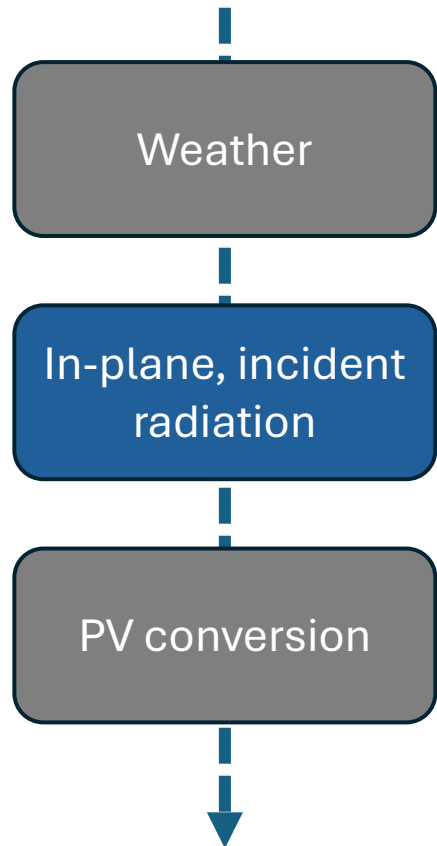


Let's imagine that

- We have the **PV system on the left**
- Tomorrow at **10 am**, FCUL's weather station reports **sunny weather** (high solar resource)

Would you expect high or low PV output?

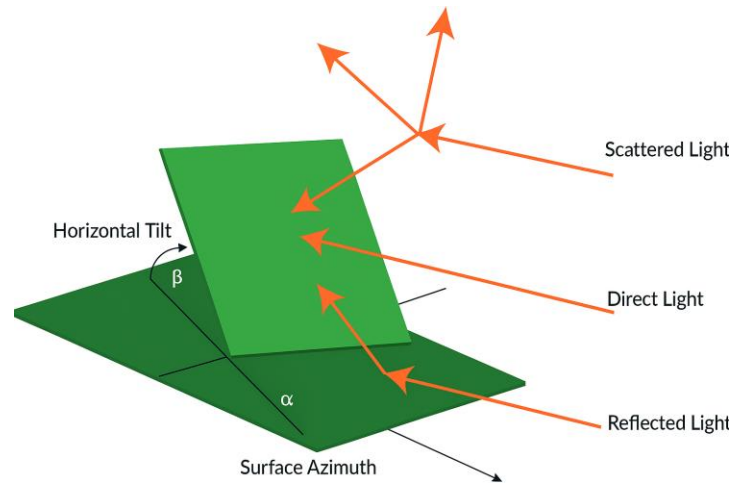
# The need to transpose solar radiation



Solar radiation is often measured in the horizontal plane

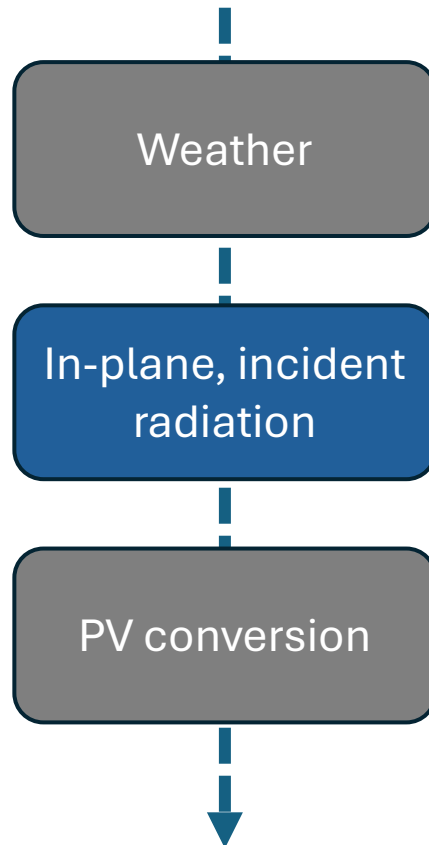
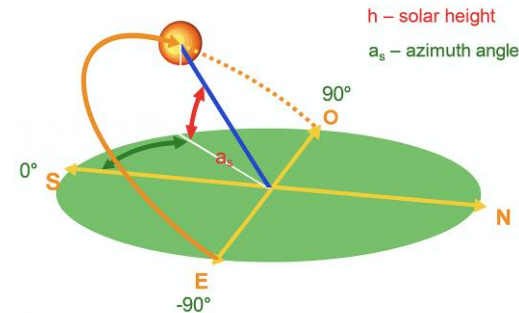
⚠ Need to account for module' inclination and azimuth (e.g. 30°S)

🔧 **Transposition** models (transposing from one angle to another)



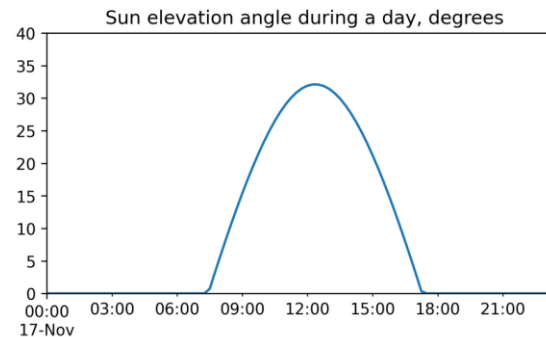
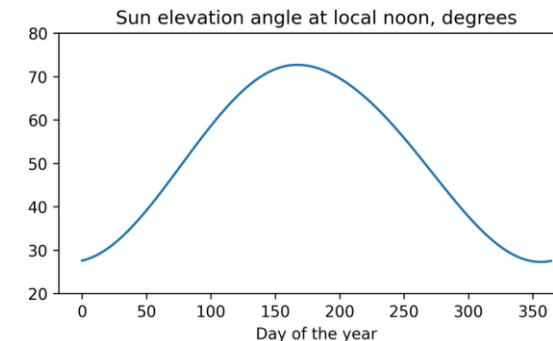
For this, we need to consider 2 key elements.

# 1<sup>st</sup>: solar apparent position



pvlib Python package includes [several algorithms](#)

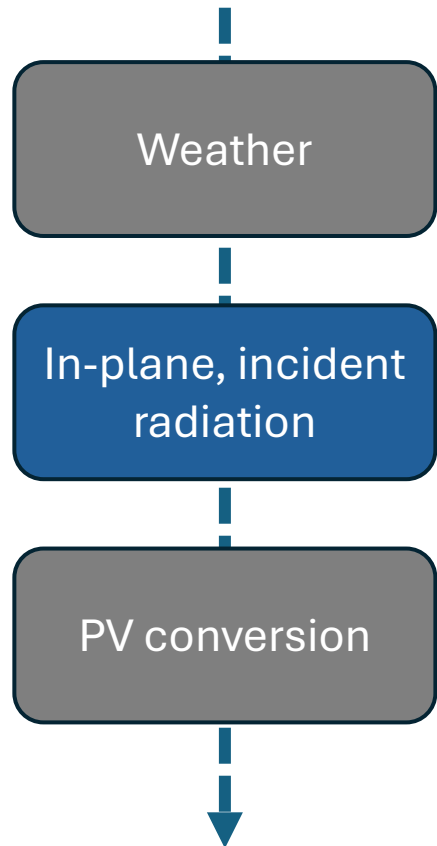
Sun elevation example @Minicampus, Lisbon



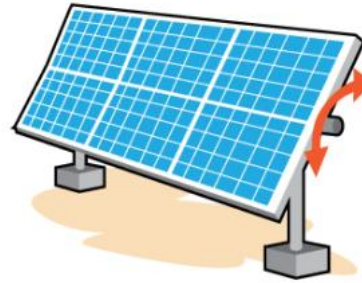
One algorithm outside of pvlib: SG2, [Blanc and Wald \(2012\)](#), <https://github.com/gschwind/sg2>

See this [video](#) if you are wondering about the “apparent” in the title means

## 2<sup>nd</sup>: PV module orientation



Utility-scale power plant  
(fixed)



Utility-scale power plant  
(tracking\*)



Rooftops



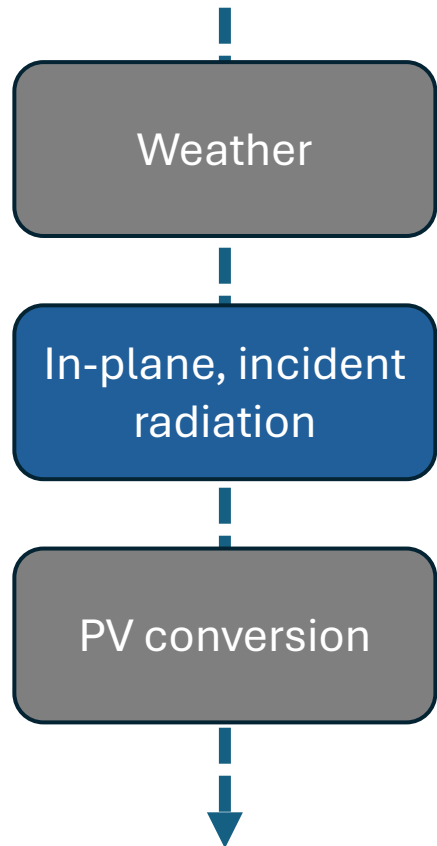
Vertical PV



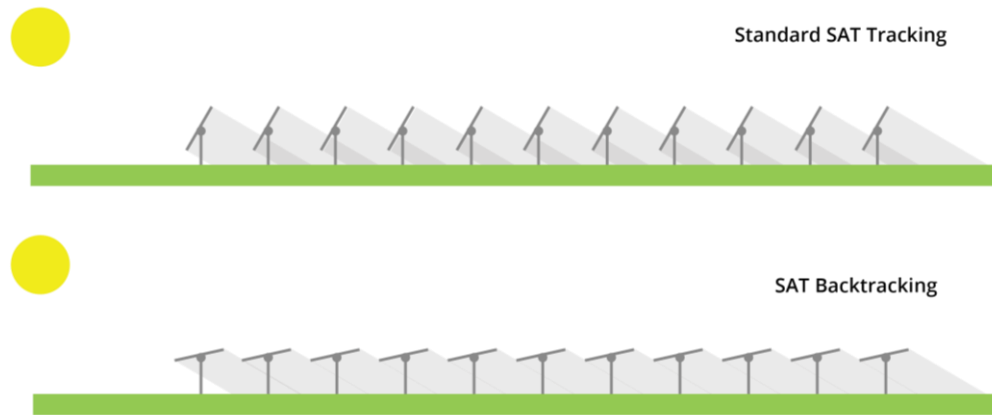
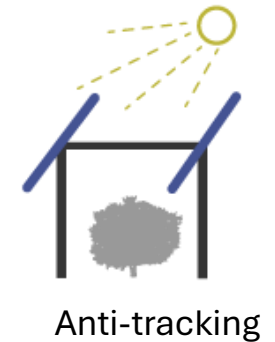
Floating PV

\*There are several tracking setups (see more [here](#)).

## 2<sup>nd</sup>: PV module orientation



And within tracking setups, there are tracking strategies!



Read more about backtracking [here](#) and anti-tracking [here](#).

# Demo moment #1

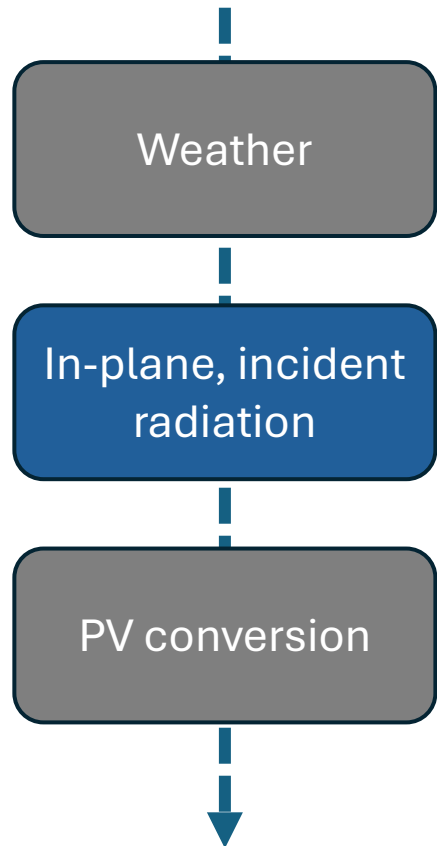
Coding demo time! Can someone please google for me:

`pvlib.solarposition.get_solarposition`  
`pvlib.irradiance.aoi`

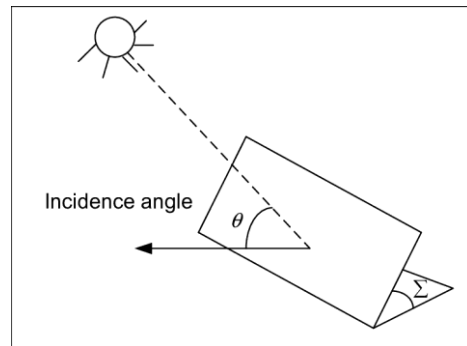
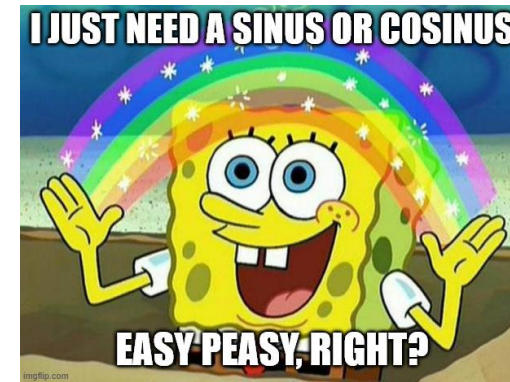
Tell me the inputs inside the ( ) before the 1st one ending in “= ...”

```
pvlib.solarposition.get_solarposition(time, latitude, longitude, altitude=None,  
pressure=None, method='correl_lookup', temperature=22.0, **kwargs) \[source\]
```

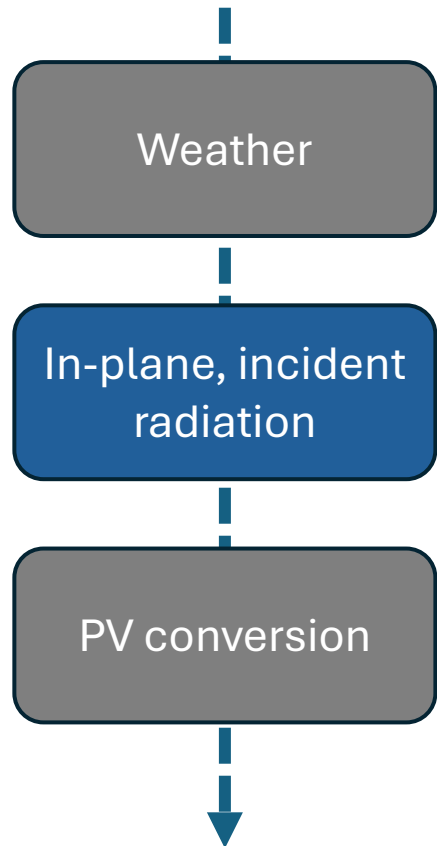
# Actually transposing solar radiation



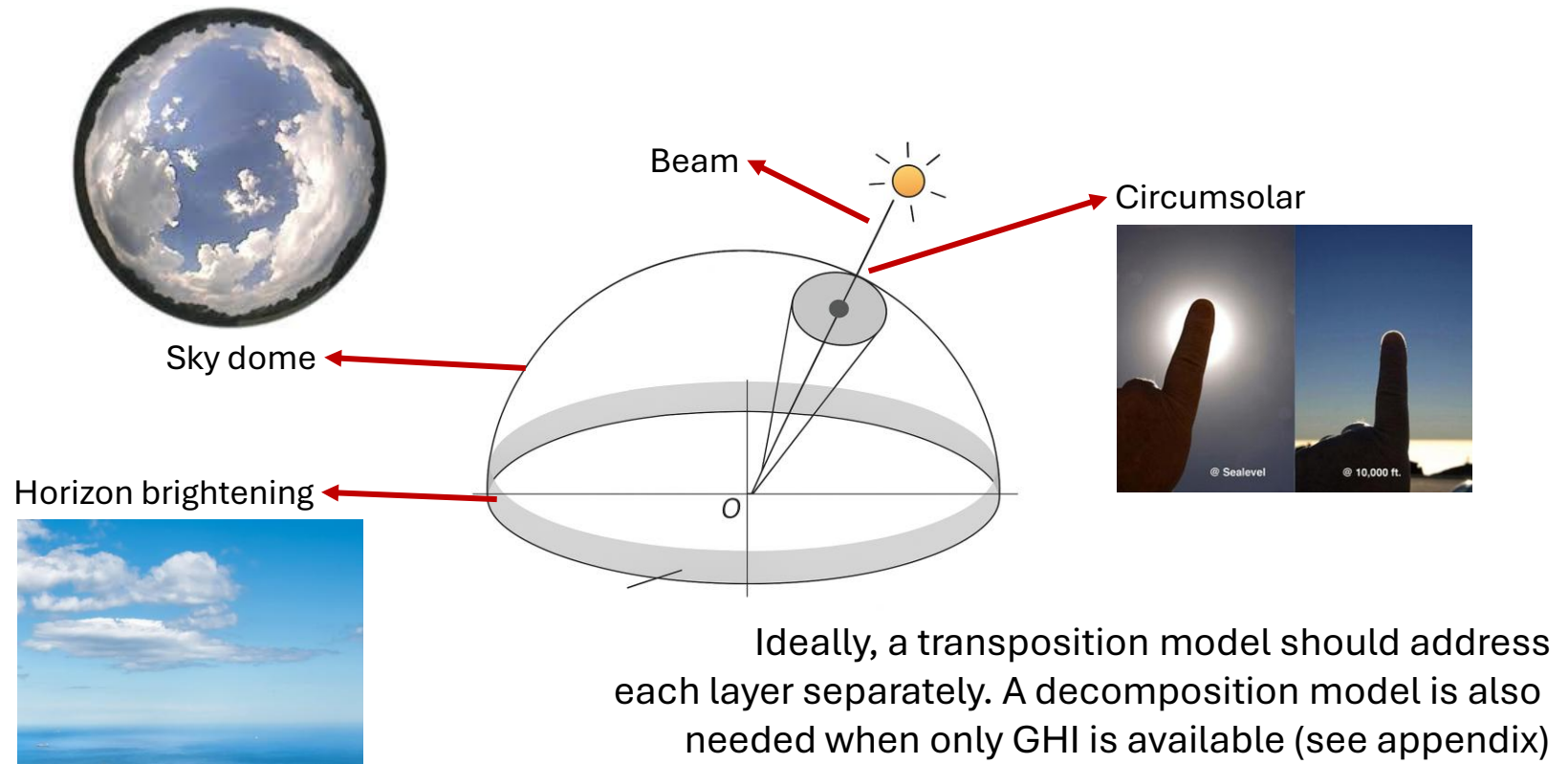
When oversimplified:



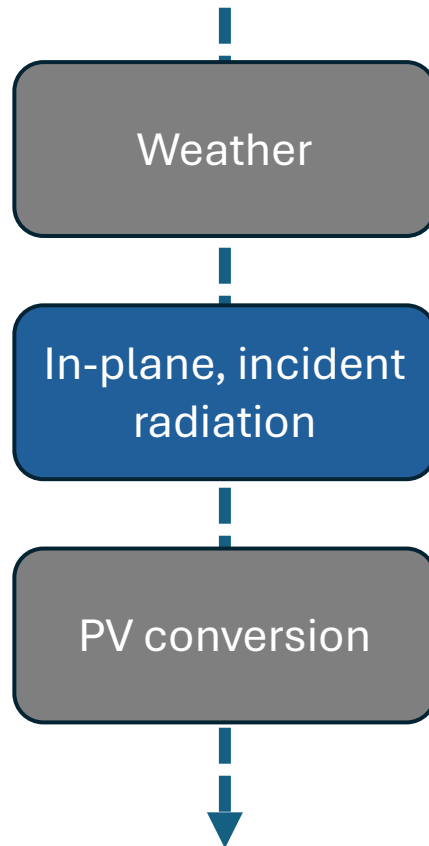
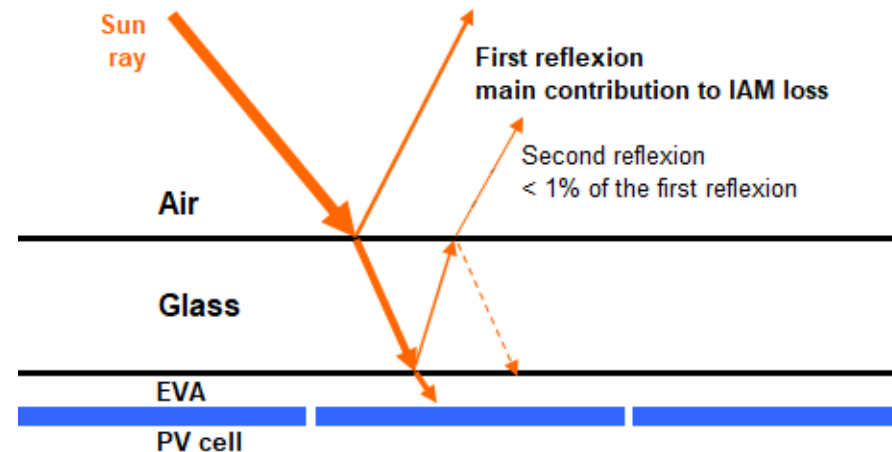
# The need to transpose solar radiation



Solar radiation is “angularly” heterogeneous



# Optical losses: from atmosphere to PV cell



Configuration

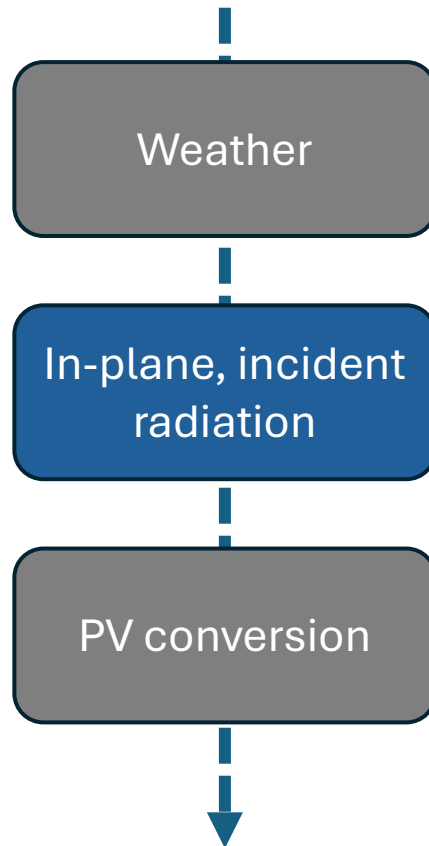
Air/glass  
Air/glass/Si  
Air/glass/SiO<sub>2</sub>/Si  
Air/glass/triple coat./Si  
Air/glass/ZnS/Si  
Air/glass/a-Si:H/Ag  
Air/glass/ITO(d1)/a-Si:H/Ag  
Air/glass/ITO(d2)/a-Si:H/Ag

Martin-Ruiz model, doi: [10.1016/S0927-0248\(00\)00408-6](https://doi.org/10.1016/S0927-0248(00)00408-6)

Marion model, doi: [10.1016/j.solener.2017.03.027](https://doi.org/10.1016/j.solener.2017.03.027)

Both models available in pvlib. Look for IAM (Incidence Angle Modifier)

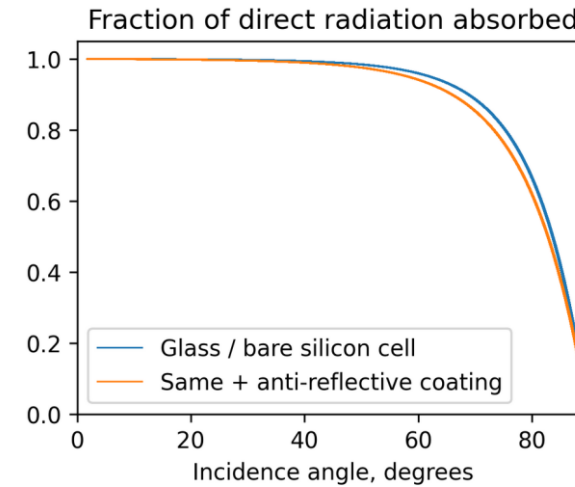
# Optical losses: from atmosphere to PV cell



Anti-reflective coating, an example from Martin-Ruiz model\*:



Illustrative example



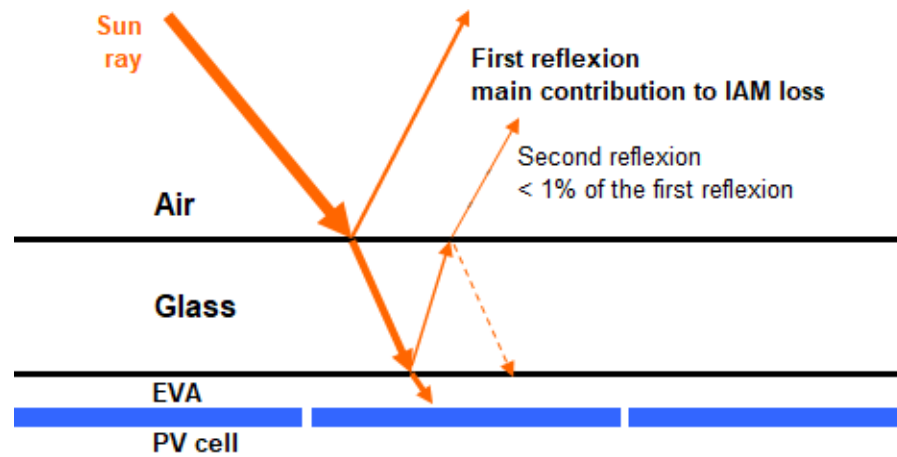
+0.5% gains @ 50°  
+5% gains @ 75°

For diffuse radiation, average losses are often considered near constant (4% and 3%).

\*Martin and Ruiz (2001), [https://doi.org/10.1016/S0927-0248\(00\)00408-6](https://doi.org/10.1016/S0927-0248(00)00408-6)

# Demo moment #2

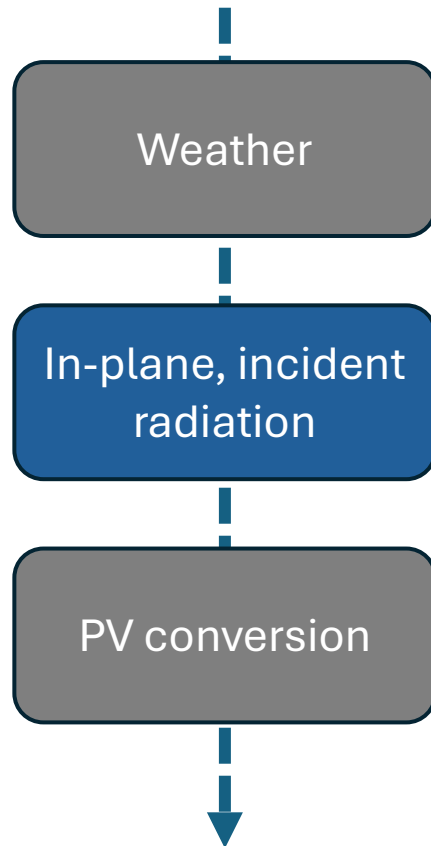
Let's calculate the IAM ourselves:



`pvlib.iam.martin_ruiz`

Inputs again please

# Optical losses: from atmosphere to PV cell



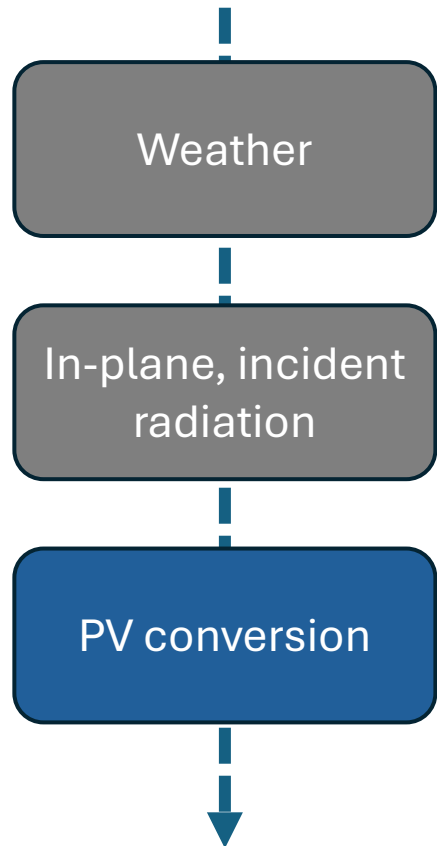
We can also add soiling to the “party”.

- [Many sources](#), but very location-dependent
- Snow is intermittent, but with drastic impacts, rest is more progressive.
- [Ilse \(2019\)](#) estimated 3-4% energy losses and 3-5 bn € in revenue



This [IEA PVPS T13 report](#) gives a nice overview on this topic.

# Optical losses: from atmosphere to PV cell



A few quick notes:

- There are ways to measure it, based on optical or electric data.
- Except for [snow](#), it is common in the industry to estimate a fixed soiling derate from historical PV generation data ([Kimber](#))
- Some physical models look at particulate matter (PM) data and try to describe deposition mechanisms (e.g. [Coello and Boyle](#))



Find [here](#) and [here](#) a nice take on soiling sensors.

# Enough for today

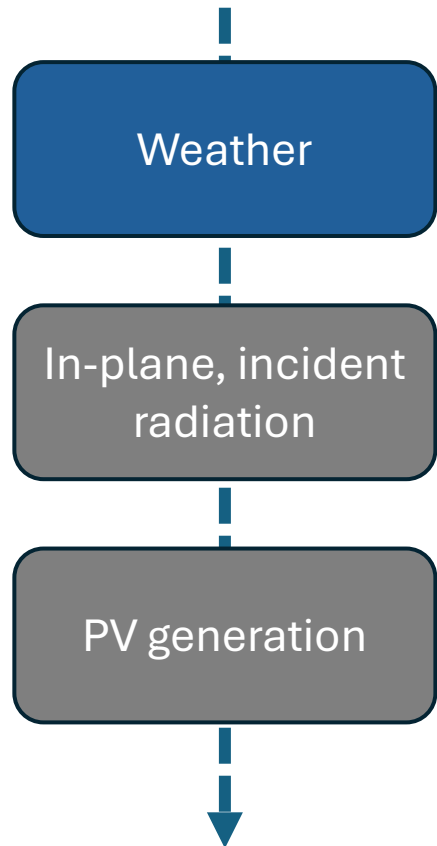
- Avoid reaching this stage



- Tomorrow we'll look at PV conversion + pvlib functionalities

# Appendix

# Weather: several sources of data



## In-situ



Pyranometer



Reference cell



All-sky imager\*



Weather station



Satellite



Airborne data



Cloud radar

## Remote sensing



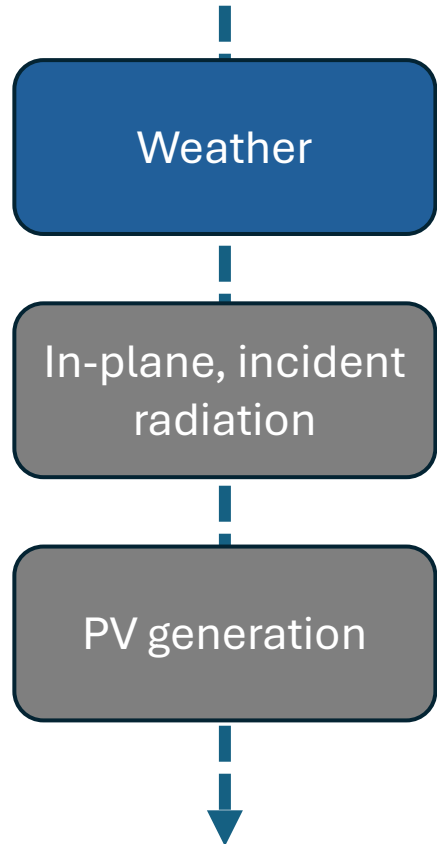
Numerical  
Weather Model

## Models

\*Also known as a sky-camera. There are also other sensors to measure, for example, module temperature.

# Weather: pyranometer setups

## Pyranometer and variations



Horizontal  
(GHI)



+ shadow band  
(DHI)



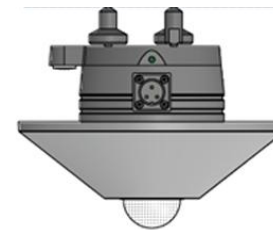
+ shadowball  
(DHI)



Pyrheliometer



Tilted



Facing down



Albedometer

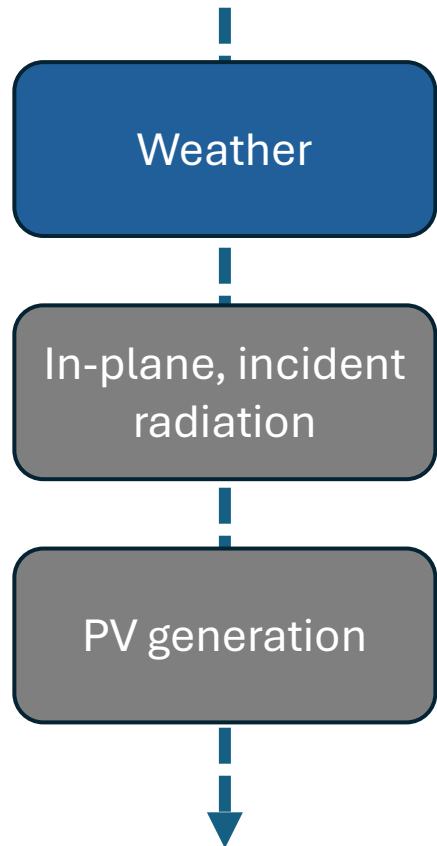
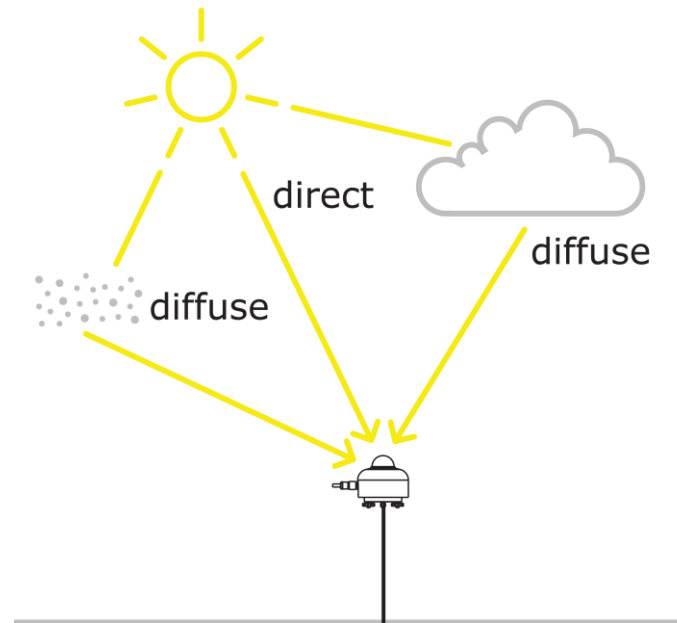


“Multi-sensor”\*

There are typically two kinds of solar radiation sensors: thermopiles and photodiodes ([link1](#), [link2](#))

\*AFAIK, there is no official name for this setup, however the example shows an SPN1 from Delta-T

# Solar radiation: components

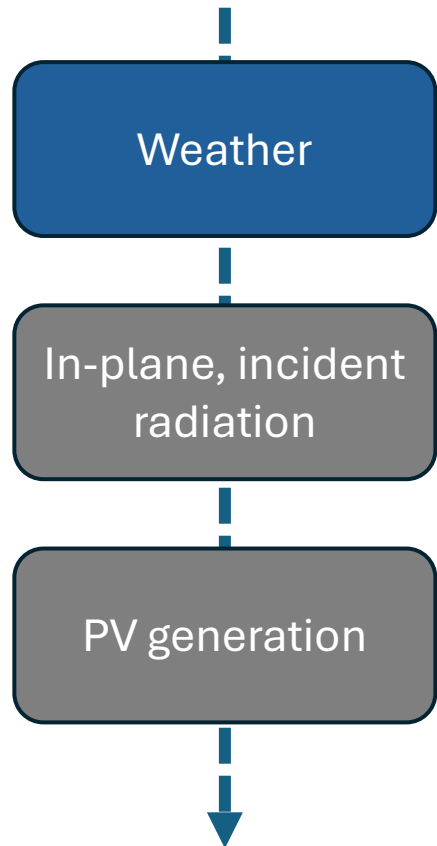
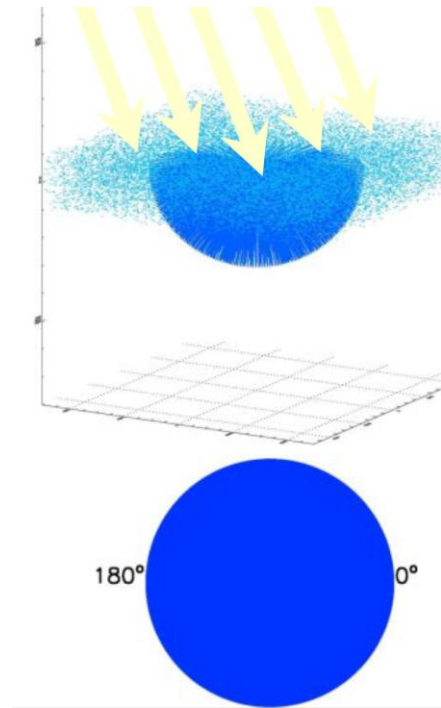


Beam horizontal irradiance (**BHI**)

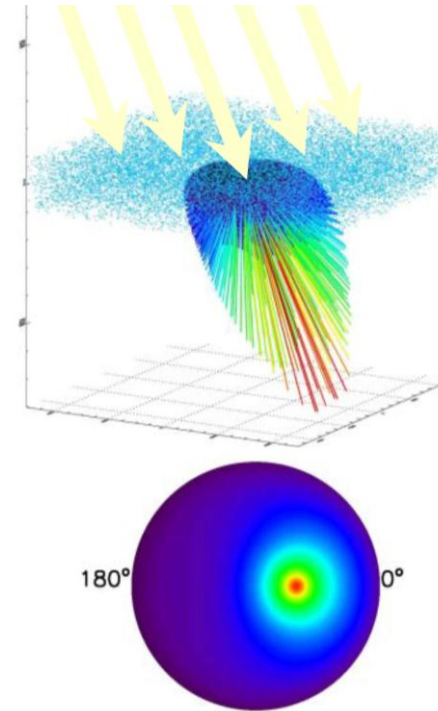
Diffuse... (**DHI**)

Global ... ( $GHI = BHI + DHI$ )

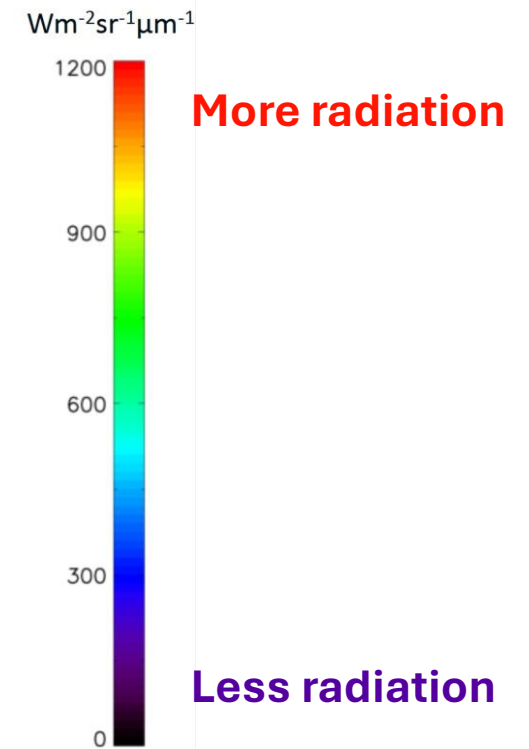
# Solar radiation: far from isotropic



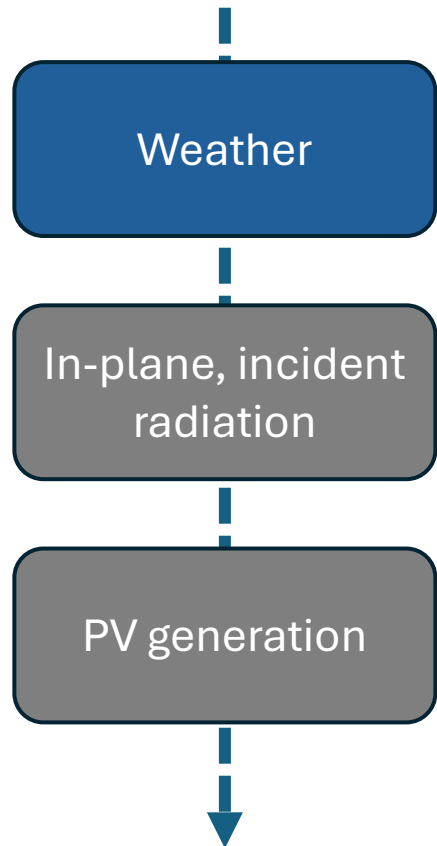
Isotropic  
assumption



Anisotropic  
reality



# Solar radiation: transposition models



Beam/direct is isotropic, so it's mainly geometric:

$$BTI = BNI \times \cos(AOI)$$

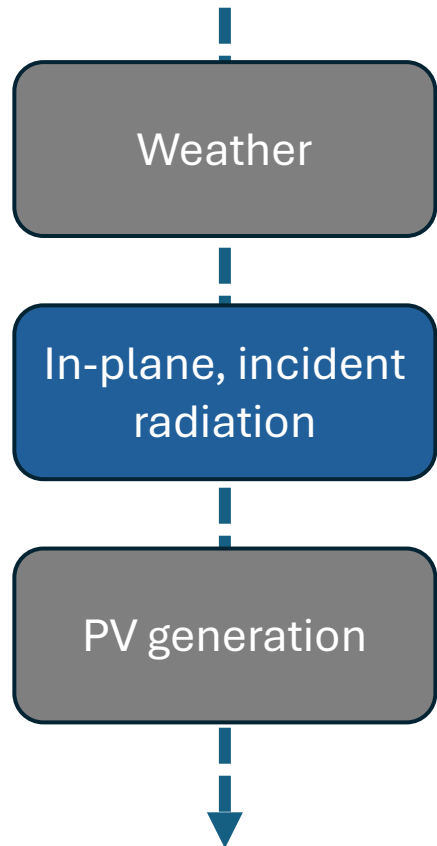
For diffuse, there are many approaches:

| Model         | Considers                                     | Good for          |
|---------------|-----------------------------------------------|-------------------|
| Liu-Jordan    | Full isotropy                                 | Very cloudy skies |
| Temps-Coulson | Full anisotropy, near-horizon and circumsolar | Clear skies       |
| Klucher       | Tries to merge previous two                   | All skies         |
| Perez         | Both (an)isotropy, more detailed modelling    | All skies         |

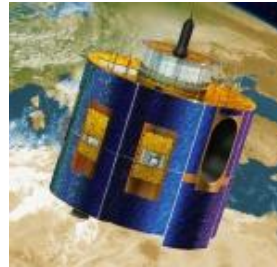
pvlib: a great Python package for this

<https://pvlib-python.readthedocs.io/en/stable/reference/irradiance/transposition.html>

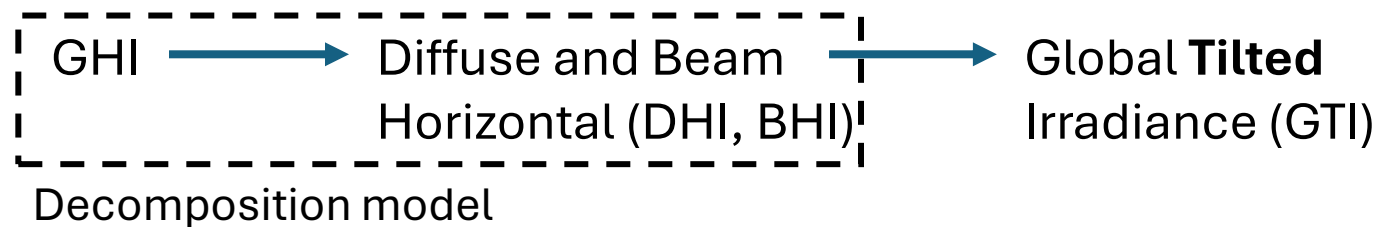
# And, sometimes, we have limited information



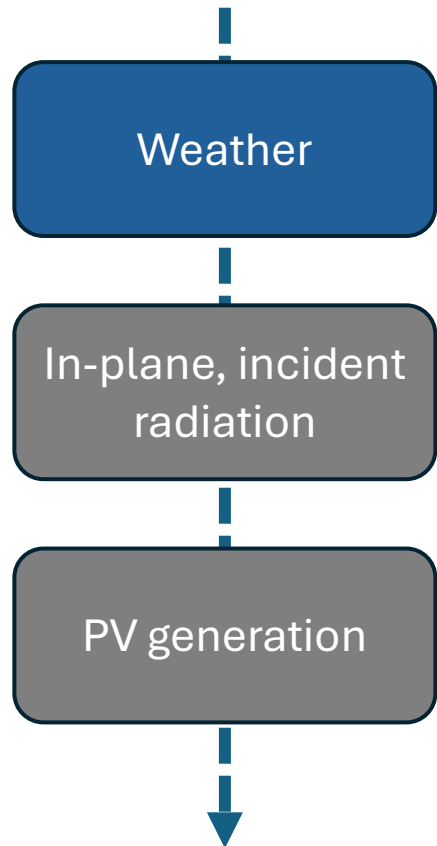
At times, only GHI data may be available



So, in this context, we also need a **decomposition** model (more details in appendix)



# Solar radiation: decomposition models



**Transposition:** we know total diffuse, but how is it distributed in the sky?

**Decomposition:** how much is total diffuse even?

| Model             | Considers                                                                                                                |
|-------------------|--------------------------------------------------------------------------------------------------------------------------|
| Erbs              | Empirical linear correlation between <b>diffuse fraction</b> and clearness index.<br>Based on observations from the USA. |
| Orgill & Hollands | Similar as Erbs but considers piece-wise linear correlation.                                                             |
| Reindl            | Includes solar zenith angle as input (as a kind of proxy to AOD)                                                         |
| DIRINT            | Semi-empirical, derives direct irradiance and adds air mass to inputs.                                                   |
| de Miguel         | Similar to Orgill & Hollands, but adjusted to North Mediterranean Belt                                                   |