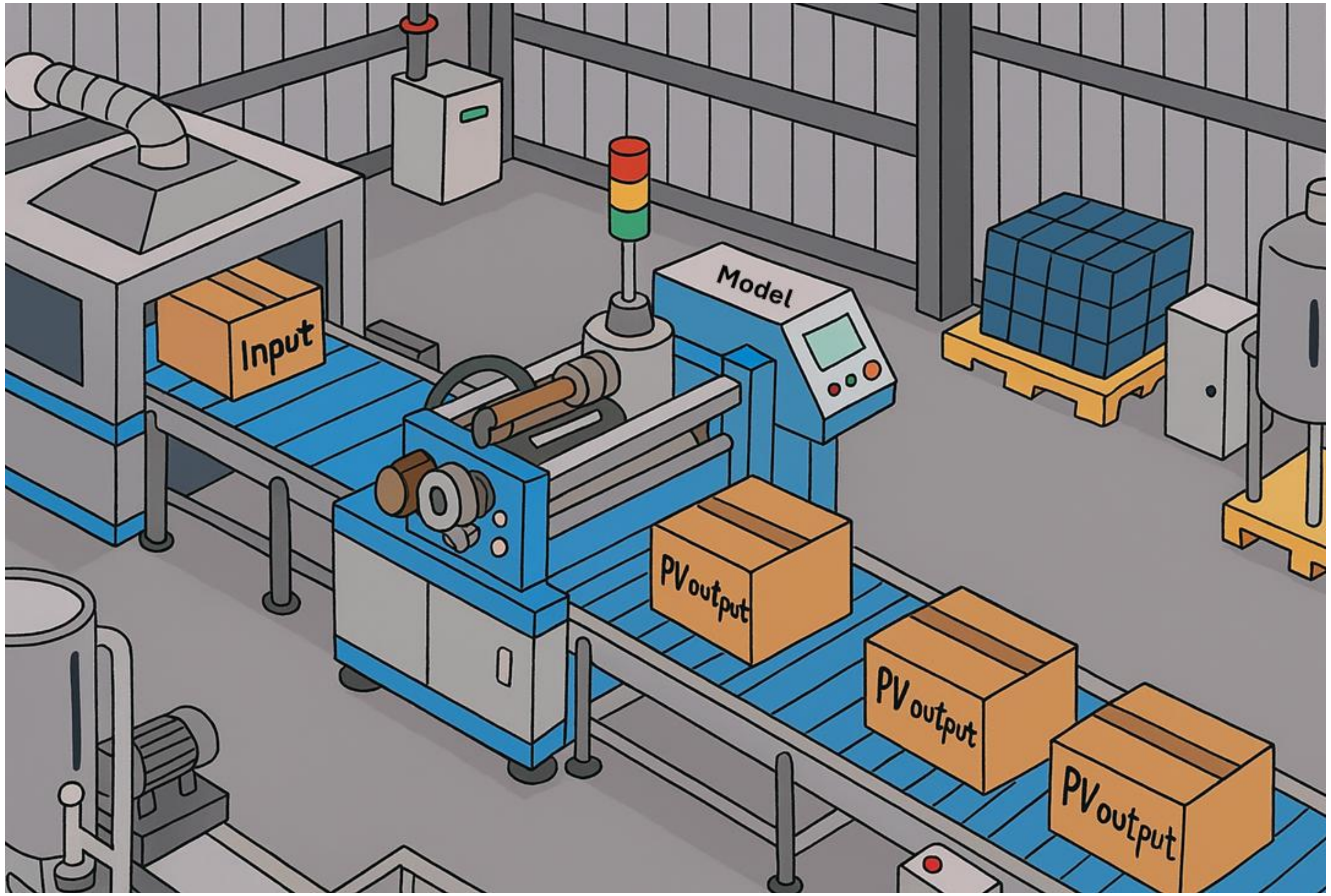
PV modelling
an overview



Rodrigo Amaro e Silva
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17/11/2025

A few words about myself

Goals for today

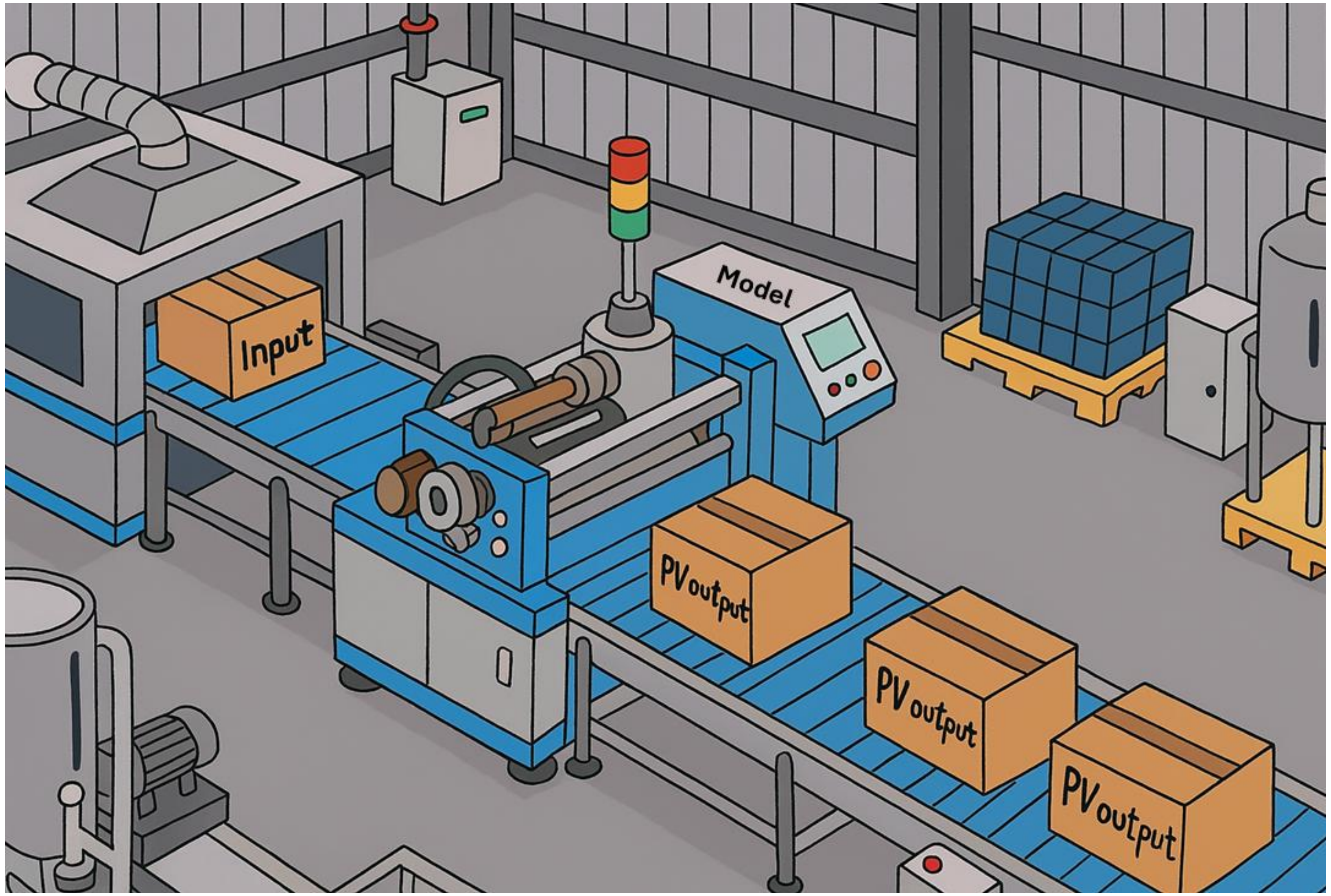
🎯 What does "PV modelling" mean and what it is used for?

🎯 How is PV modelling actually done?

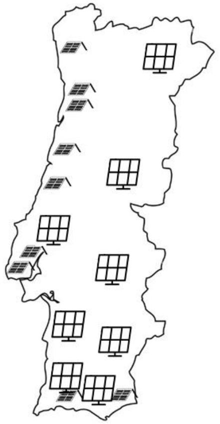
🎯 What loss factors impact PV output?

Context

What it means:

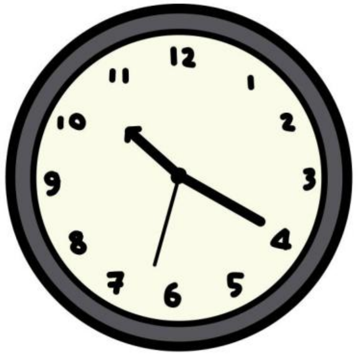


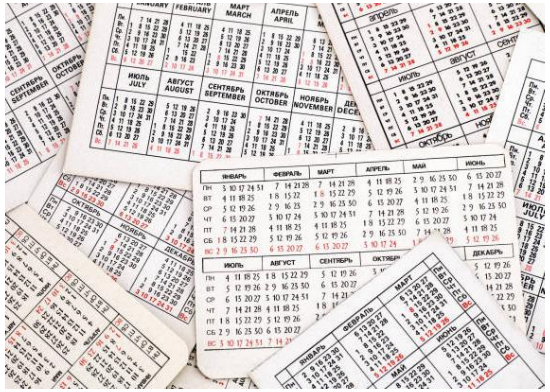
A variety of scales: space



Rooftop | Power plant | Neighborhood/City | Country

A variety of scales: time





From minutes to days

From days to weeks

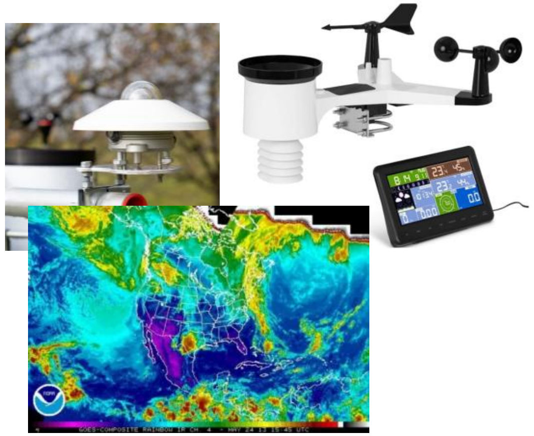
From months to years

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



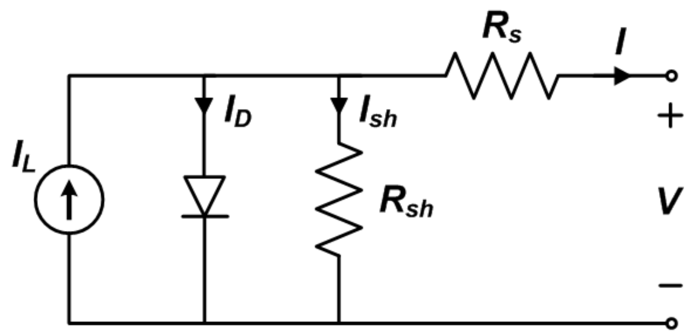
Weather

Own PV system

Portfolio and neighboring systems

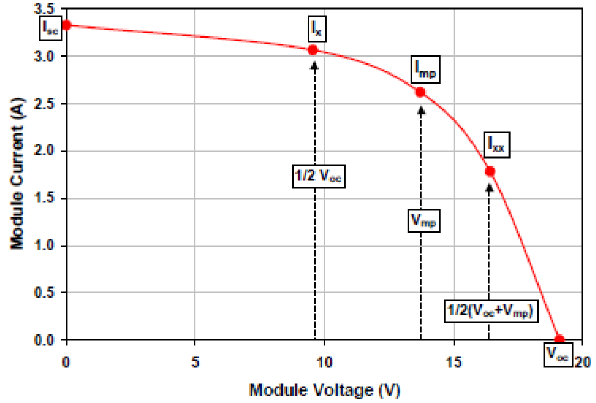
Note: in small setups (weather station, small PV systems) data collection is done mostly through dataloggers.
However, large PV plants implement a more comprehensive Supervisory Control and Data Acquisition (SCADA) system.
More on this here, here, here, and here.

A variety of approaches



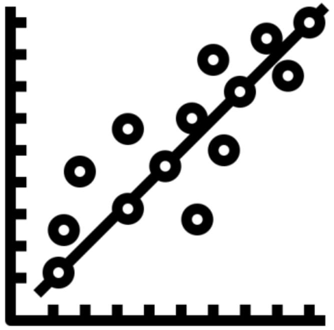
Diode-equivalent models

(provide I-V curves)



Point-value models

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

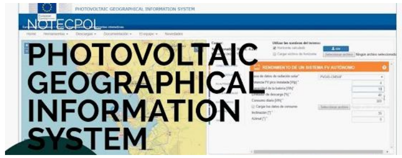


Statistical models

(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



RatedPower
A PART OF ENVERUS

System Advisor Model

PVWatts™

PVSYST
PHOTOVOLTAIC SOFTWARE

PV
PV*SOL

HelioScope
By aurora

PVcase

Glint Solar

pvlib

PSIM

PSpice®

What it is used for

Conceptual uses for PV modelling

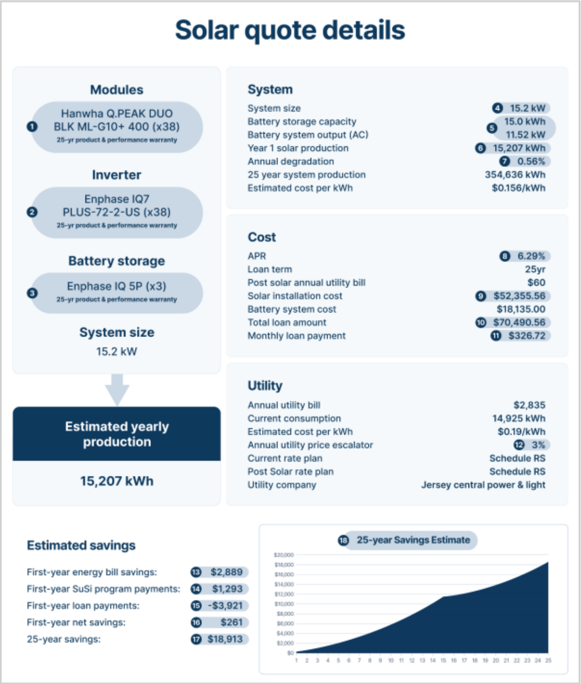
Prospection (a project-to-be)

- 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?

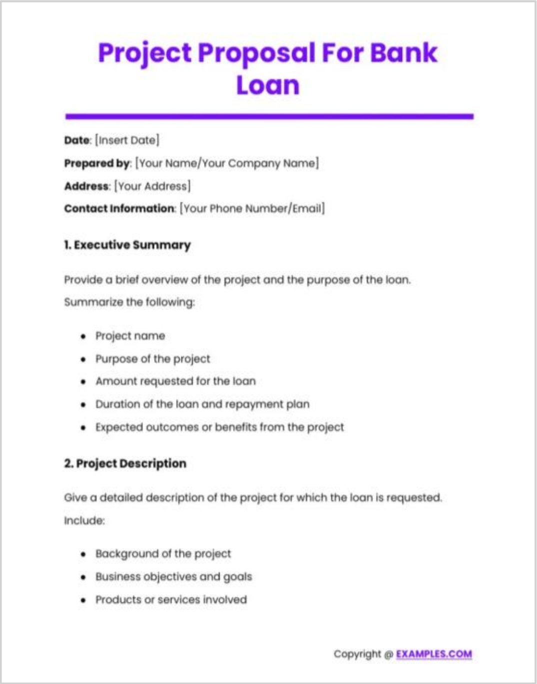
Operation (a project already installed)

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

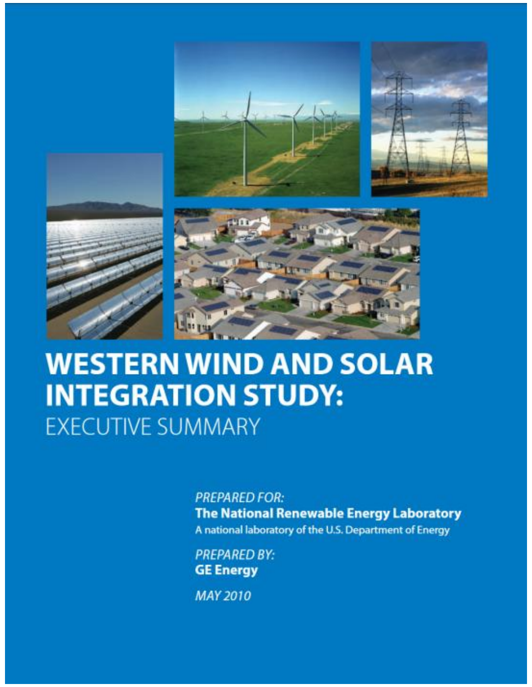
Prospection: what for?



Project design & quoting



Project 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.

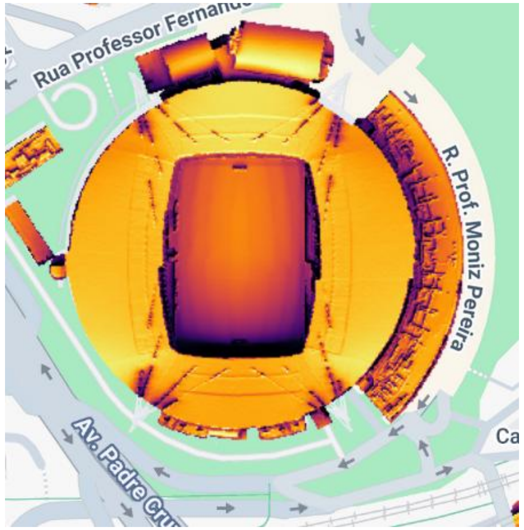
Prospection: what for?

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

solis

LISBOA E-NOVA

The FCUL campus



The best stadium in Lisbon

Find here the Solis website

Operation: what for?

Maintenance
and insurance claims

Market bidding

Better time matching
PV and demand

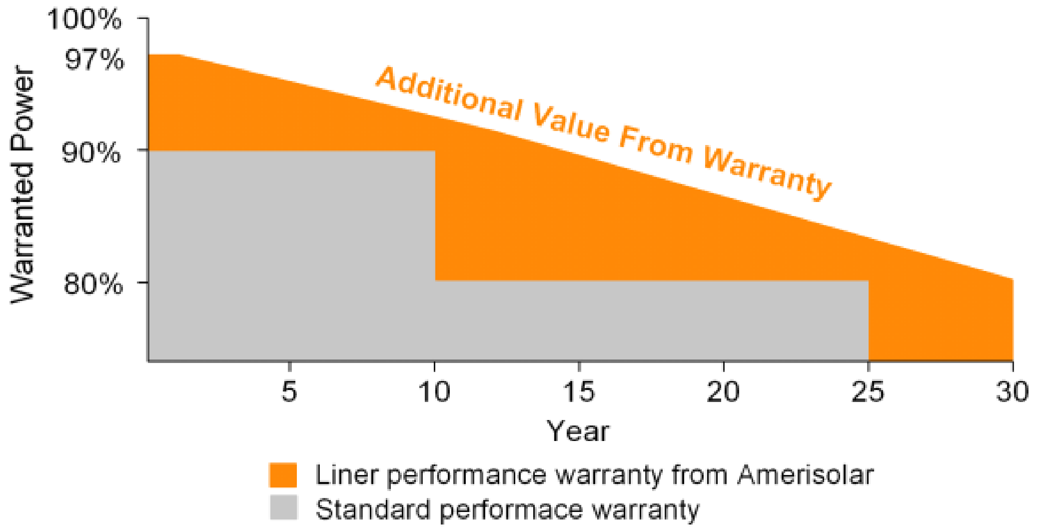
On project maintenance: links from Oviedo Hernandez (2022), Micheli (2021)

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:



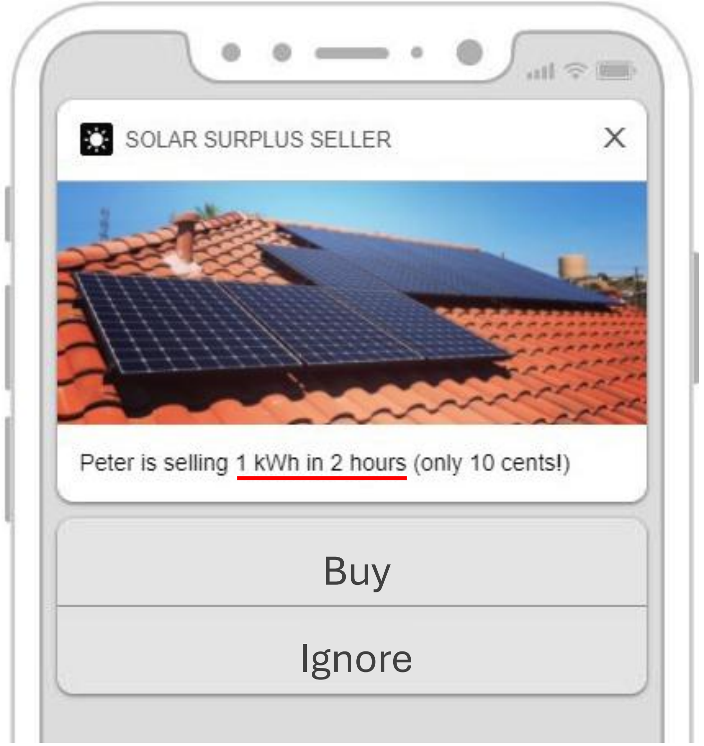
Verifying this requires accurate and credible generation estimates under "normal working conditions"

More on module warranties here

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

Operation: what for?

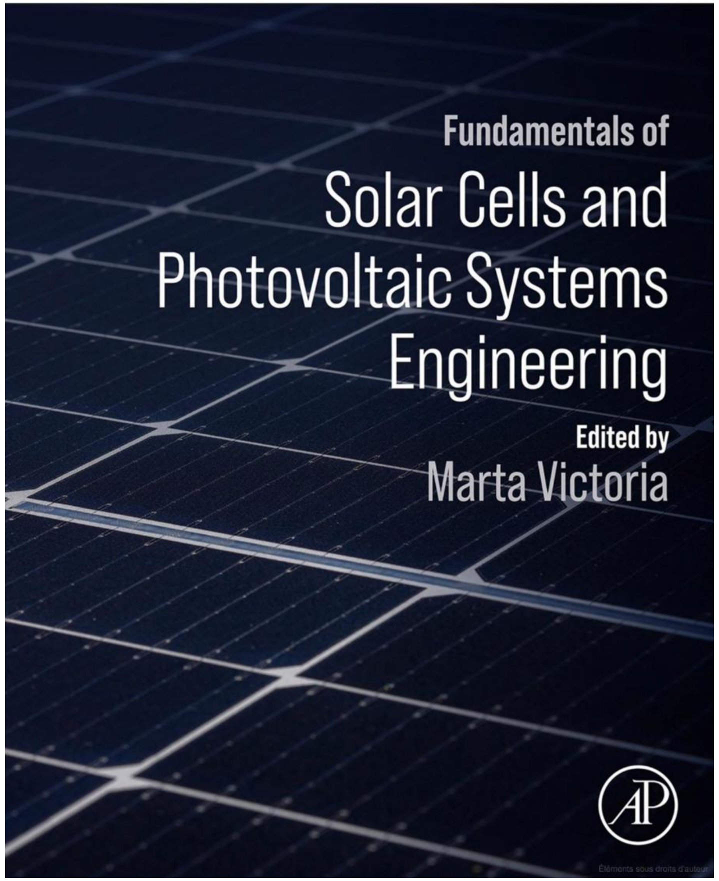
It can also enable peer-to-peer trading

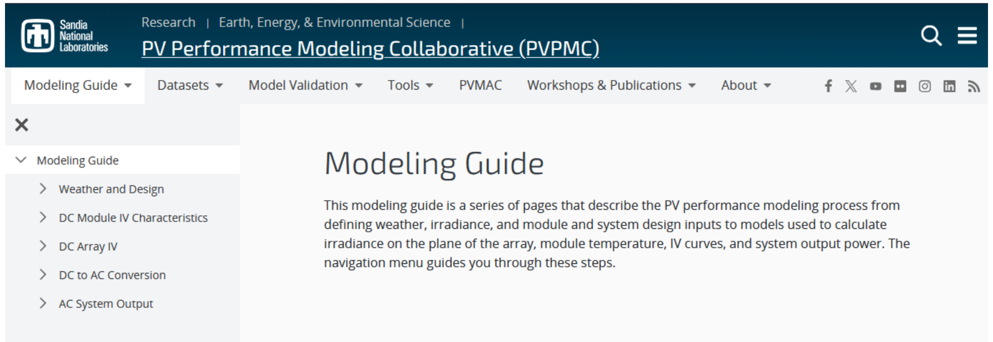


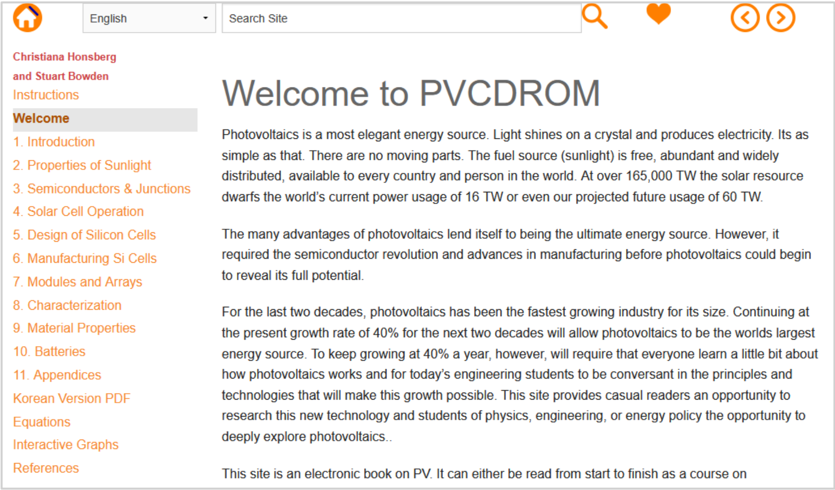
You might want to take a look at IRENA's Peer-to-peer electricity trading or Neves (2020).

How it is done

Suggested materials



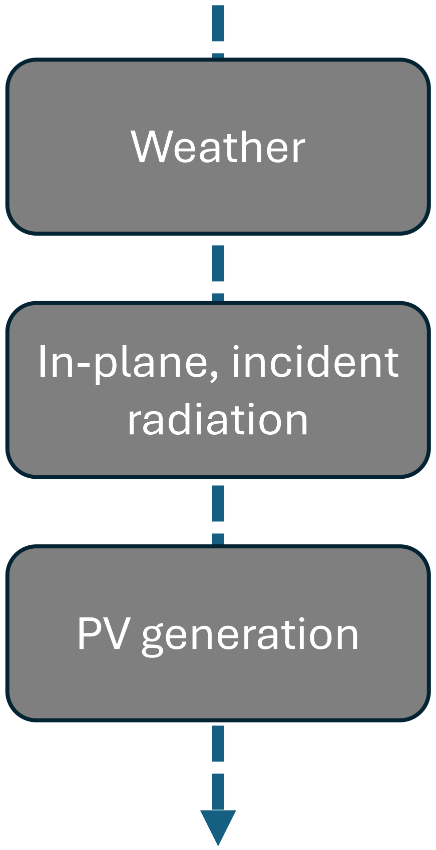




https://pvpmc.sandia.gov/modeling-guide/

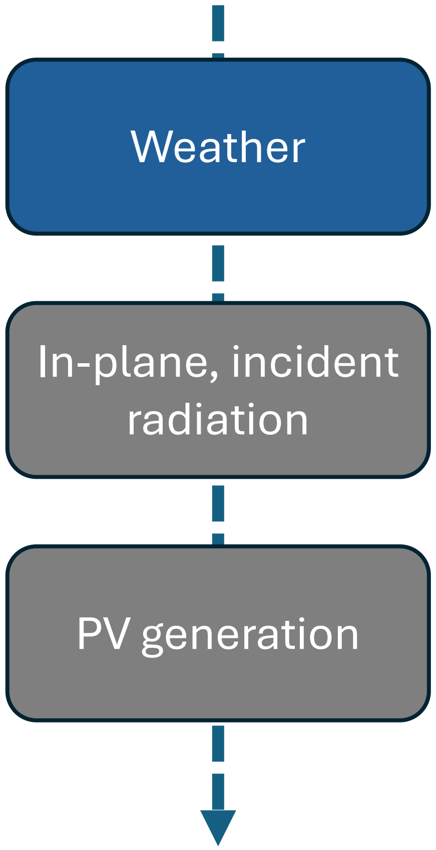
https://www.pveducation.org/pvcdrom/welcome-to-pvcdrom

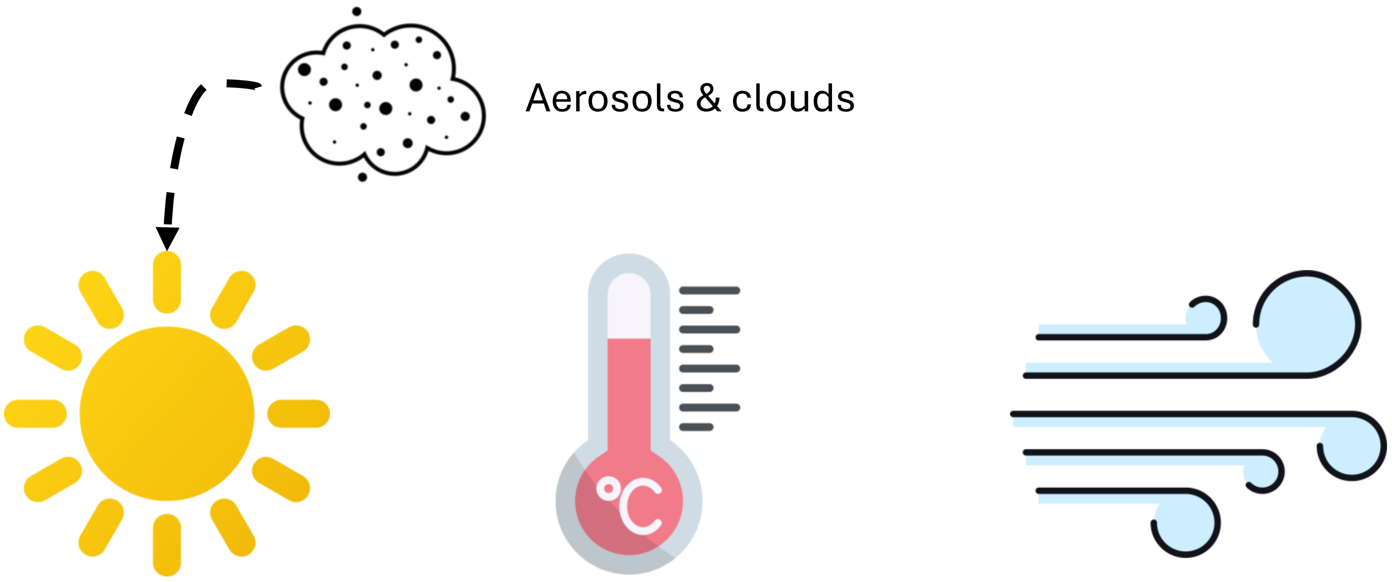
High-level workflow



"Modelling" could include all of this

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

In-plane, incident radiation

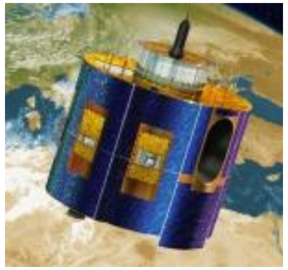
PV generation

In-situ

Pyranometer

Weather station

Remote sensing



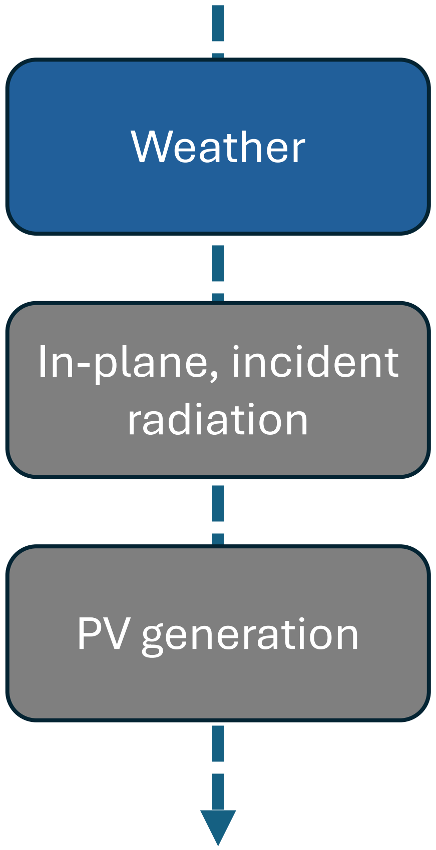
Satellite

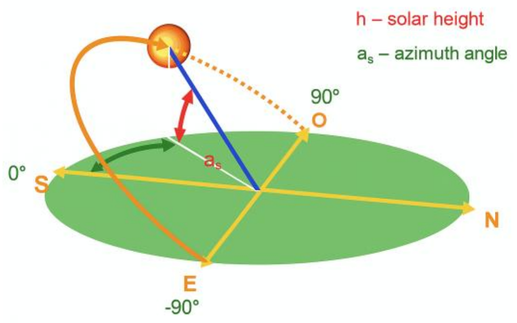
Numerical Weather Model

Models

Many many more sources, see appendix! 👀

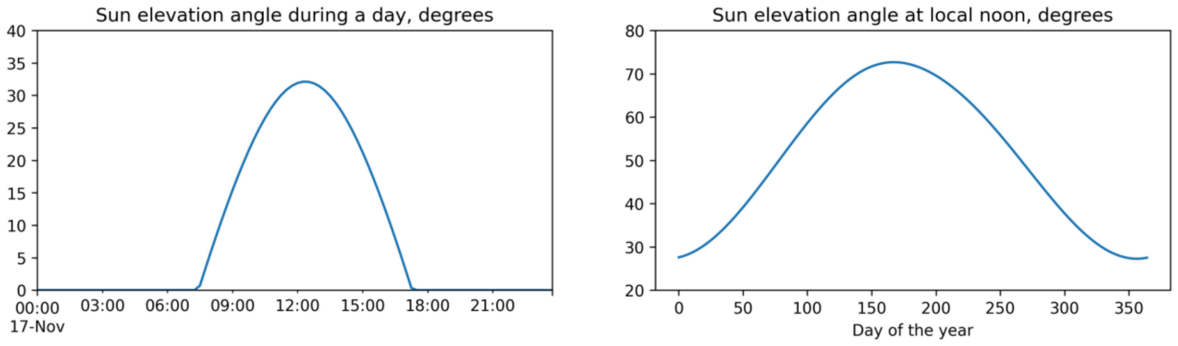
Solar apparent position





pvlib Python package includes several algorithms

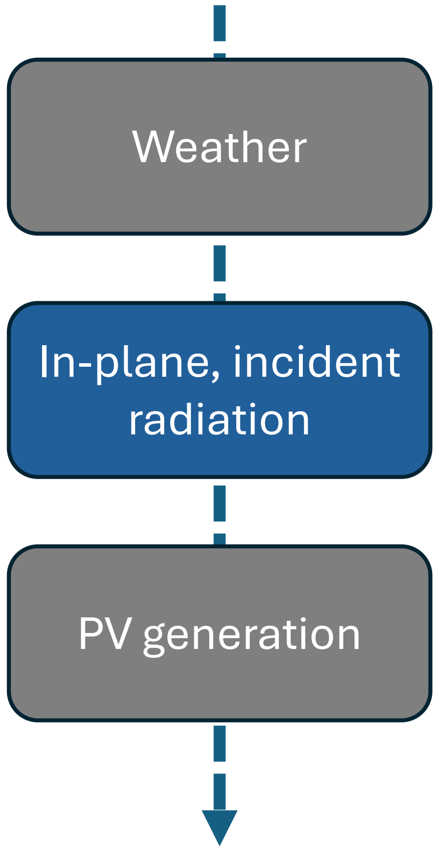
Sun elevation example @Minicampus, Lisbon



One algorithm outside of pvlib: SG2, Blanc and Wald (2012), https://github.com/gschwind/sg2

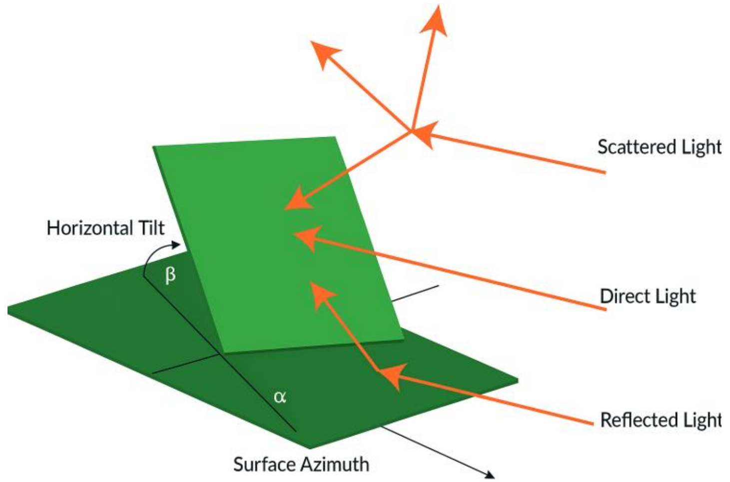
See this video if you are wondering about the “apparent” in the title means

The need to transpose solar radiation

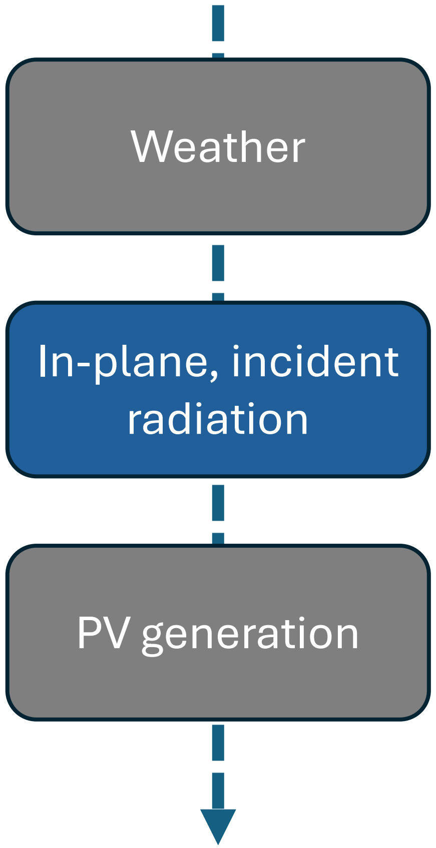


Solar radiation is often measured in the horizontal plane

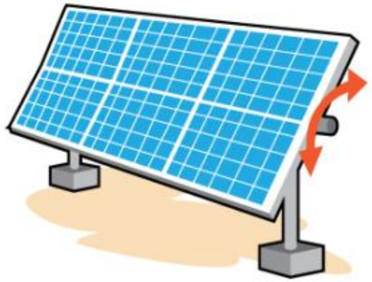
- ⚠️ Need to account for module’ inclination and azimuth (e.g. 30°S)
- 🔧 **Transposition** models (transposing from one angle to another)



PV modules are rarely horizontal



Utility-scale power plant (fixed)



Utility-scale power plant (tracking*)

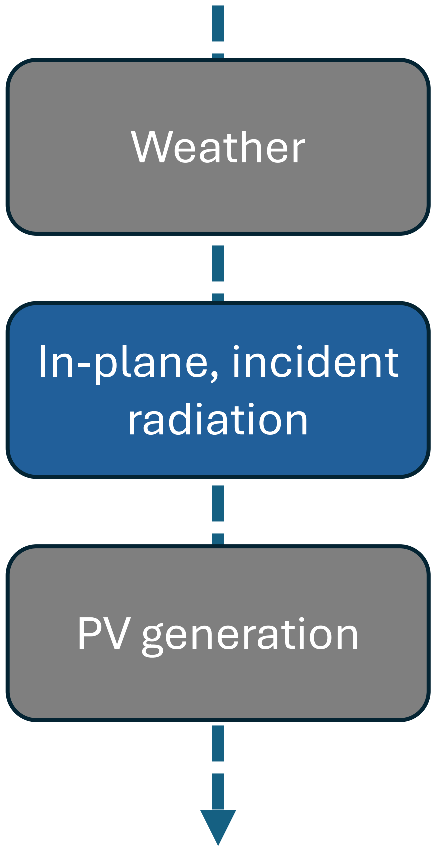
Rooftops

Vertical PV

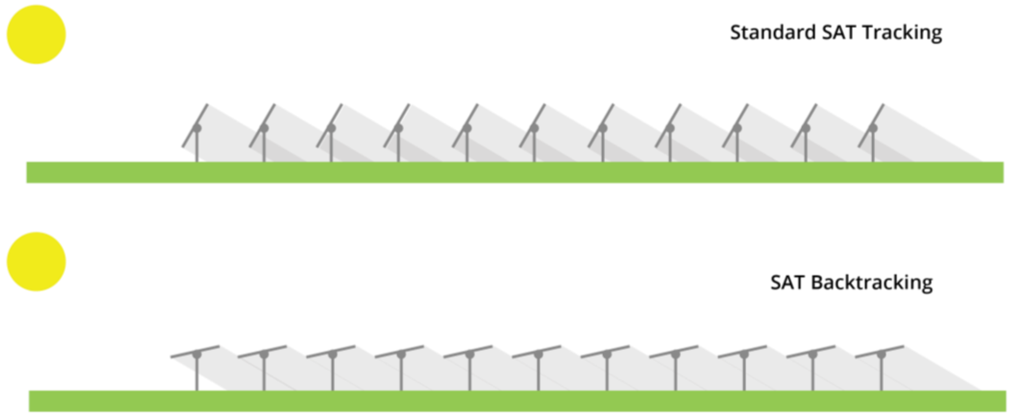
Floating PV

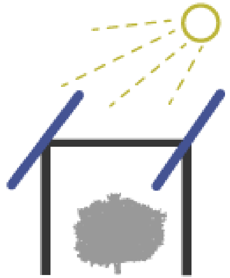
*There are several tracking setups (see more here).

PV modules are rarely horizontal



And within tracking setups, there are tracking strategies!

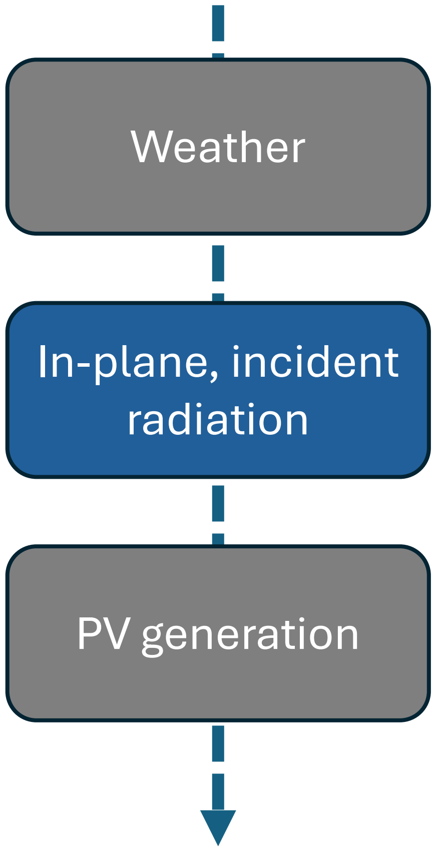




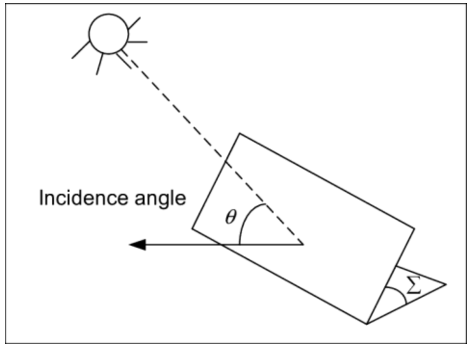
Anti-tracking

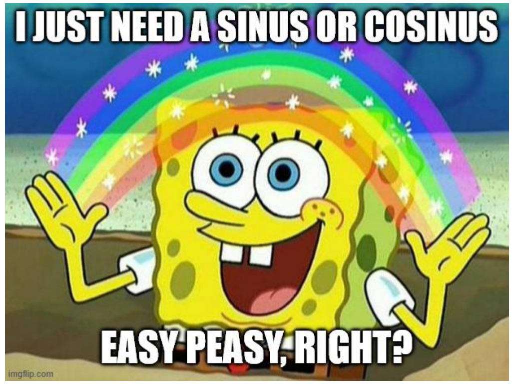
Read more about backtracking here and anti-tracking here.

The need to transpose solar radiation

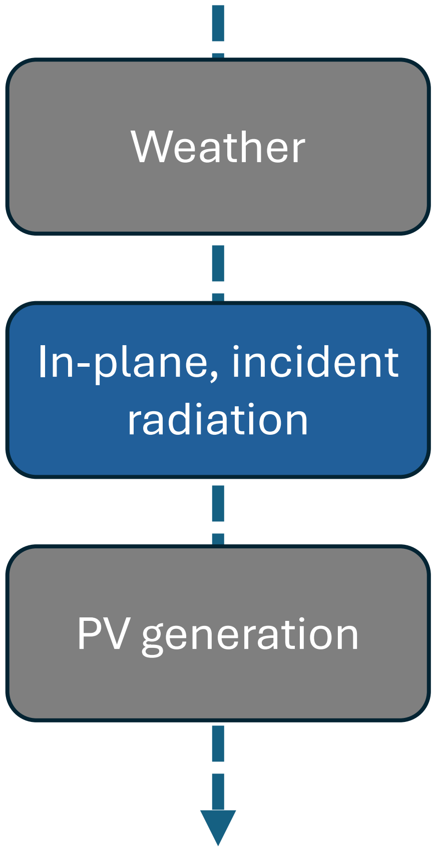


When oversimplified:

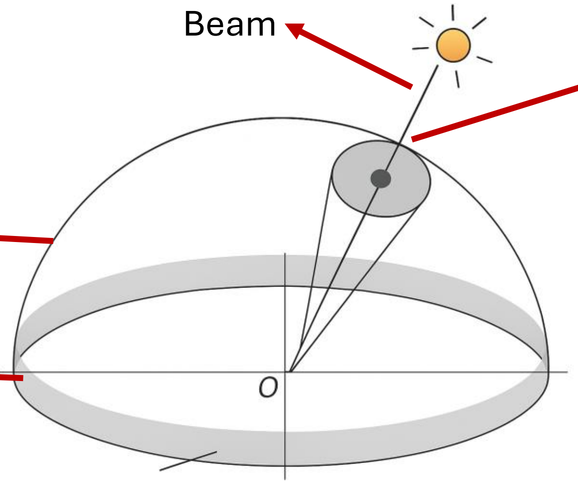




The need to transpose solar radiation

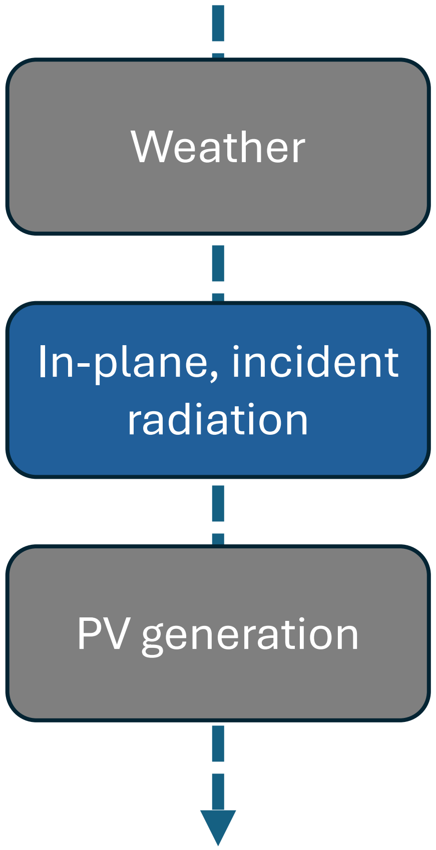


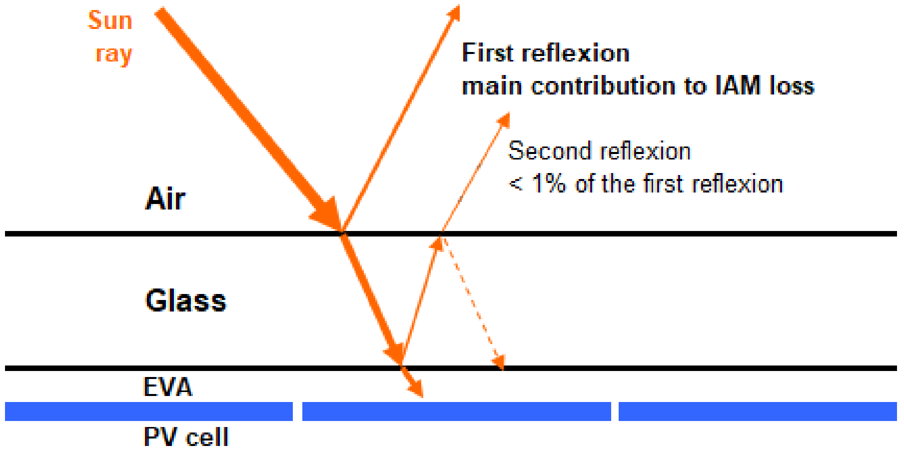
Solar radiation is “angularly” heterogeneous



Ideally, a transposition model should address each layer separately. A decomposition model is also needed when only GHI is available (see appendix)

Optical losses: from atmosphere to PV cell



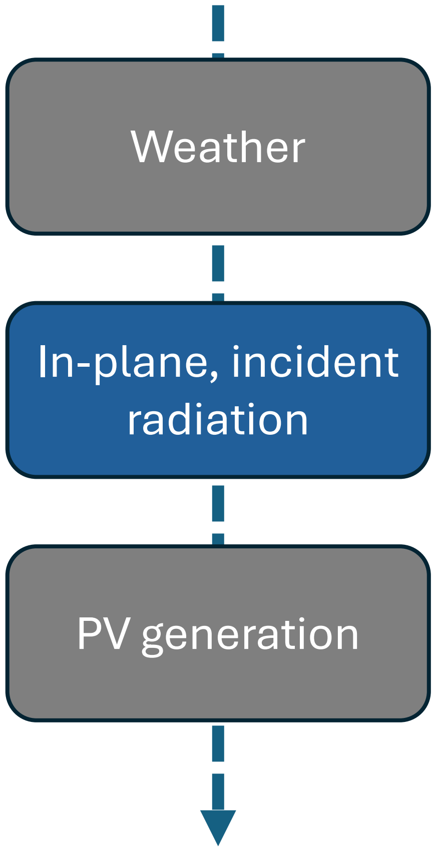


Configuration
Air/glass
Air/glass/Si
Air/glass/SiO_2/Si
Air/glass/triple coat./Si
Air/glass/ZnS/Si
Air/glass/a-Si:H/Ag
Air/glass/ITO(*d*1)/a-Si:H/Ag
Air/glass/ITO(*d*2)/a-Si:H/Ag

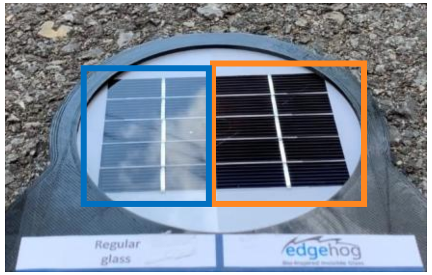
Martin-Ruiz model, doi: 10.1016/S0927-0248(00)00408-6
Marion model, doi: 10.1016/j.solener.2017.03.027

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

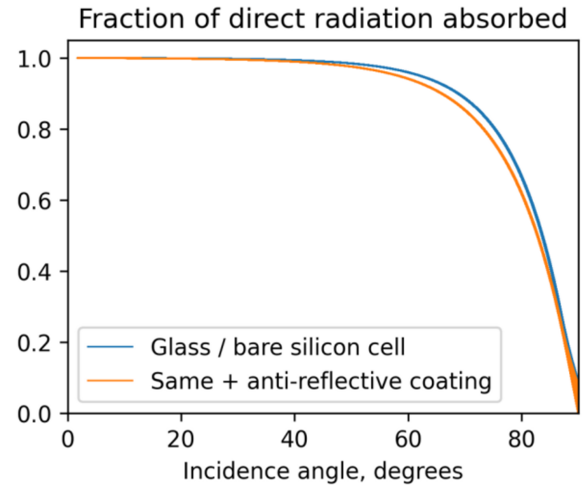
Optical losses: from atmosphere to PV cell



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



Illustrative example

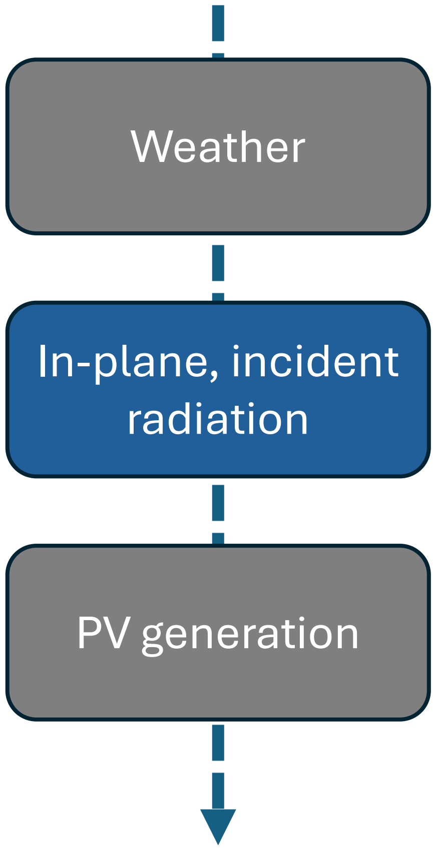


+0.5% gains @ 50°
+5% gains @ 75°

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

Optical losses: from atmosphere to PV cell



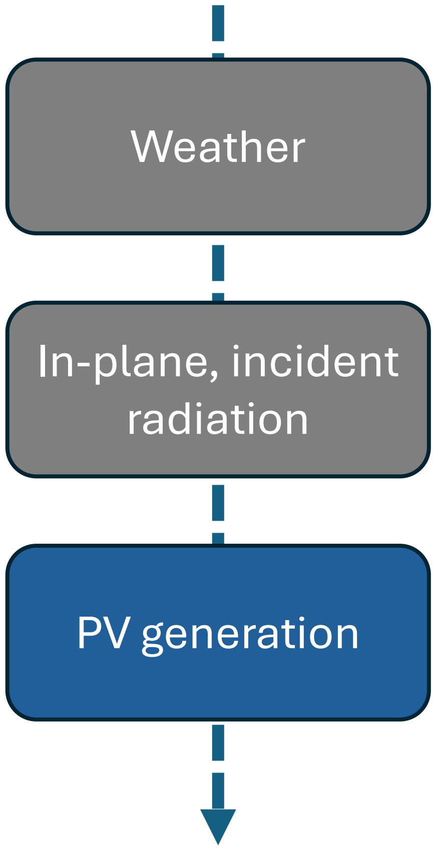
We can also add soiling to the “party”.

- 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


Snow

This IEA PVPS T13 report gives a nice overview on this topic.

Optical losses: from atmosphere to PV cell

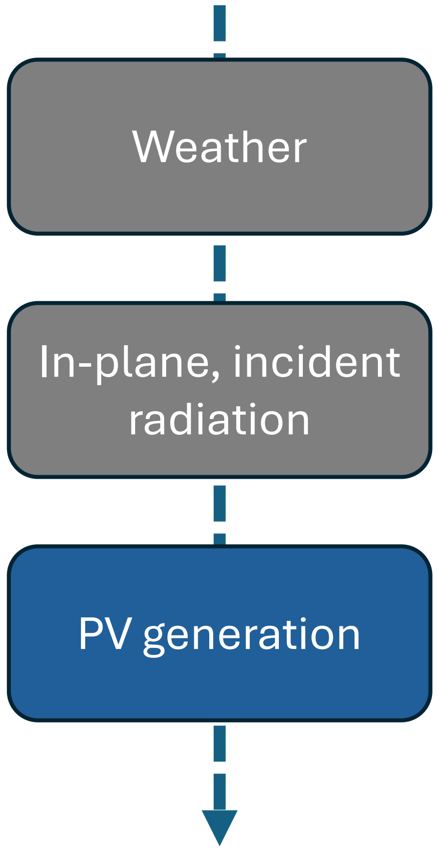


A few quick notes:

- 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)

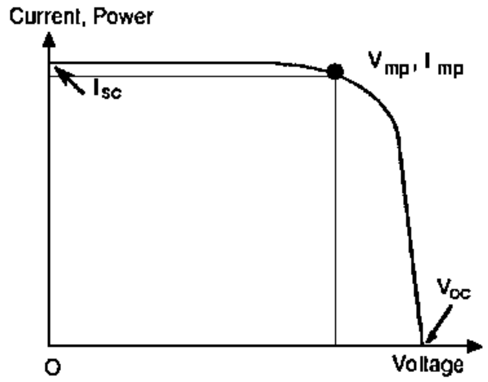
Find here and here a nice take on soiling sensors.

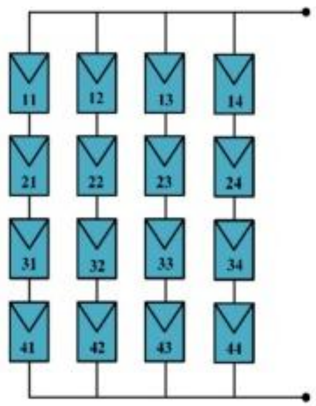
Modelling frameworks



Diode equivalent models+ (e.g., PVsyst):

- Describe a PV module in detail
- Get full I-V curve which is relevant for PV system design
- Requires many PV inputs* (often specifying equipment)



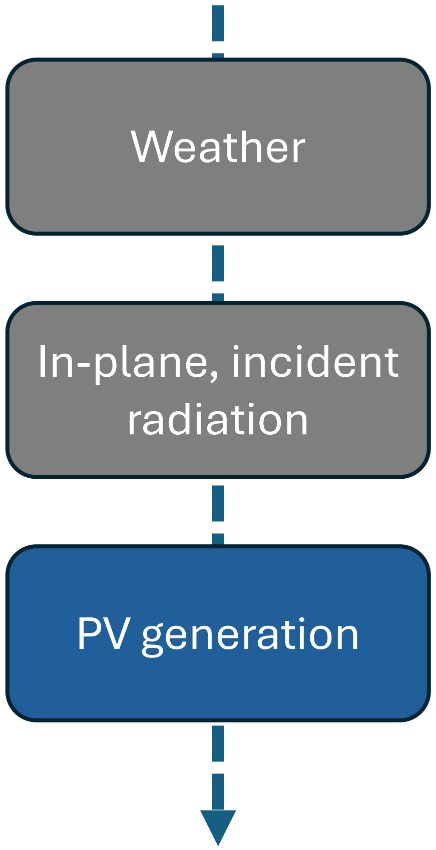


Relevant for designing arrays (with series and parallels) and their connection to the inverter

+ Find more here.

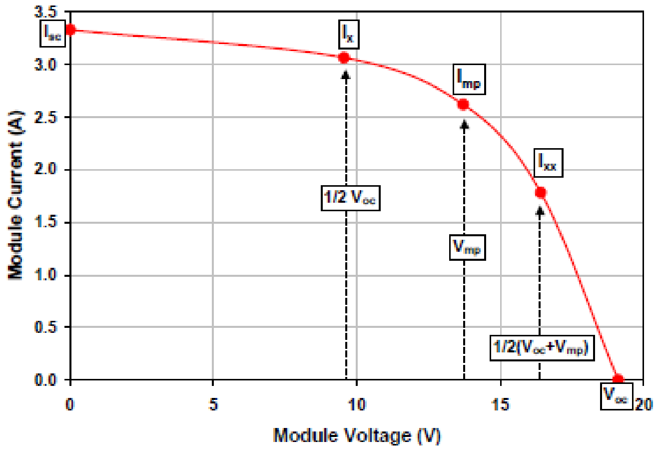
* E.g., series and shunt resistances, band gap, short-circuit and open-circuit voltage in STC.

Modelling frameworks



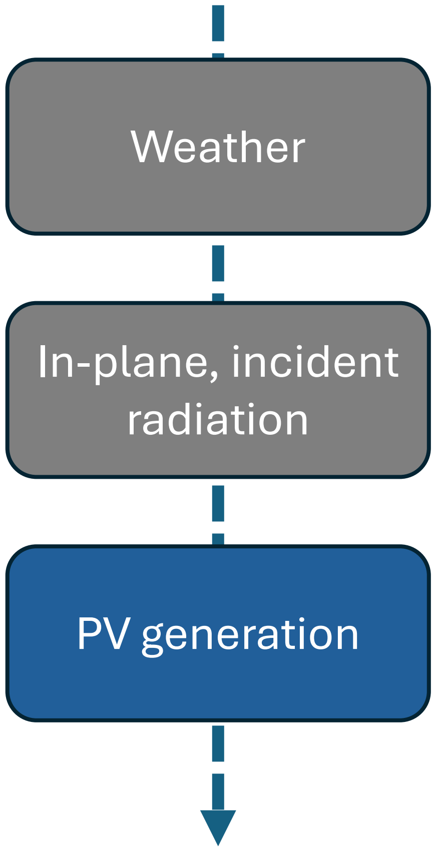
The SAPM point-value approach only considers 5 points from which the whole I-V curve can be derived.

- Still is input-demanding* (and, likely, specifying equipment)



* Requires equipment-specific empirical coefficients defined by Sandia National Laboratory.
(but database only has a limited scope)

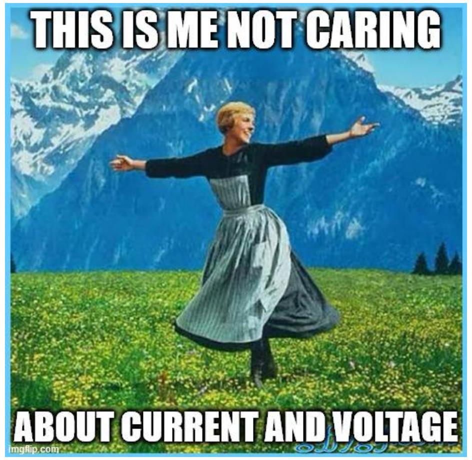
Modelling frameworks



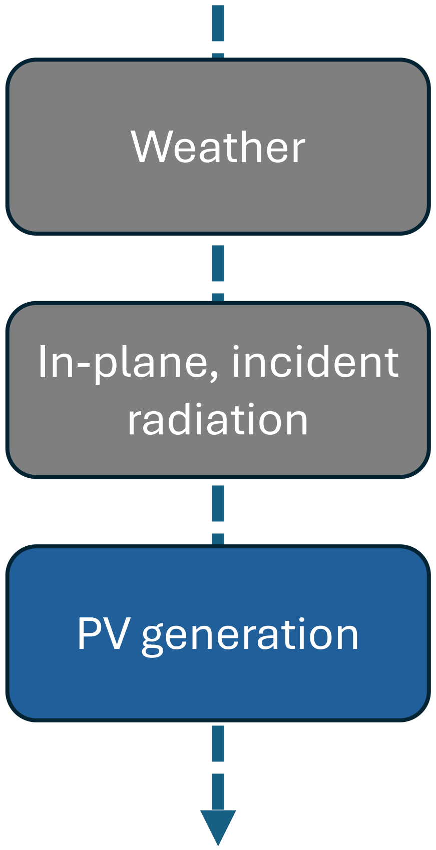
In turn, PVWatts assumes a simplified approach focusing on power output and "maximum power" conditions.

- Works rather well from a power perspective
- Ignores current and voltage, needed for proper system design
- Good solution for high-level or "first guess" studies

$$P_{out} = \frac{GTI_{eff}}{1000} P_{STC}$$



PV conversion: STC efficiency



PV efficiency in standard test conditions (STC)

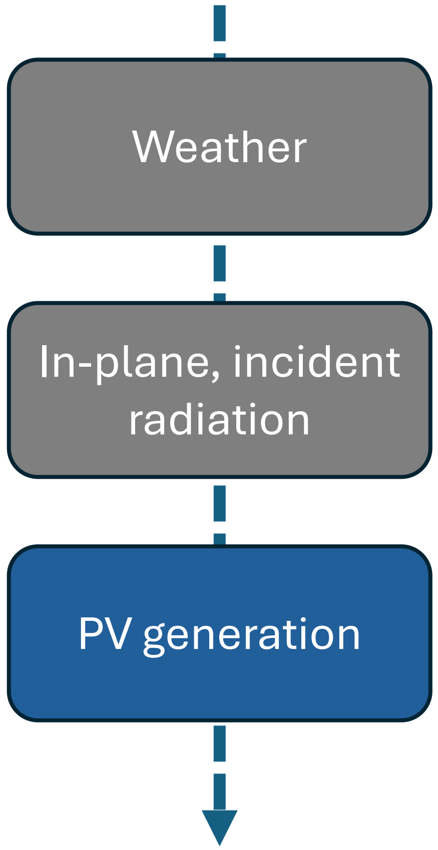
Chef Ramsay, PV expert

Specifications (STC)
Maximum Power – Pmax [Wp]
Maximum Power Voltage – Vmp [V]
Maximum Power Current – Imp [A]
Open-circuit Voltage – Voc [V]
Short-circuit Current – Isc [A]
Module Efficiency STC [%]
Power Tolerance
Temperature Coefficients of Pmax
Temperature Coefficients of Voc
Temperature Coefficients of Isc

STC: Irradiance 1000W/m^2, Cell Temperature 25°C, AM=1.5

Parameters change from module to module

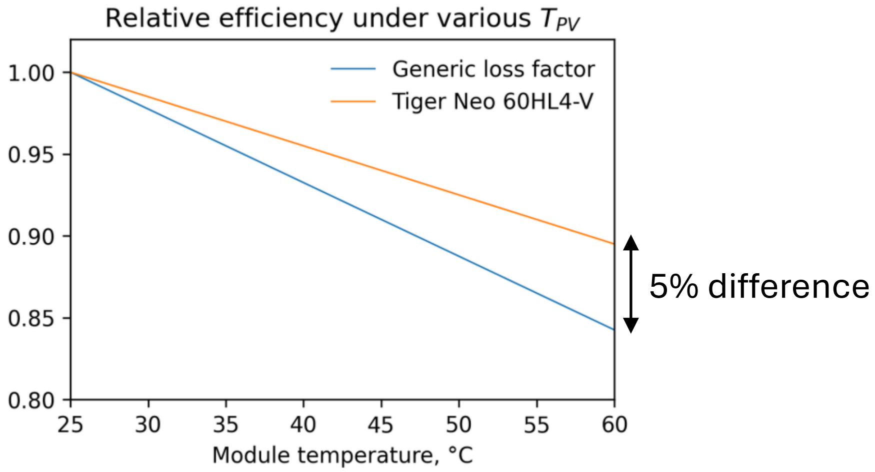
PV conversion: thermal losses



Typically modelled as a linear loss factor γ

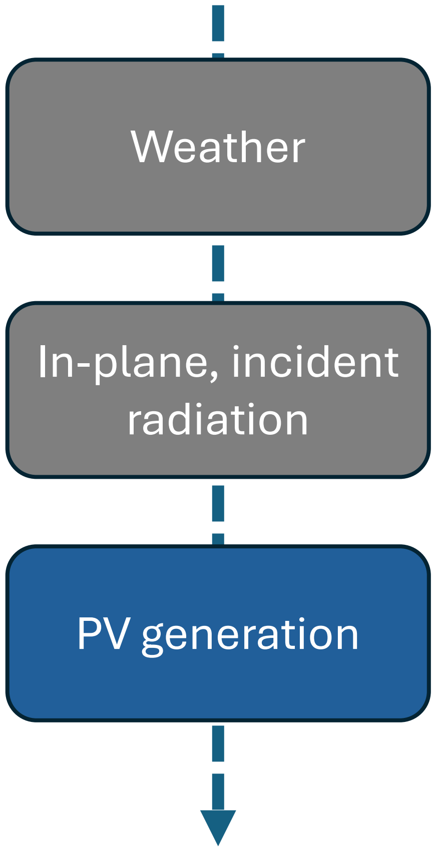
$$\eta = 1 - \gamma \times (T_{PV} - 25)$$

Depends on module, but -0.45 %/°C as a generic (outdated) γ value
-0.30 %/°C for Tiger Neo 60HL4-V



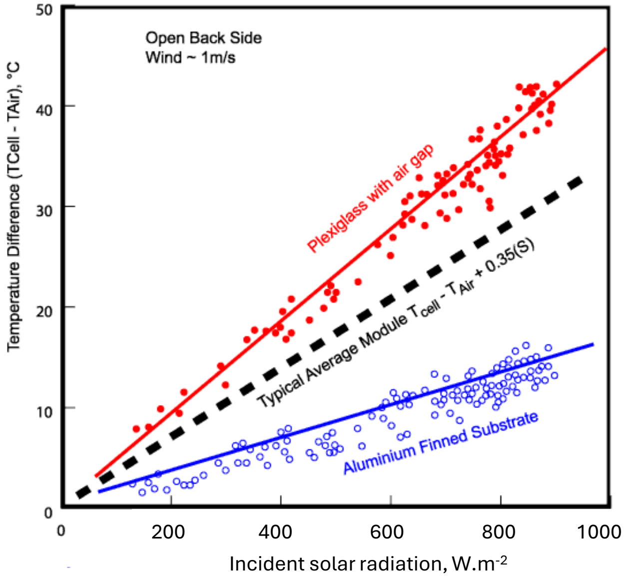
More on this topic in appendix.

PV conversion: thermal losses



Need to calculate PV cell temperature

- Various models, with different degrees of complexity* / input needs
- Grows rather linearly with incident radiation

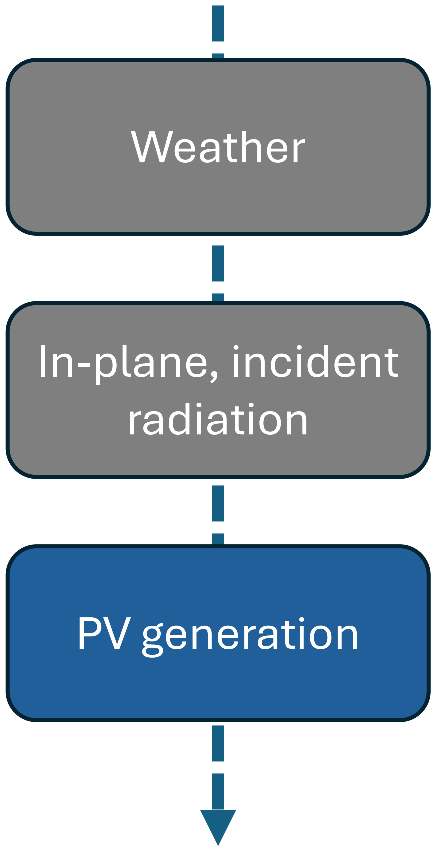


Slope depends on:

- backside material
- wind conditions

*More complex solutions also account for wind speed or relative humidity

PV conversion: thermal losses



Need to calculate PV cell temperature

- Various models, with different degrees of complexity* / input needs
- A classic example*:

$$T_{PV} = T_{air} + \frac{GTI}{800} \times (NOCT - 20)$$

NOCT: T_{PV} @ GTI = 800 W/m^2
T_{air}=20°C
w_s=1m/s
open back side

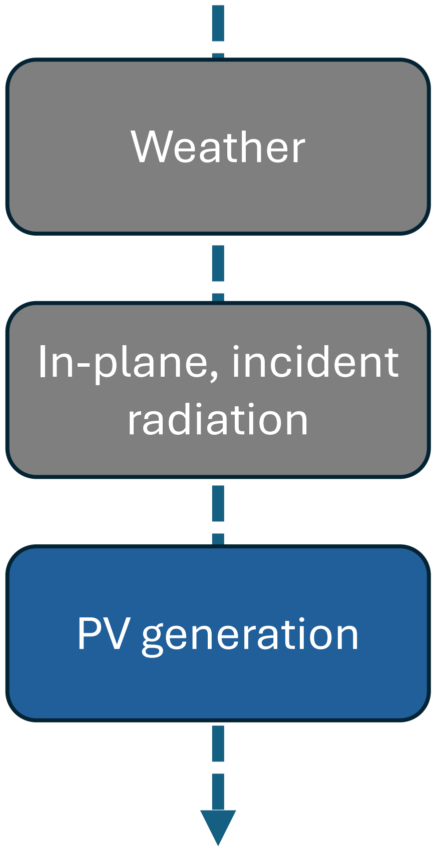
$$= T_{air} + GTI \times \frac{NOCT-20}{800-0}$$

Ross coefficient, *k*
(°C increase per W/m^2)

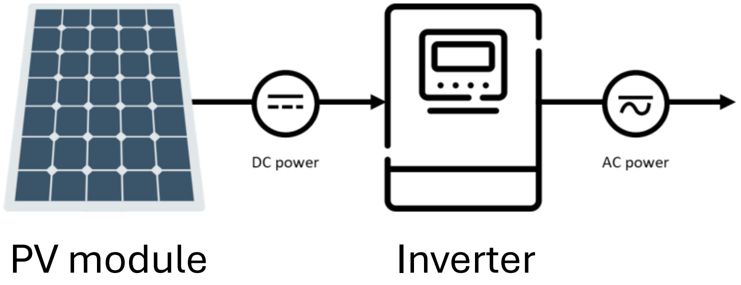
Skoplaki et al. (2009) list *k* values for PV setups with different degrees of back ventilation

*More complex solutions also account for wind speed or relative humidity

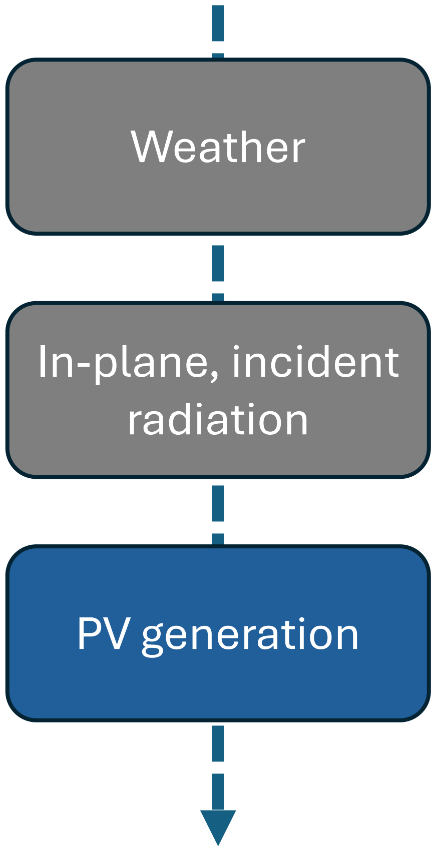
Inverter and other electric losses



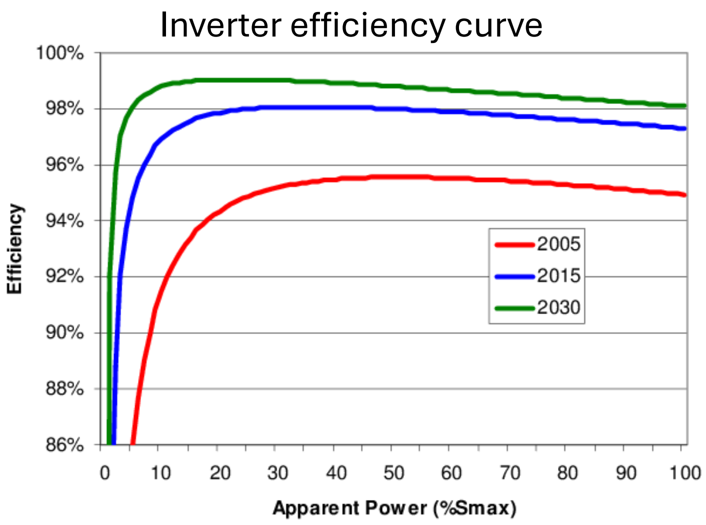
Electric conversion losses: inverter, cabling, and others.



Inverter and other electric losses



Electric conversion losses: cabling, inverter, and others.



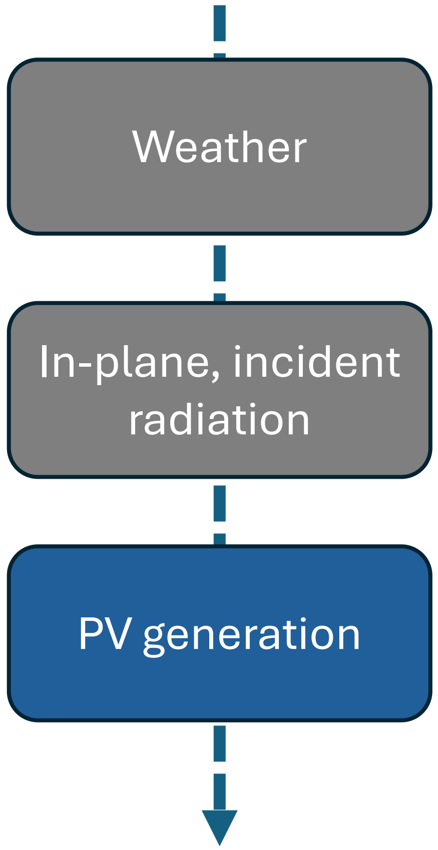
- Very low at P_{in} < 5-10%
- Peaks at a certain P_{out}
- Then slowly decreases

Source: Braun (2007)

This means that inverter losses are dynamic, vary in time.

Engineering practice of oversizing module capacity wrt inverter.
One of the advantages: overall increase in inverter efficiency.

Inverter and other electric losses



From a 2005 NREL study (should be seen as outdated/pessimistic)

Table 1. Derate Factors for A.C. Power Rating

Item	Typical
d.c. cabling	0.98
Diodes and connections	0.995
Mismatch	0.98
Transformers	0.97
a.c. wiring	0.99

An aggregate value of 0.917 (more than 8% losses)

Optimistic values at the time would be around 0.946 (5.4% loss)

According to Aurora Solar, DC cabling losses can be lower (1%) when short/thicker cables are used

More specific nuances

Today's focus was on a more generic framework.

However, more niche applications may require some "add-ons".

Bifacial PV

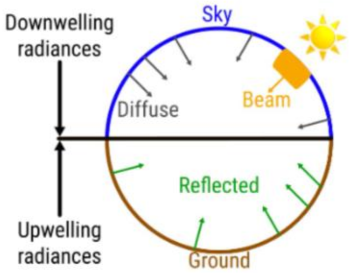
Floating PV

For bifacial PV, take a look at Sandia, Ernst (2024), Nygard (2025), and Brecl (2025).

For floating PV, take a look at Kjeldstad (2021) and IEA PVPS Task13 report.

More specific nuances

Main topics for bifacial (shared by vertical PV):

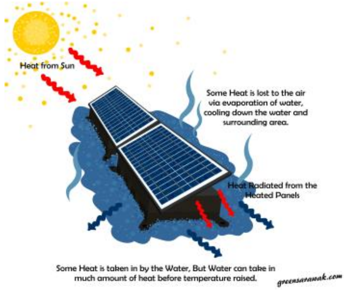


Angle of incidence

Ground albedo

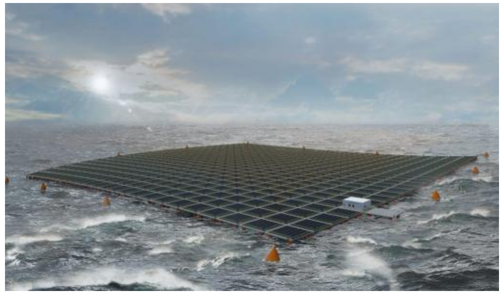
Sky radiance

Main topics for floating PV:



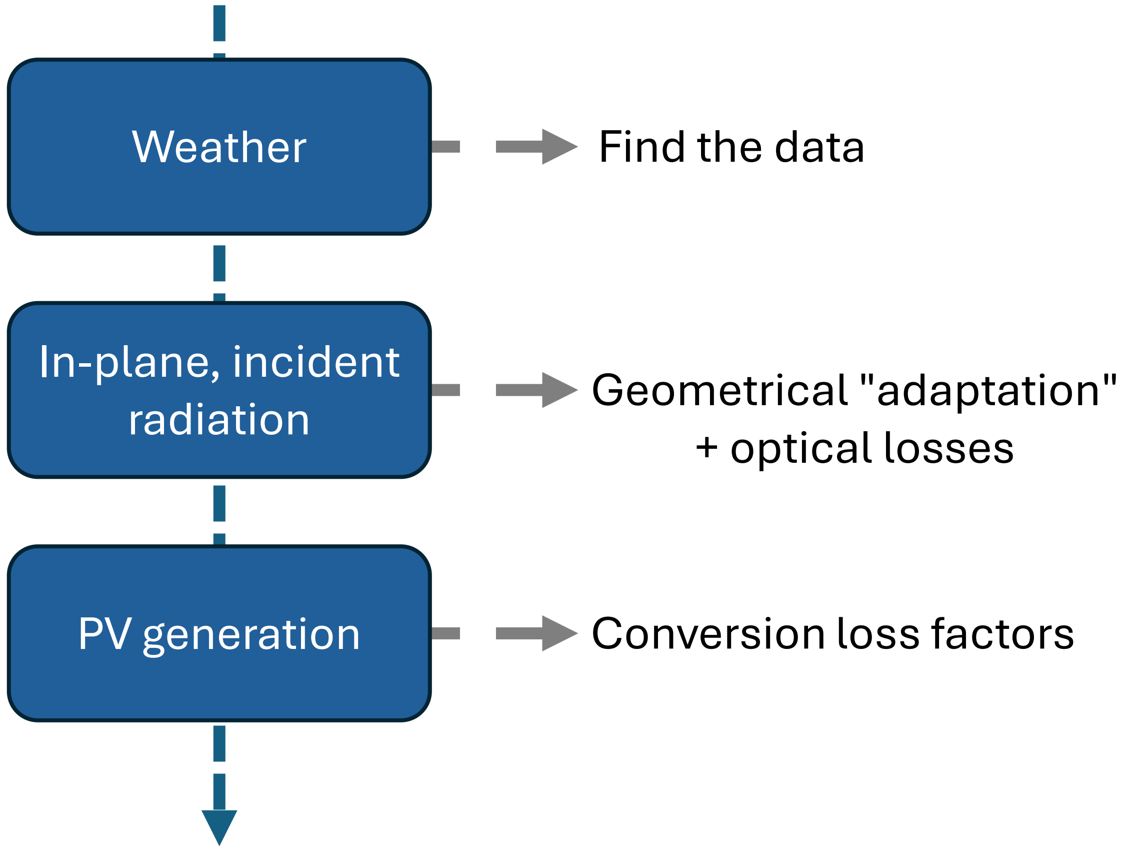
Thermal dynamics

Soiling



Waves & angle of incidence

In a nutshell



<u>PV conversion</u>

$$PV = GTI \times A \times \eta$$

<u>Overall efficiency</u>

$$\eta = \eta_{optics} \times \eta_{STC} \times F_{thermal} \times F_{electric}$$

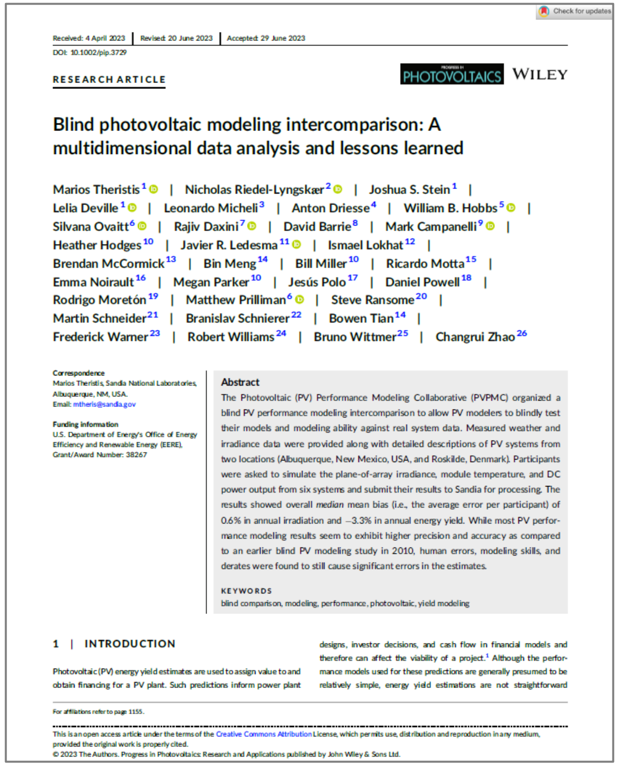
Many modelling choices to be done, these end up being done based on:

- available data,
- geography of interest
- personal experience

Final remark: blind test example

In 2021 a blind intercomparison between PV models raised a very interesting point:

> "While most PV performance modeling results seem to exhibit higher precision and accuracy as compared to an earlier blind PV modeling study in 2010, human errors, modeling skills, and derates were found to still cause significant errors in the estimates."



Check for updates

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RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Blind photovoltaic modeling intercomparison: A multidimensional data analysis and lessons learned

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Abstract
The Photovoltaic (PV) Performance Modeling Collaborative (PVPMC) organized a blind PV performance modeling intercomparison to allow PV modelers to blindly test their models and modeling ability against real system data. Measured weather and irradiance data were provided along with detailed descriptions of PV systems from two locations (Albuquerque, New Mexico, USA, and Roskilde, Denmark). Participants were asked to simulate the plane-of-array irradiance, module temperature, and DC power output from six systems and submit their results to Sandia for processing. The results showed overall *median* mean bias (i.e., the average error per participant) of 0.6% in annual irradiation and −3.3% in annual energy yield. While most PV performance modeling results seem to exhibit higher precision and accuracy as compared to an earlier blind PV modeling study in 2010, human errors, modeling skills, and derates were found to still cause significant errors in the estimates.

KEYWORDS
blind comparison, modeling, performance, photovoltaic, yield modeling

1 | INTRODUCTION

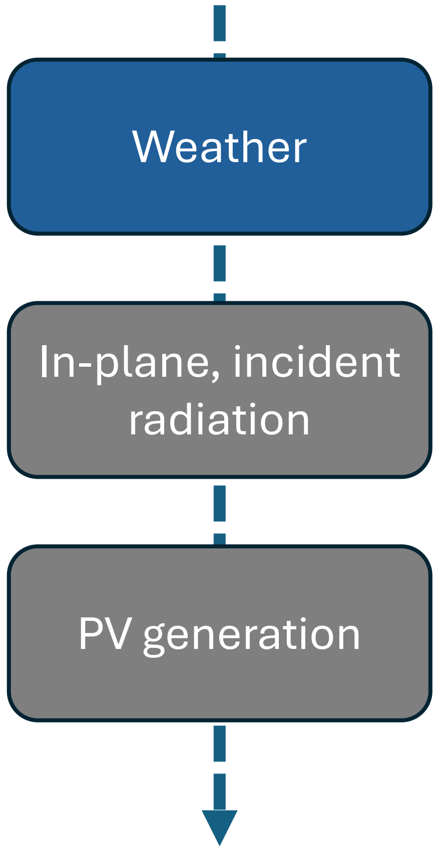
Photovoltaic (PV) energy yield estimates are used to assign value to and obtain financing for a PV plant. Such predictions inform power plant designs, investor decisions, and cash flow in financial models and therefore can affect the viability of a project.[1] Although the performance models used for these predictions are generally presumed to be relatively simple, energy yield estimations are not straightforward

For affiliations refer to page 1155.

Theristis et al. (2021)

Appendix

Weather: several sources of data



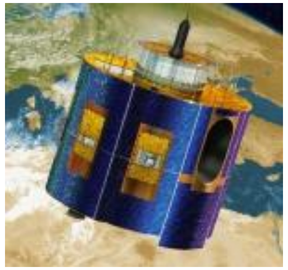
In-situ

Pyranometer

Reference cell

All-sky imager*

Weather station



Satellite

Airborne data

Cloud radar

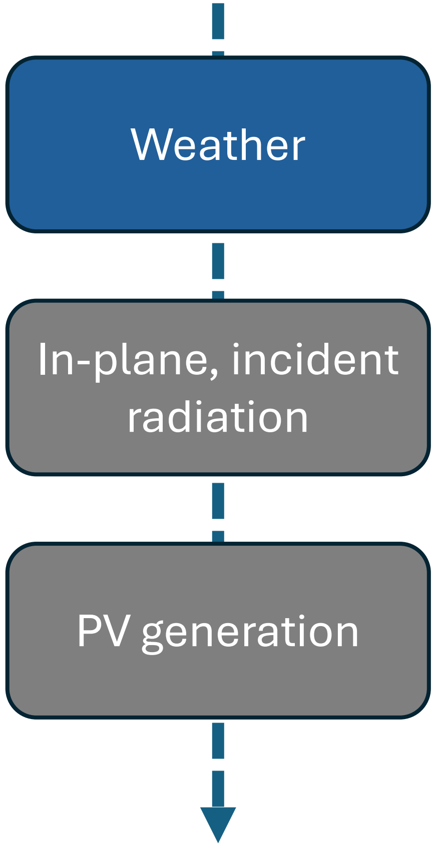
Remote sensing

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

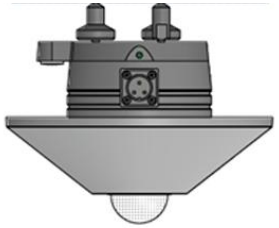

Horizontal (GHI)


+ shadow band (DHI)


+ shadowball (DHI)


Pyrheliometer


Tilted


Facing down

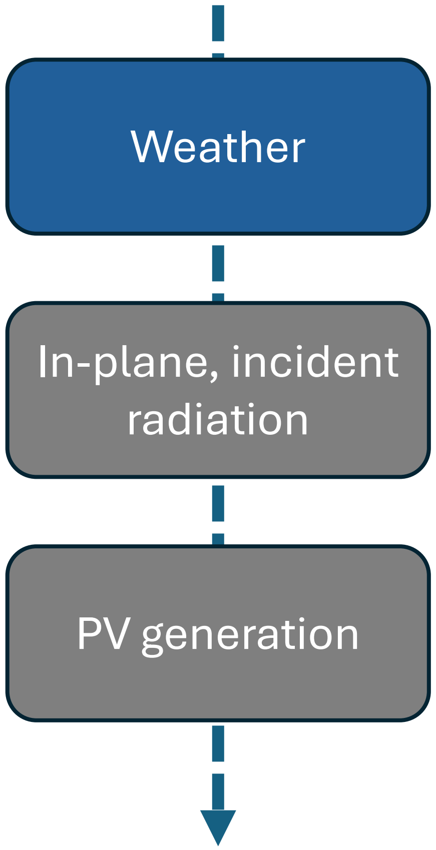

Albedometer

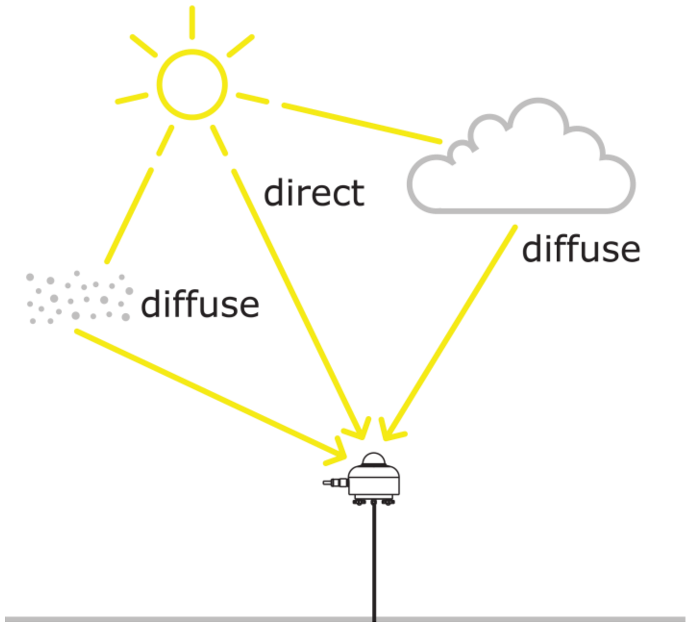

"Multi-sensor"*

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



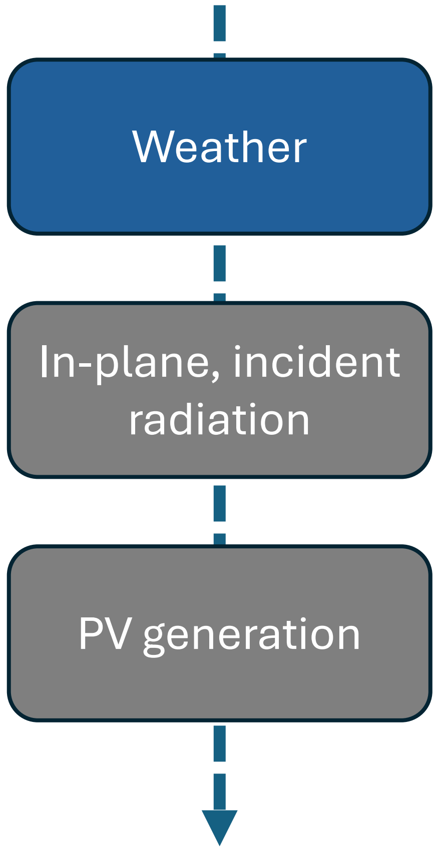


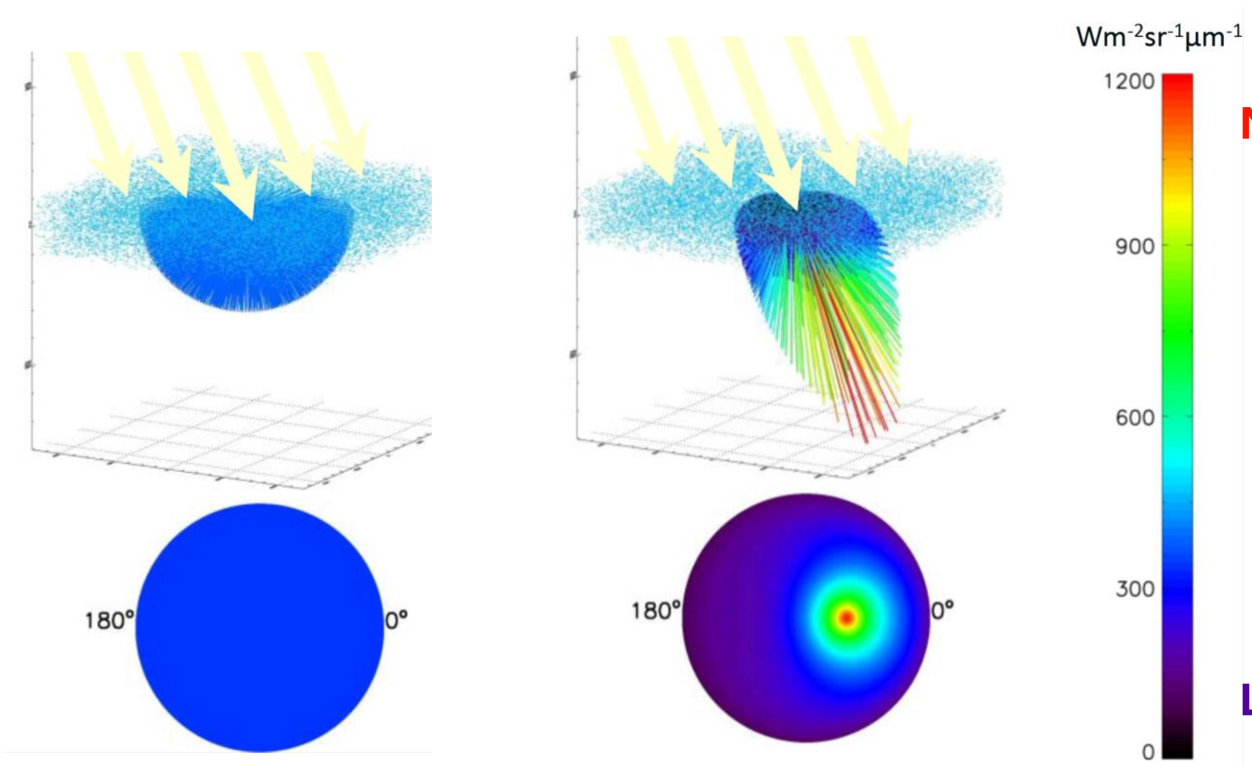
Beam horizontal irradiance (**BHI**)

Diffuse… (**DHI**)

Global … (GHI = BHI + **DHI**)

Solar radiation: far from isotropic





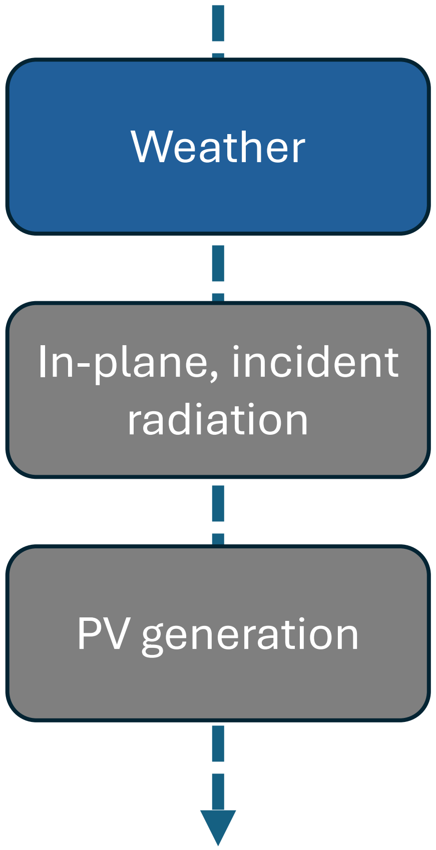
More radiation

Less radiation

Isotropic assumption

Anisotropic reality

Solar radiation: transposition models



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

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

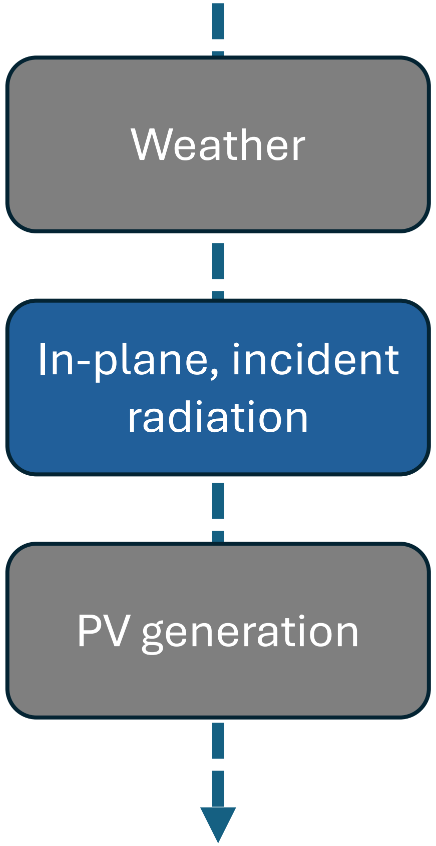
For diffuse, there are many approaches:

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

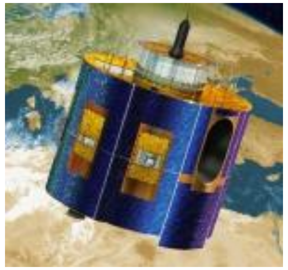
pvlib: a great Python package for this

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

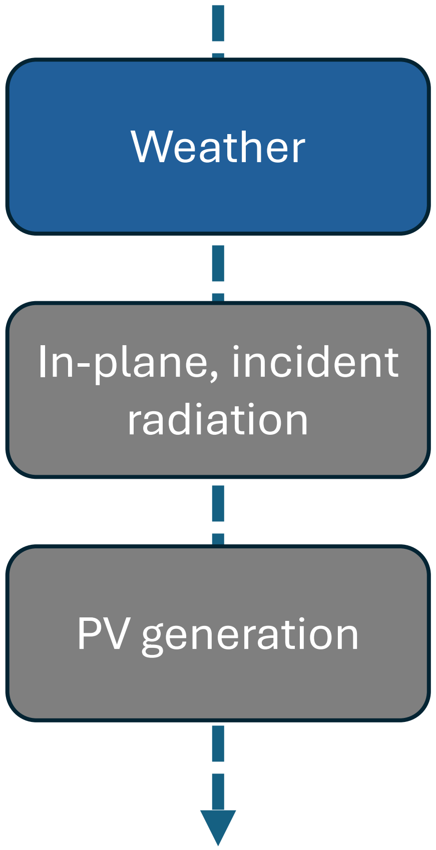


So, in this context, we also need a **decomposition** model (more details in appendix)

GHI → Diffuse and Beam Horizontal (DHI, BHI) → Global **Tilted** Irradiance (GTI)

Decomposition model

Solar radiation: decomposition models

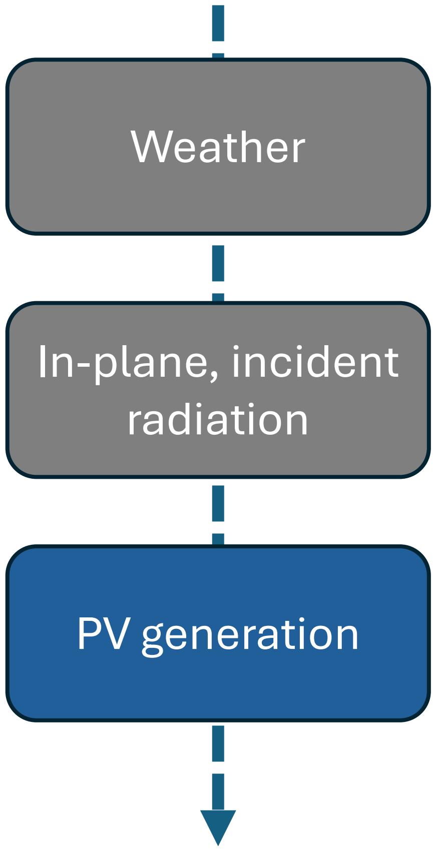


Transposition: we know total diffuse, but how is it distributed in the sky?

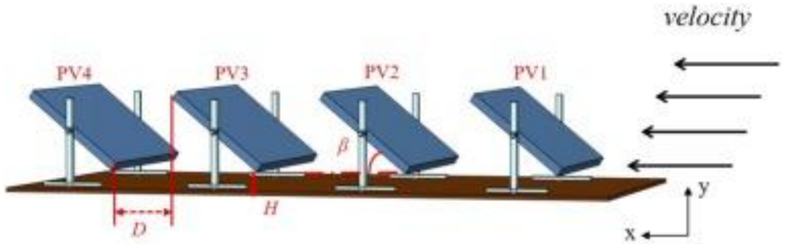
Decomposition: how much is total diffuse even?

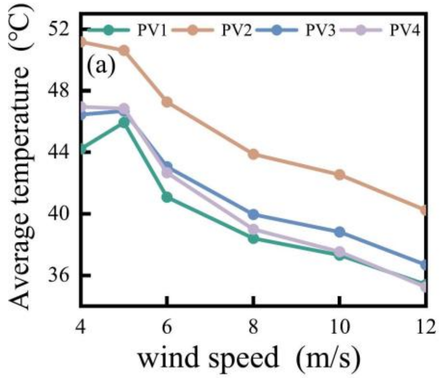
Model	Considers
Erbs	Empirical linear correlation between **diffuse fraction** and clearness index. Based on observations from the USA.
Orgill & Hollands	Similar as Erbs but considers piece-wise linear correlation.
Reindl	Includes solar zenith angle as input (as a kind of proxy to AOD)
DIRINT	Semi-empirical,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

PV conversion: thermal losses

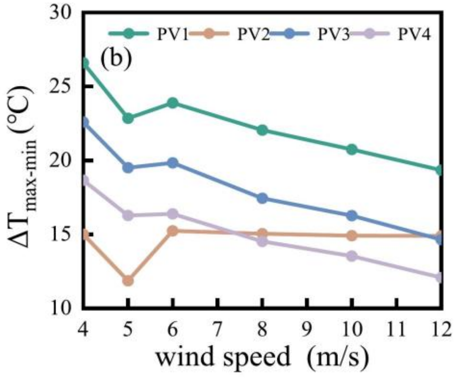


Also impacted by spatial arrangement



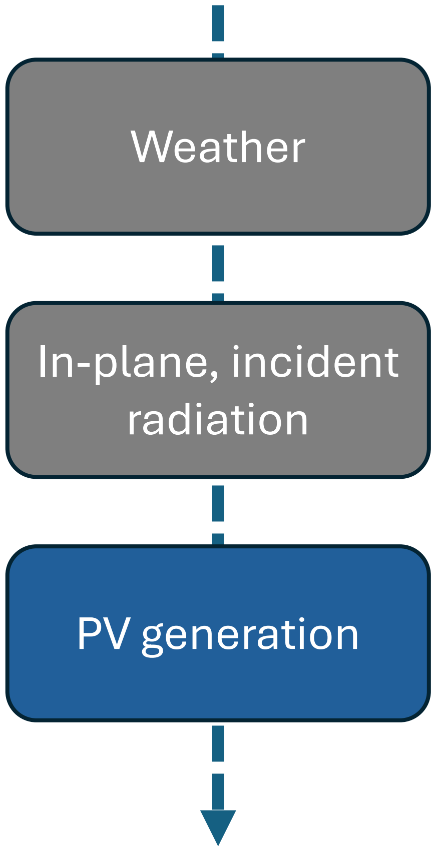


(a) Average temperature



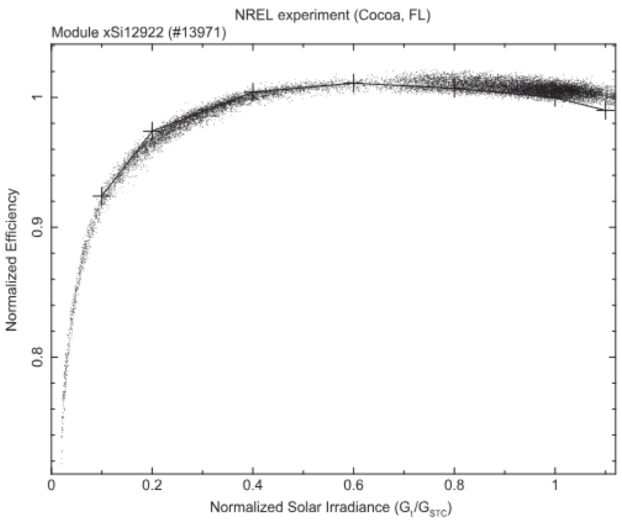
(b) Maximum temperature difference

PV conversion: low-irradiance losses



Then, account for low-level irradiance loss

- Typical in crystalline silicon, due to parasitic shunt resistance
- Example: Marion model (eq. 11)



Mavromatakis et al. (2017)