Session 3: Solar power spatial planning techniques

IRENA Global Atlas
Spatial planning techniques
2-day seminar

Central questions we want to answer

- After having identified those areas which are potentially available for renewables, we want to estimate…
  - what the potential solar **PV capacity** per km² and in total is (W/km²), and,
  - **how much electricity** (Wh/km²/a) can be generated in areas with different solar resource availability.
- We also need to know which parameters are the **most sensitive** ones in order to identify the most important input parameters.
- In this section, we will focus on grid-tied PV but also provide useful numbers for CSP.

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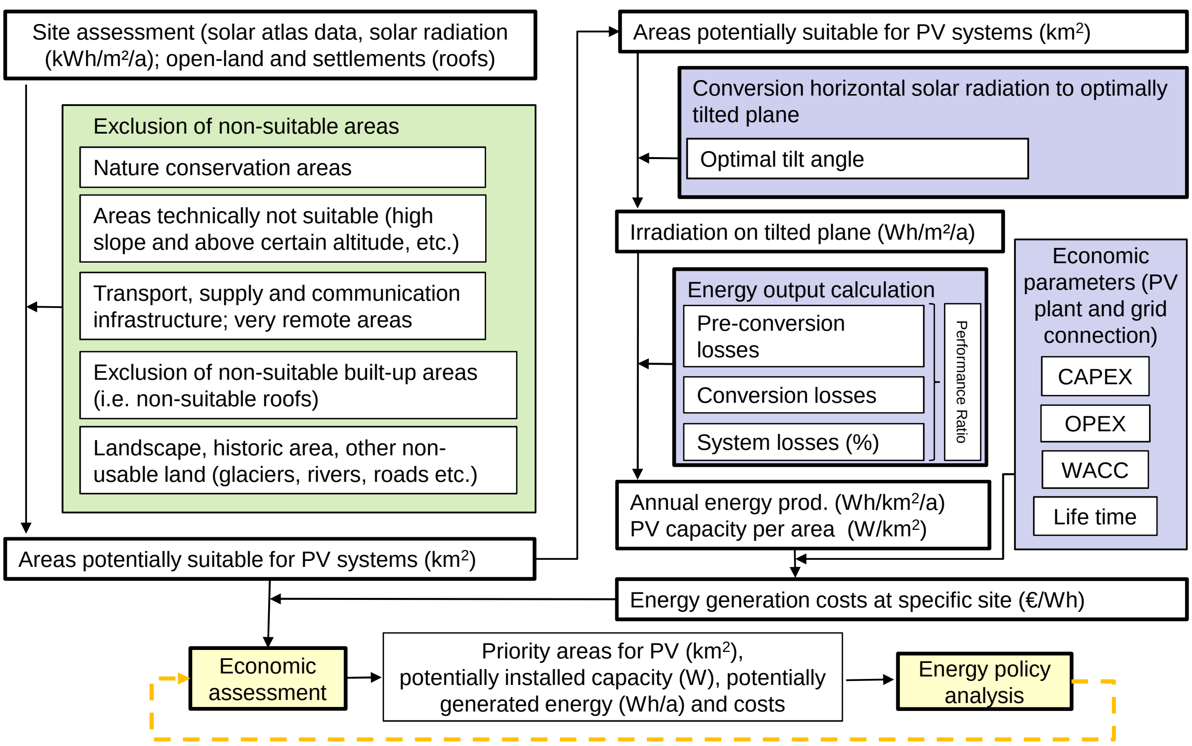

CAPEX = Capital expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (debt, equity) renac renewables academy

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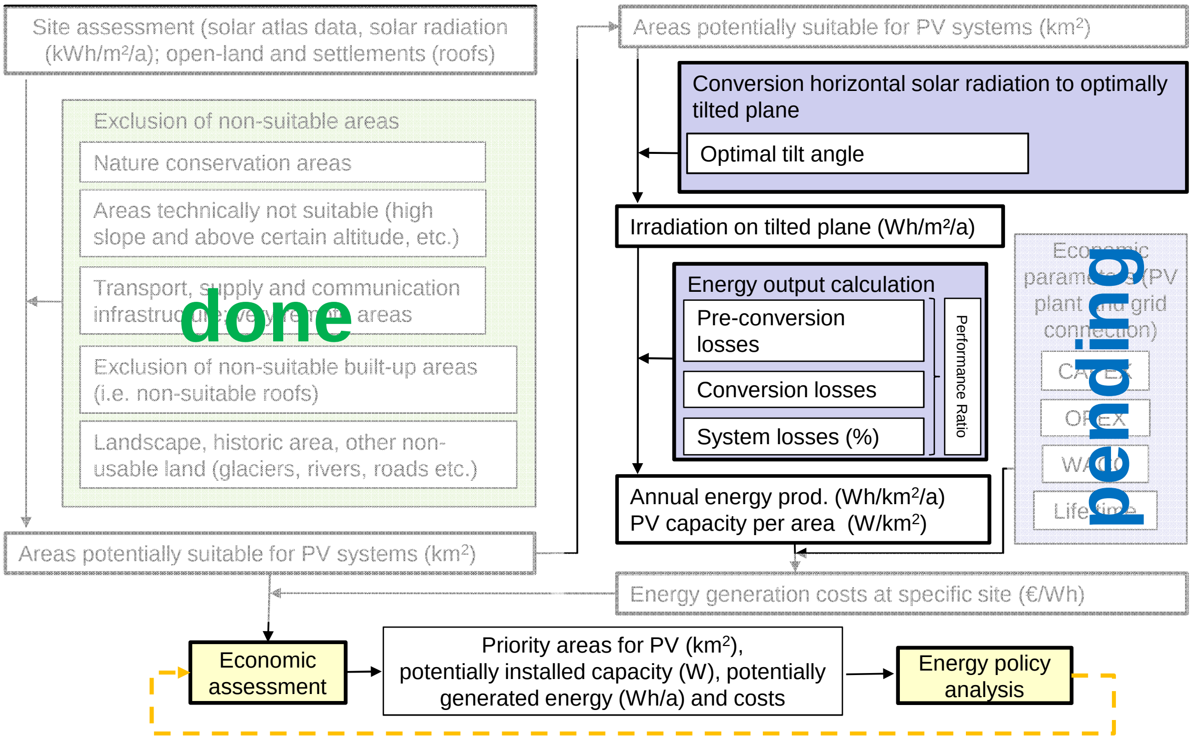

CAPEX = Capital expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (debt, equity)

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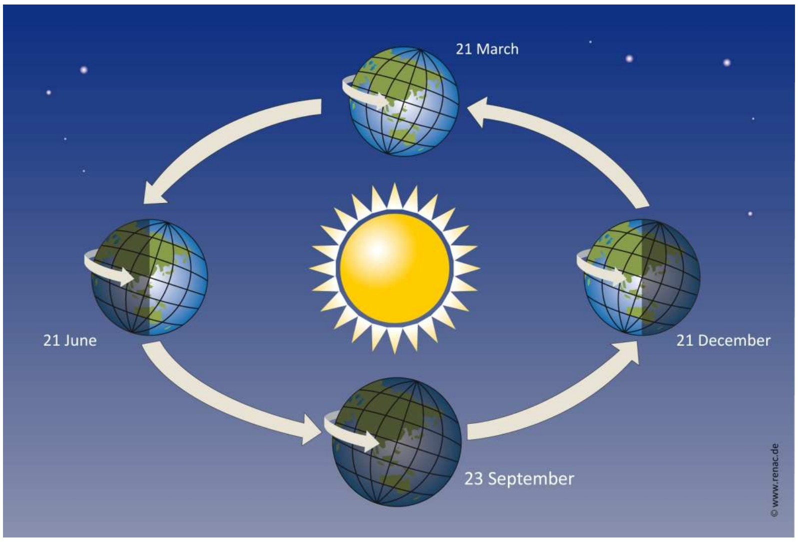
1. SOLAR RESOURCE

Solar radiation variation

- The sun's power density when its rays reach the earth's atmosphere is known as the solar constant and equals 1366 ±7 W/m^2



Graph: RENAC

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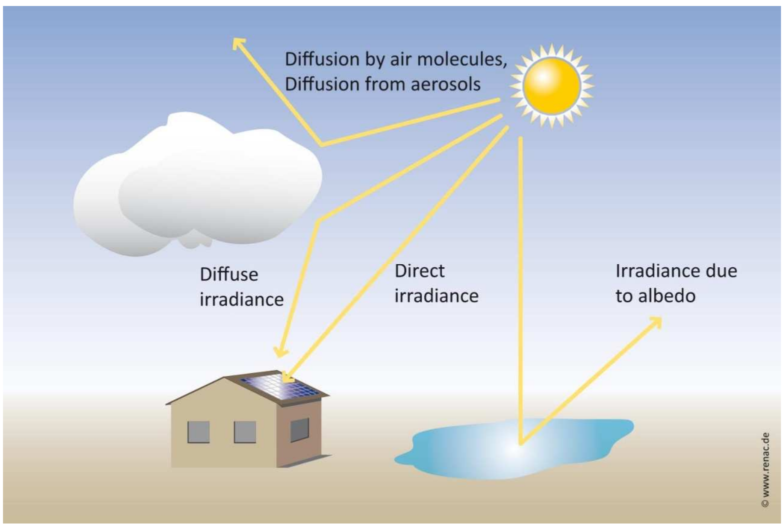
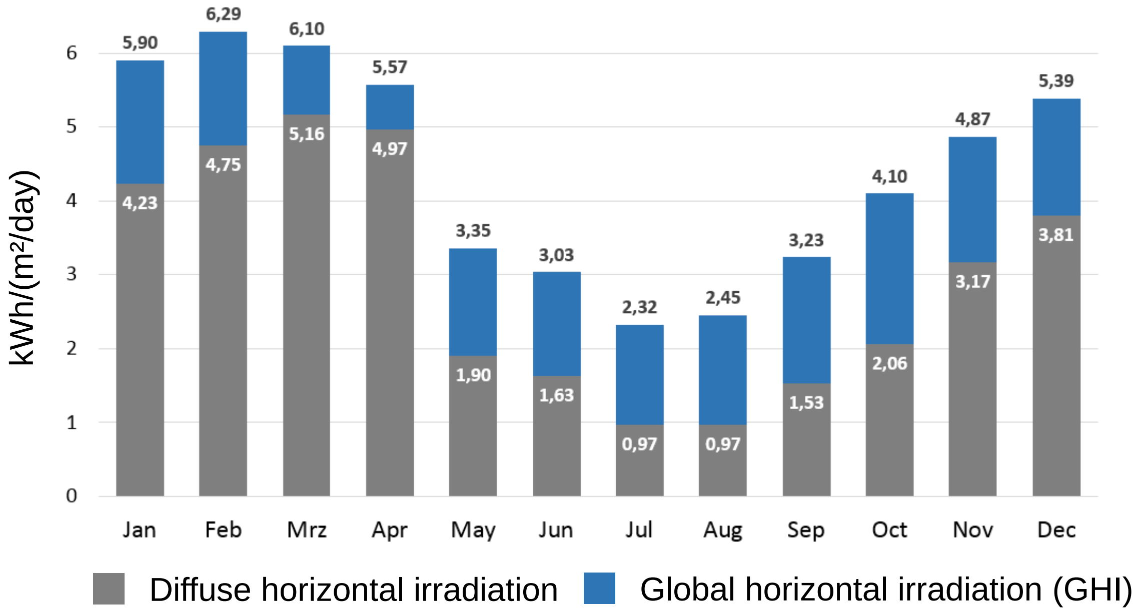
Three component radiation model

- Global radiation is composed of
  - direct radiation (coming directly from sun, casting shadows)
  - diffuse radiation (scattered, without clear direction), and,
  - reflected radiation (albedo).



Solar irradiation – Lima, Peru



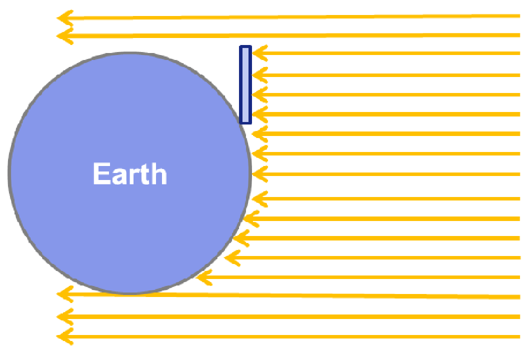
Source: Data from Meteonorm 7

Global horizontal irradiation and irradiation on the tilted plane

- Irradiation data is usually provided as global horizontal irradiation (GHI)
- If moving away from the equator, more irradiation can be received by tilting solar modules

Rules of thumb:

1. Tilt angle against the horizontal = Latitude of the PV installation site*
2. Minimum angle of 10°…15° to avoid settlement of dust and dirt.



**In regions with latitudes >30° the tilt angle is usually between 5° and 20° less than the latitude. The greater the latitude the higher the subtracted value.*

2. SPATIAL SETUP OF LARGE-SCALE PV PLANTS

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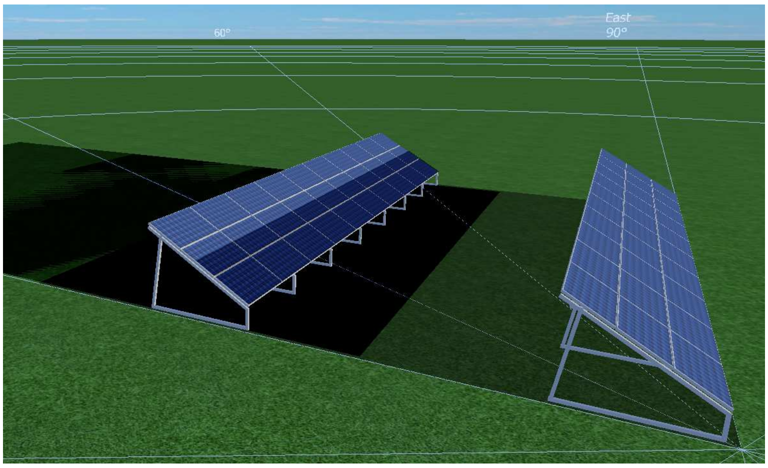
How much power (MWp) can we fit in one km²…

Source: Albrecht Tiedemann

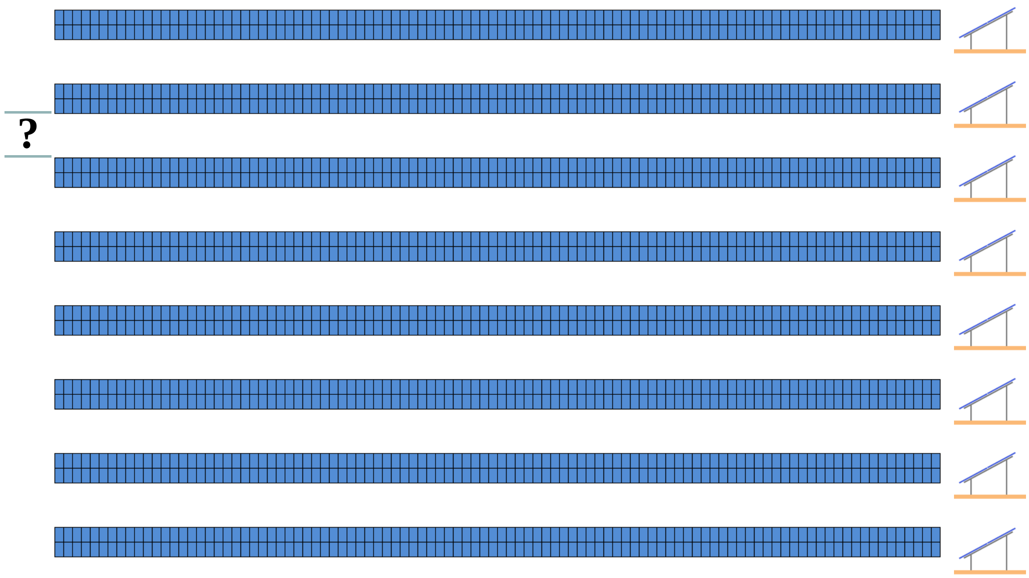
…and limit excessive shading?

- Self-shading occurs when the rows of PV modules in arrays partially shade the PV modules in the rows behind.
- The only unaffected row is the one in the front.



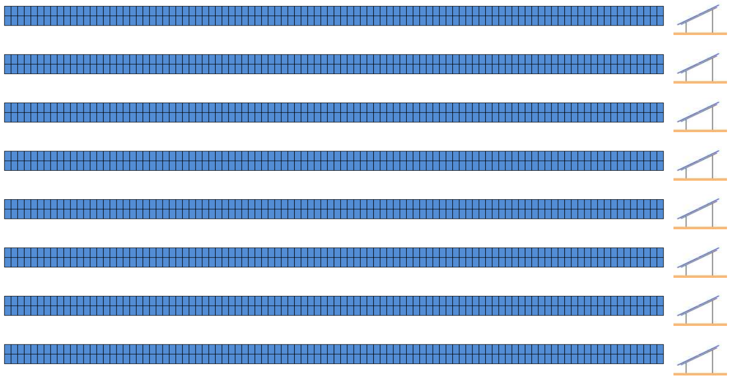
Source: RENAC (Simulation made using PV*SOL premium 7.0)

Which space between rows is needed?



Which space between rows is needed?

- Space between rows depends on:
  - Latitude (sun path)
  - Inclination of solar panels
  - Setup of solar panels on mounting structure
  - Minimum space needed for O&M (car/small truck should fit through)



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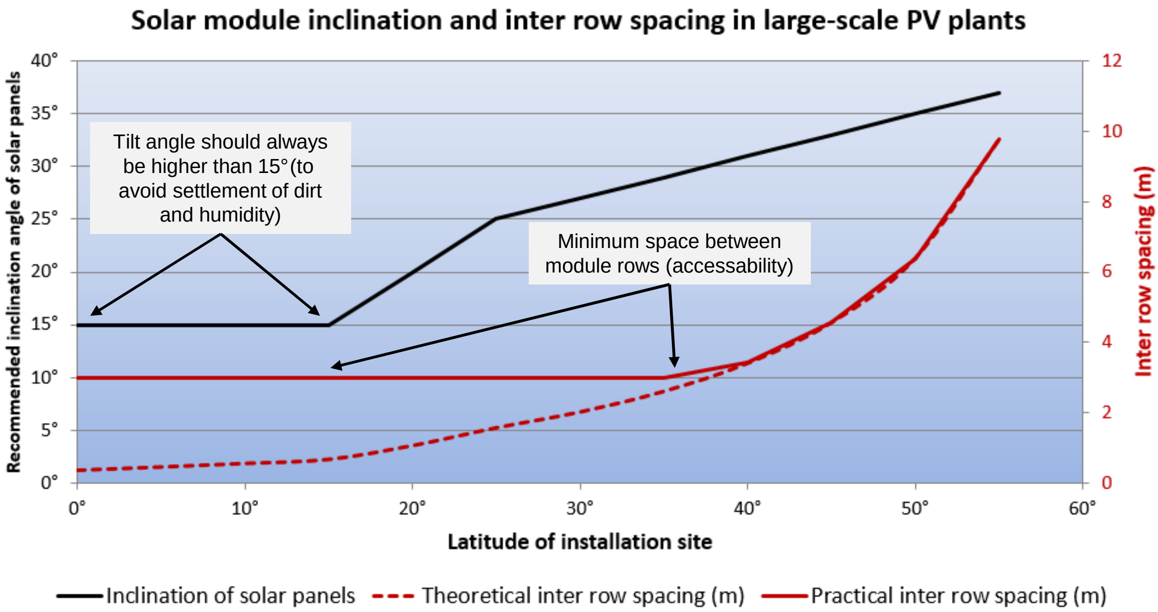
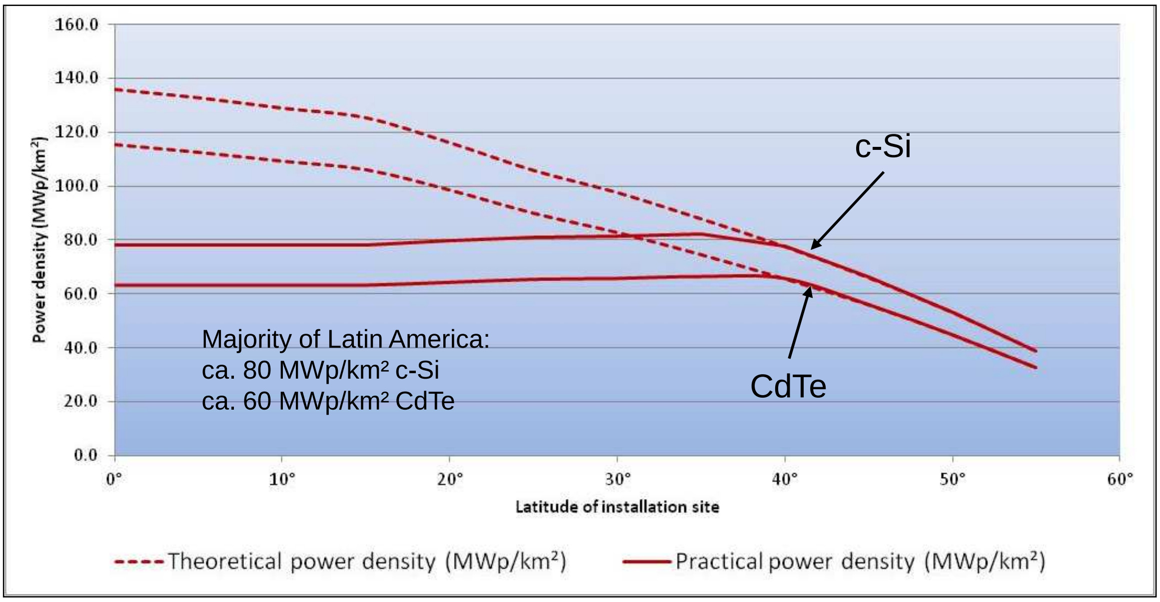
Solar panel inclination and inter-row spacing



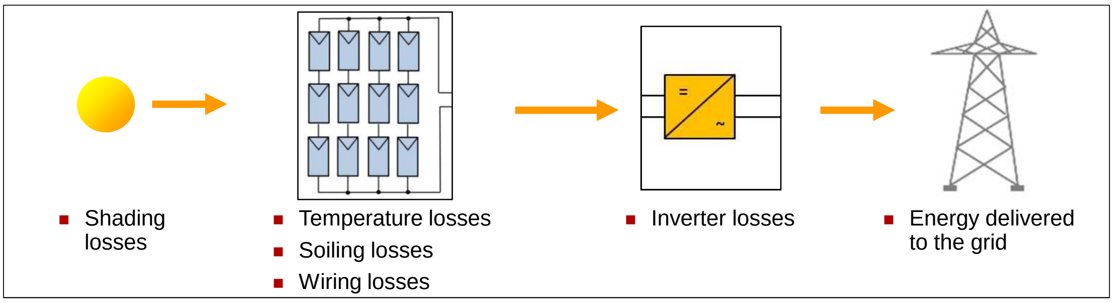
Power density of large-scale PV plants



3. ESTIMATING PV ELECTRICITY YIELD

Yield of a solar PV system

- The fundamental question to answer is how well the system performs and how much electricity does the solar PV system deliver to the grid
- Energy losses occur at every step of the conversion between solar energy and AC electricity fed into the grid
    - Pre-PV generator losses
    - PV generator losses (module and thermal losses)
    - System losses
- The task of the design engineers is to optimize the plant maximizing energy yield by reducing losses



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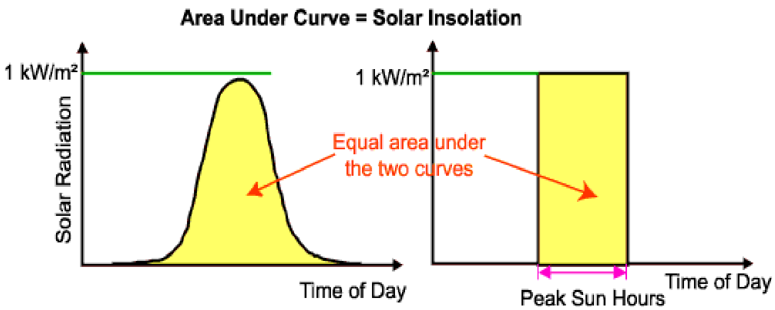
Performance ratio as a measure of the quality of a PV plant

- The performance ratio PR defines the overall solar PV plant performance
- It is calculated as the relation between the energy yield that has actually been generated (Y_{real}) and the theoretical energy yield (Y_{ideal}):

$$PR = Y_{real} / Y_{ideal}$$

- How to calculate the ideal yield Y_{ideal} ?
    - Peak-sun hour method!



Source (diagram): http://pvcdrom.pveducation.org/index.html

Estimating PV plant electricity yield using expected Performance Ratios

- Note: Only for rough estimations!
- Electricity yield of a PV system:

$$E = h \cdot n_{pre} \cdot n_{rel} \cdot n_{sys} \cdot P_{nom} = \boxed{h \cdot PR \cdot P_{nom}}$$

h Peak Sun Hours
n_{pre} Pre-conversion efficiency
n_{sys} System efficiency
n_{rel} Relative efficiency
P_{nom} Nominal power at STC

- '*h*' is Peak Sun Hours, unit: hrs (do not confuse with sunshine hours!)

Peak Sun Hours = Annual irradiation in kWh/(m²*a) / 1000 W/m²

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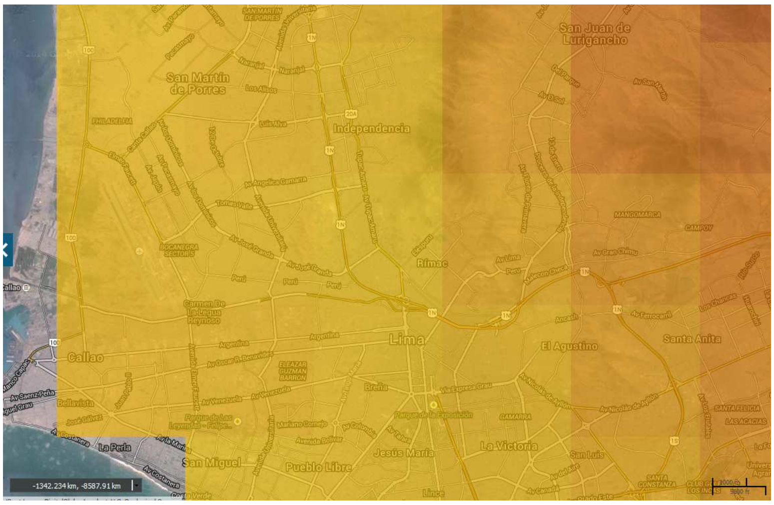
Worked example:

4. ESTIMATING PV CAPACITY AND YIELD AT A GIVEN SITE

PV energy yield estimation in Lima

- Steps performed:
    1) Retrieve global horizontal irradiation data from Global Atlas
    2) Estimate specific electricity yield (kWh/kWp)
    3) Estimate PV capacity and potential solar energy yield per km² at given location



Source: IRENA Global Atlas

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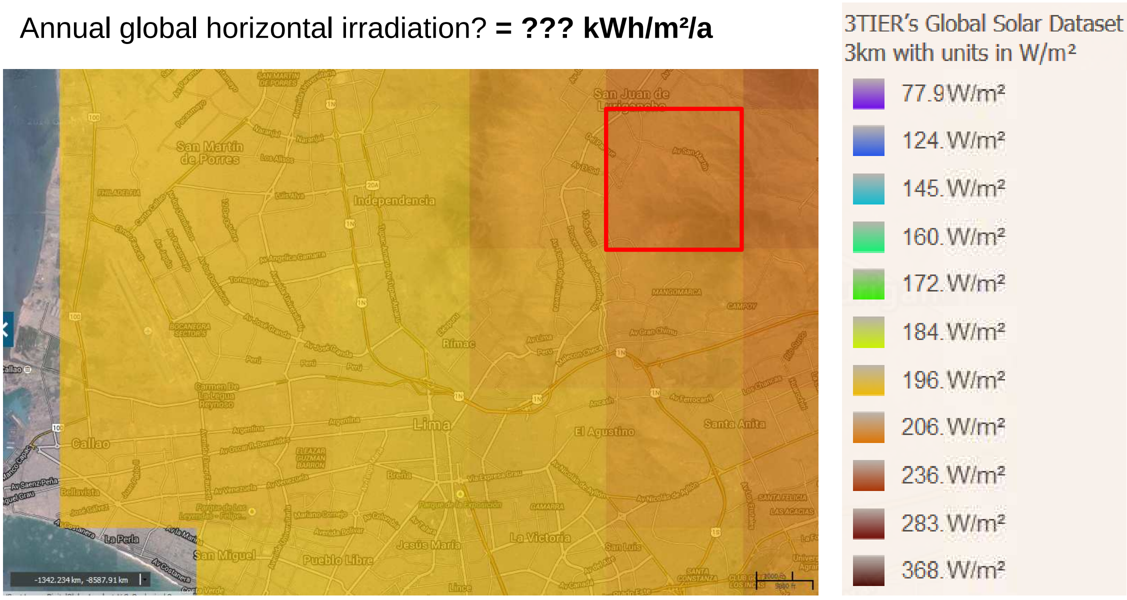
→ Pen and paper exercise (start)

Retrieving global horizontal irradiation

- Hourly average global horizontal irradiance of **??? W/m²**
  Annual global horizontal irradiation? **= ??? kWh/m²/a**

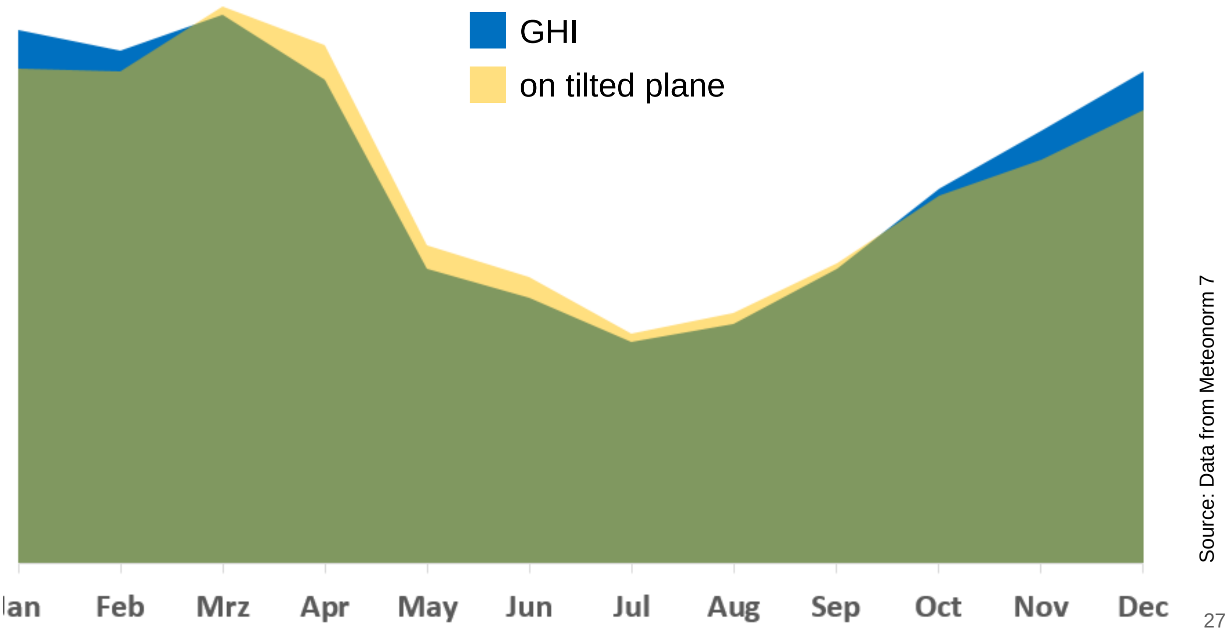


Source: IRENA Global Atlas

Adjusting horizontal irradiation to irradiation on tilted plane

- Coordinates of the chosen site in Lima: 12.05°S and 77.05°W.
- Tilt angle of PV modules at this location should be about 15°.
- GHI at this location : 1,600 kWh/m²/a global horizontal irradiation. At this latitude, irradiation on the tilted plane approximately equals GHI. However, the monthly distribution of energy will change (see next slide).
- For other locations, online tools or professional databases such as Meteonorm produce can be used to find the optimum tilt angle and its resulting irradiation value.
- **Irradiation in the optimally inclined modules plane: = ??? kWh/m²/a**

Monthly distribution of solar irradiation (in Lima)

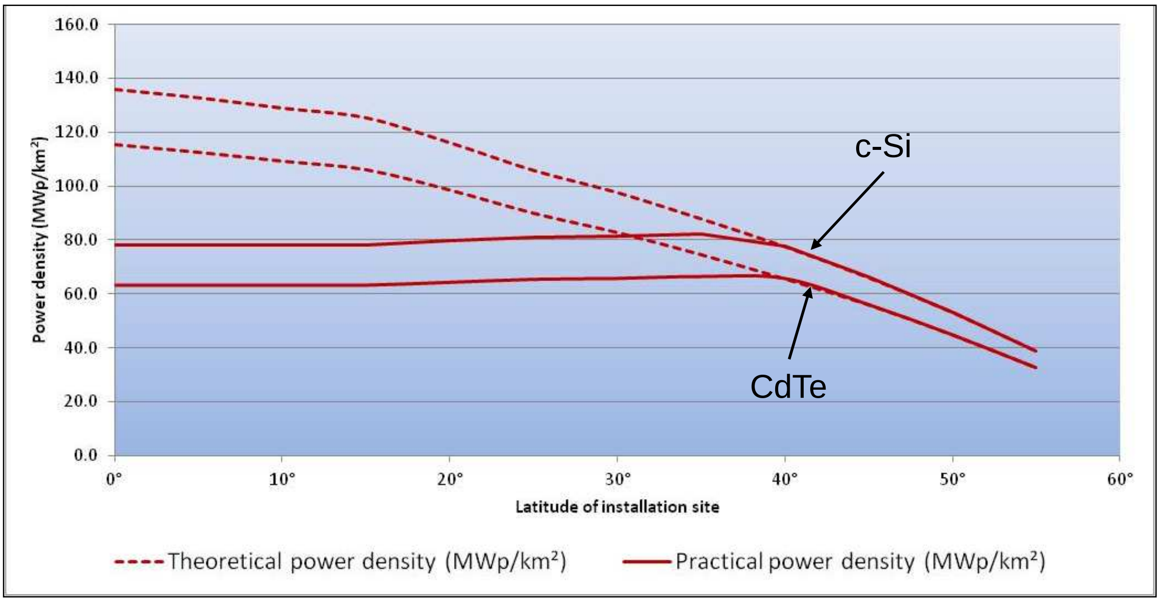


Estimating the specific PV electricity yield

- Assumptions*:
  - Free-standing arrays
  - PR of c-Si modules = 75%
  - PR of CdTe modules = 78% (mainly due to lower temperature sensitivity)
- **Annual Peak Sun Hours = ???**
- Annual electricity yield estimation:
  - c-Si: = **??? kWh/kWp/a**
  - CdTe: = **??? kWh/kWp/a**

*PR: own estimates

Power density of large-scale PV plants



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Estimating energy per km² and capacity factor

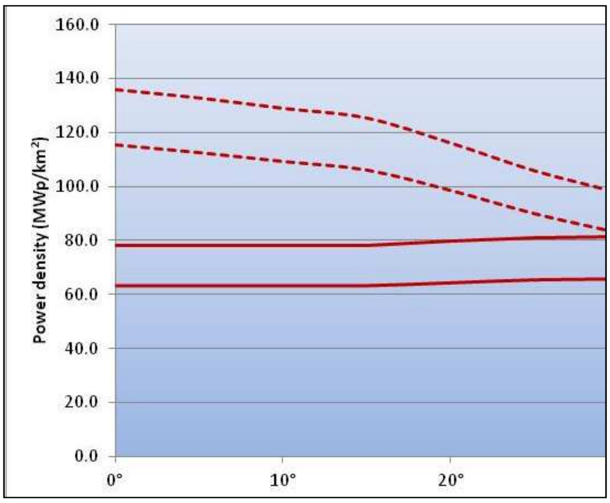
- c-Si:
  -

    = **??? GWh/km²/a**
- CdTe:
  -

    = **??? GWh/km²/a**

- Capacity factor:

  = **???%**



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Please remember

- The previous worked example is only a rough estimate and results are only true for the given assumptions (open-land installation, module types, solar resource data, Performance Ratio assumptions, etc.)

- Factors which might influence electricity output, which have not been considered in detail here are for instance: heavy soiling of modules, shading from other objects, additional temperature losses if ventilation is lower than in the case of free-standing arrays (e.g. roof-parallel installation), etc.

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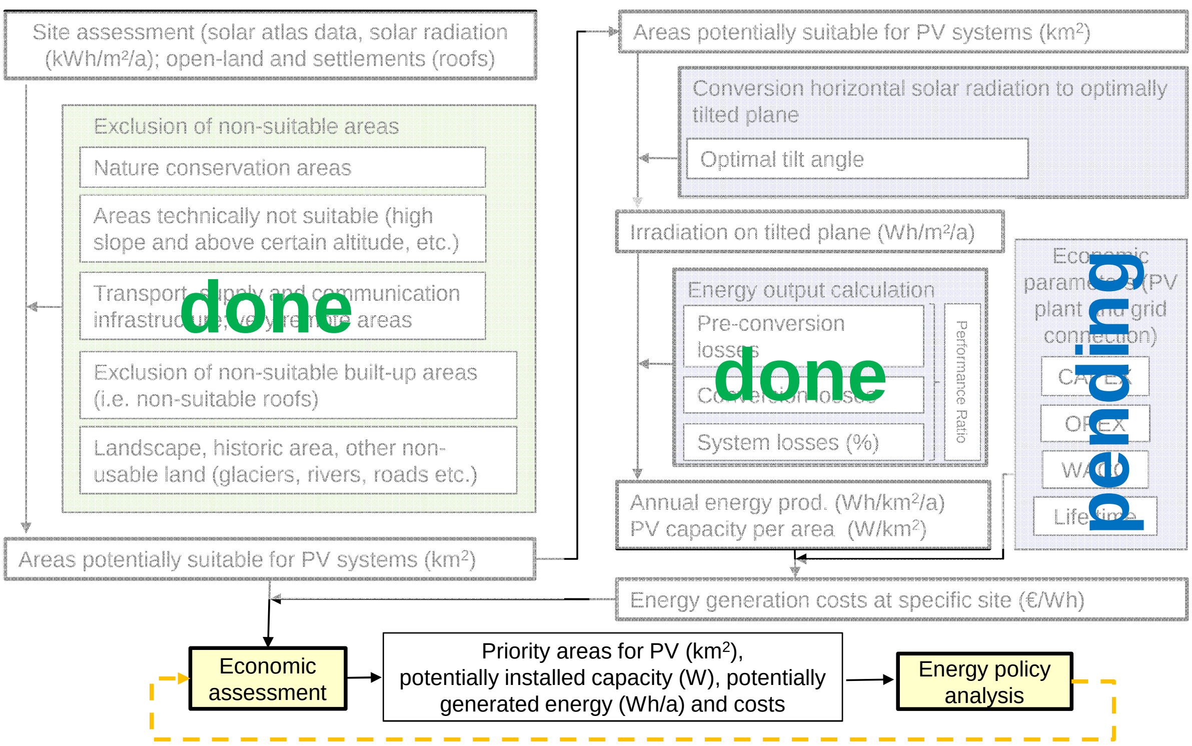

CAPEX = Capacity expenditure, OPEX = Operation expenditure, WACC = Weighted average cost of capital (depth, equity)

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5. A FEW WORDS ON CSP

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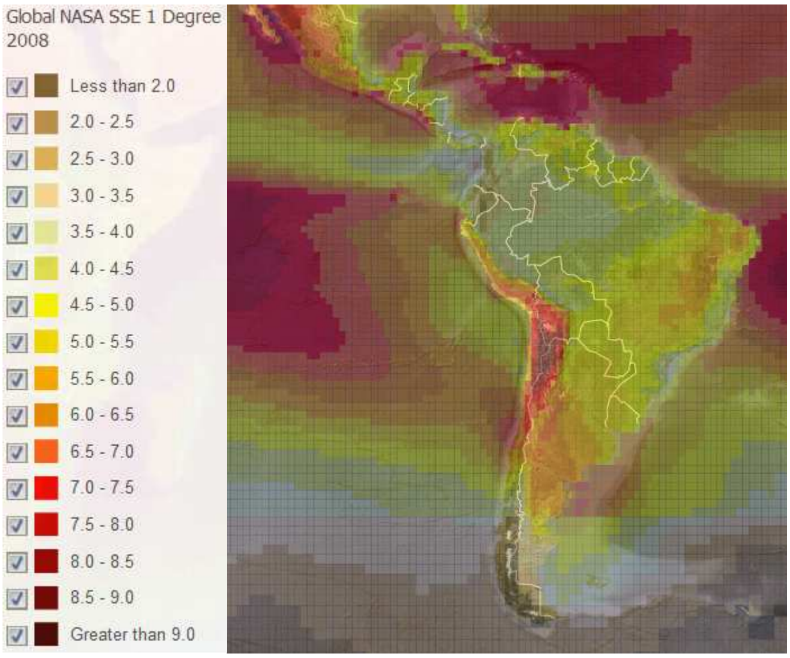
Geographical and irradiation requirements for CSP

- Map shows annual Direct Normal Irradiation (DNI) in kWh/m²/day
- CSP needs not only high levels of DNI (> 2,000 kWh/m²/year considered economically viable) but also flat ground and sufficient water supply



Map: IRENA Global Atlas; NASA data

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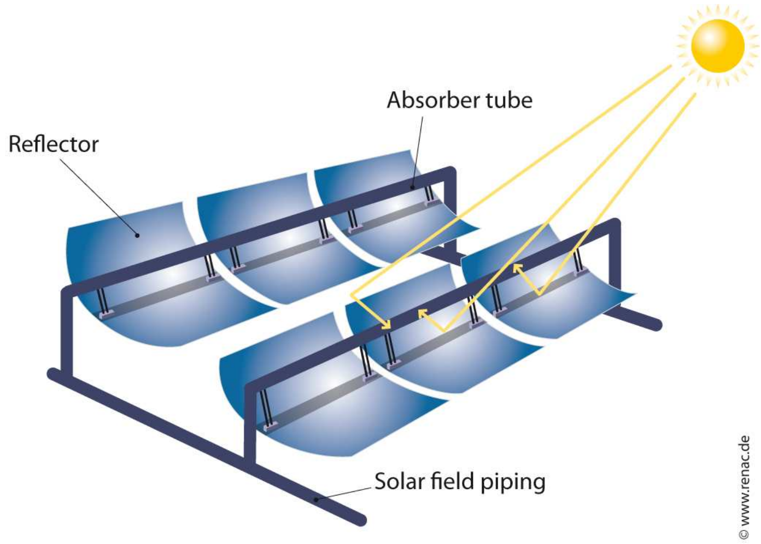
Parabolic trough collector - principle

- Parabolic mirror tracks the sun in one axis and reflects Direct Normal Irradiation (DNI) on Heat Collecting Element (HCE)



Graph: RENAC

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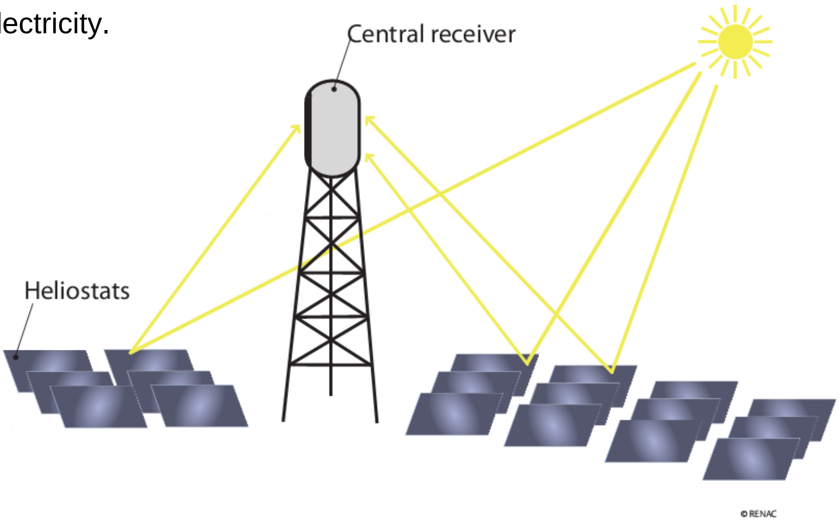
Parabolic trough power plant

- Operating temperature: 300℃ to 500℃
- Concentration Factor 70 - 90
- Heat transfer fluid: thermal oil, direct steam, molten salt
- Typical power size: 50 to 400 MW_{el} (for a solar field for 50 MW_{el} over 500,000 m² of aperture area)
- High manufacturing quality requirements: System will have to be aligned to track the sun with 0.1° precision!

Solar tower

- Solar radiation is reflected from heliostats (large steel reflectors) onto a receiver (heat exchanger) at the top of the solar tower.
- Here the heat is transferred to water to produce steam to drive a steam generator to generate electricity.



Graph: RENAC

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CSP Plants – Costs and cost trends

- The LCOE of CSP plants varies considerably depending on –
  - the technology
  - the location of the plant, i.e. irradiation levels
  - the level of thermal storage, i.e. capacity factors
- Potential further reduction in LCOE of 45-60% predicted by 2025 by IRENA in 2012.

Technology	Estimated LCOE
Parabolic Trough[1)] (DNI: 2,000 – 2,500 kWh/m²*a; PR=90%)	0.15 – 0.20 EUR_{2013}
Solar Tower[2)]	0.12 – 0.21 EUR_{2011}/kWh
PV[1)] (utility scale; 2,000 kWh/m²*a; PR=85%)	average: 0.08 EUR_{2013}/kWh

Sources: 1) Fraunhofer Institute for Solar Energy Systems ISE: Levelized cost of electricity - renewable energy technologies, November 2013; 2) IRENA_CSP Cost Analysis, June 2012; 2)

Thank you very much for your attention!

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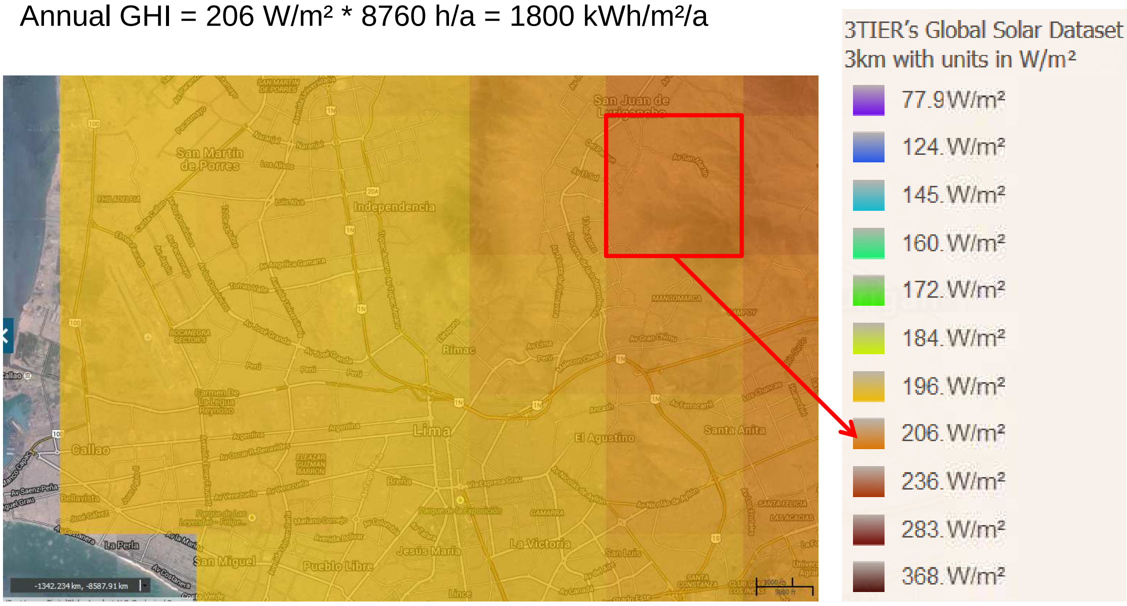
→ Solutions

Retrieving global horizontal irradiation

- Hourly average global horizontal irradiance of 206 W/m²
  Annual GHI = 206 W/m² * 8760 h/a = 1800 kWh/m²/a



Source: IRENA Global Atlas

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Adjusting horizontal irradiation to irradiation on tilted plane

- Not applicable for our site in Lima for the annual values.
- For other latitudes, please consult online tools/softwares/databases to transform GHI ito values for the tilted plane.

Estimating the specific PV electricity yield

- Assumptions*:
  - Free-standing arrays
  - PR of c-Si modules = 75%
  - PR of CdTe modules = 78% (mainly due to lower temperature sensitivity)
- Annual Peak Sun Hours = (1,800 kWh/m²/a) / (1,000 W/m²) = 1,800 h/a

- Electricity yield estimation:
  - c-Si: 1kWp * 75% * 2,330 h/a ≈ **1,350 kWh/kWp/a**
  - CdTe: 1kWp * 78% * 2,330 h/a ≈ **1,400 kWh/kWp/a**

*PR: own estimates

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Estimating energy per km² and capacity factor

- c-Si:
  - 80 MWp/km² * 1,350 MWh/MWp/a
    = **108 GWh/km²/a**
- CdTe:
  - 60 MWp/km² * 1,400 MWh/MWp/a
    = **84 GWh/km²/a**