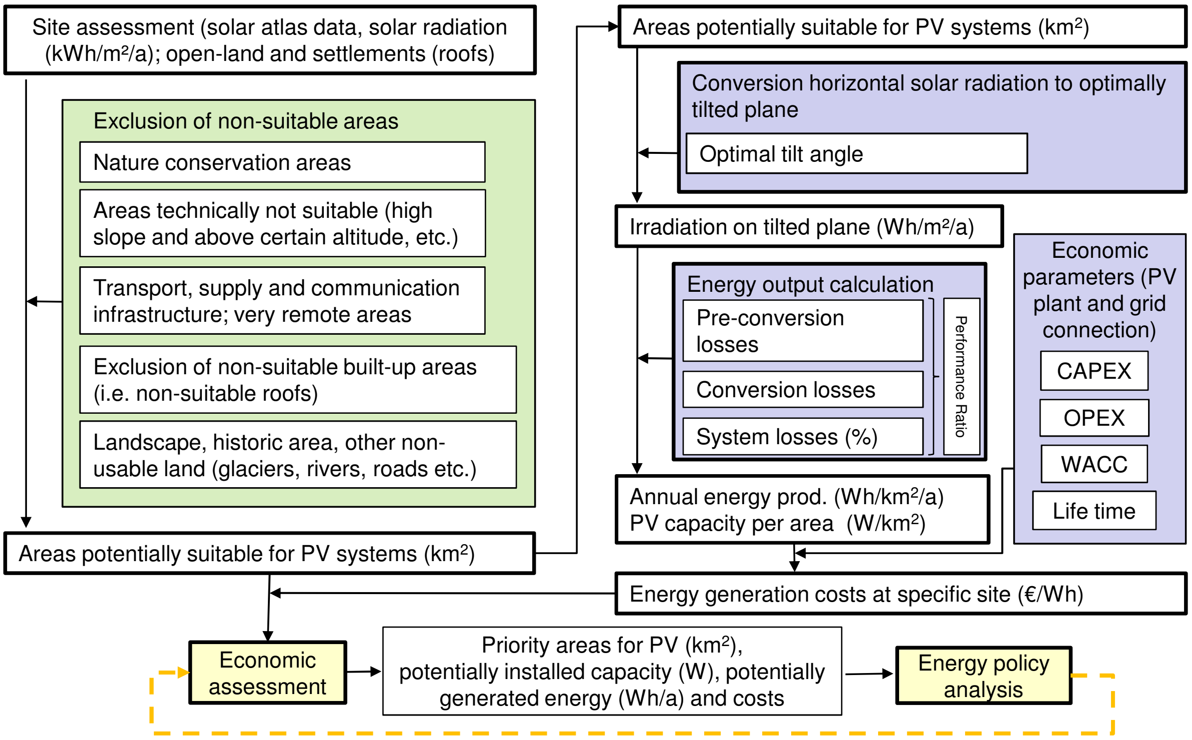
Session 2a:
Solar power spatial planning techniques

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.

Contents



Site assessment (solar atlas data, solar radiation (kWh/m²/a); open-land and settlements (roofs)

Exclusion of non-suitable areas

- Nature conservation areas
- Areas technically not suitable (high slope and above certain altitude, etc.)
- Transport, supply and communication infrastructure; very remote areas
- Exclusion of non-suitable built-up areas (i.e. non-suitable roofs)
- Landscape, historic area, other non-usable land (glaciers, rivers, roads etc.)

Areas potentially suitable for PV systems (km²)

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Conversion horizontal solar radiation to optimally tilted plane

- Optimal tilt angle

Irradiation on tilted plane (Wh/m²/a)

Energy output calculation

- Pre-conversion losses
- Conversion losses
- System losses (%)

Performance Ratio

Economic parameters (PV plant and grid connection)

- CAPEX
- OPEX
- WACC
- Life time

Annual energy prod. (Wh/km²/a)
PV capacity per area (W/km²)

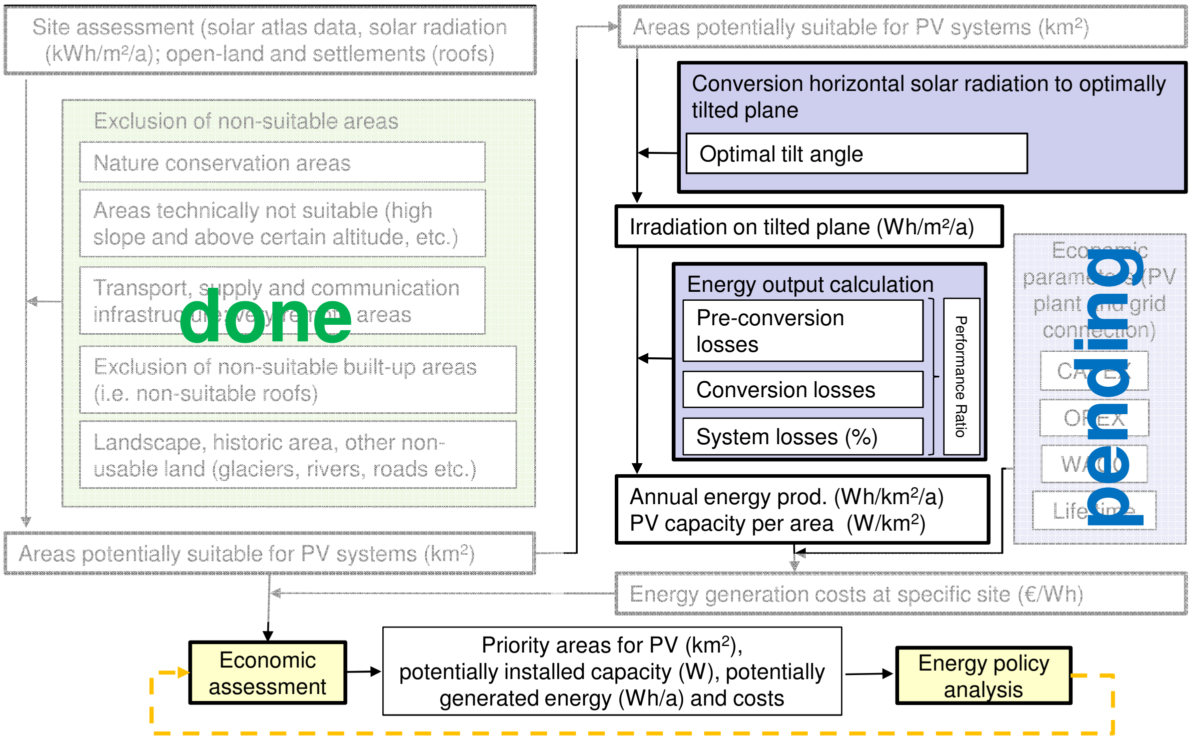
Energy generation costs at specific site (€/Wh)

Economic assessment

Priority areas for PV (km²), potentially installed capacity (W), potentially generated energy (Wh/a) and costs

Energy policy analysis

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



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done

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pending

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1. OVERVIEW ON PV OUTPUT ESTIMATION

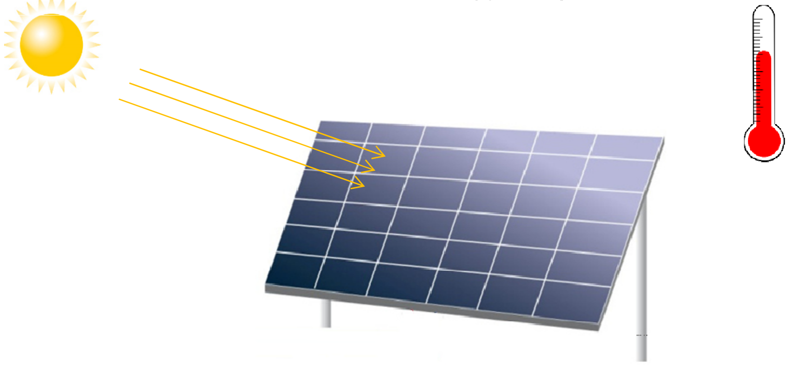
Spatial design

- In PV plants where we are applying a tilt angle on modules we have to optimise space between module rows minimising self-shading losses

Influence of radiation and temperature

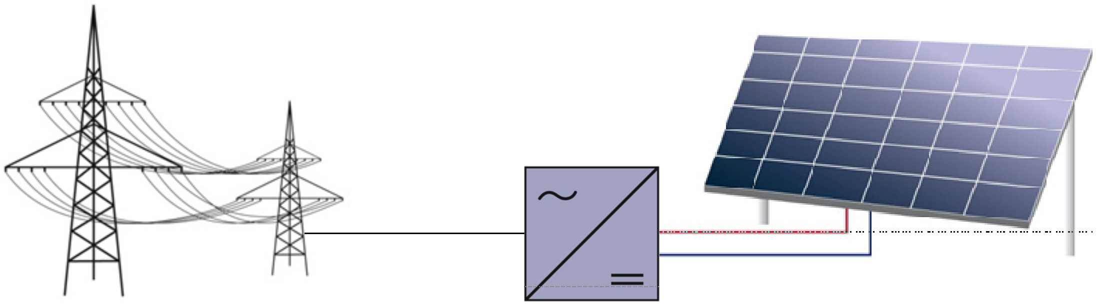
Variable solar radiation & Variable temperatures

Influence energy output



Electrical system losses

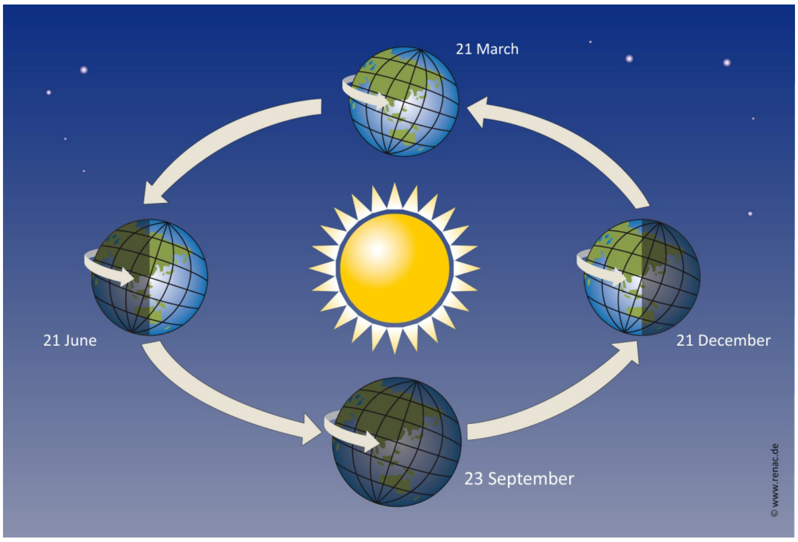
Ohmic losses in cabling and electronic components (e.g. inverters) also reduce output



2. SOLAR RESOURCE

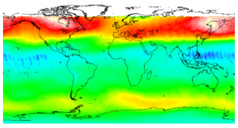
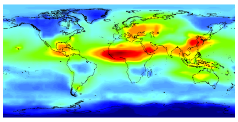
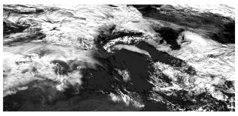
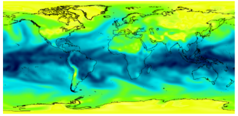
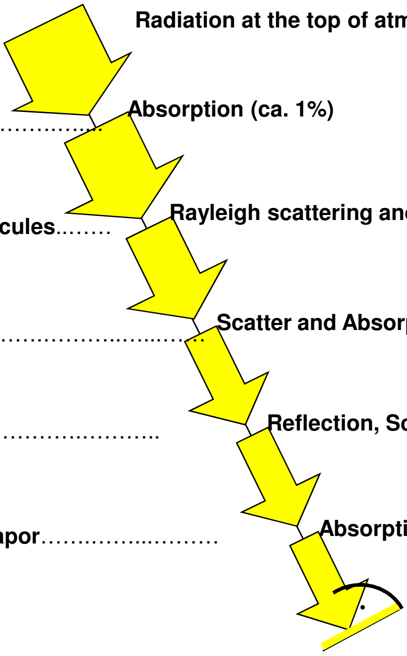
Solar radiation variation

- The sun’s power density when its rays reach the earth’s atmosphere is known as the solar constant and equals 1366 ±7 W/m²



Graph: RENAC

Absorption and Scattering in the Atmosphere

Radiation at the top of atmosphere

Ozone……………….. **Absorption (ca. 1%)**

Air molecules…….. **Rayleigh scattering and absorption (ca. 15%)**

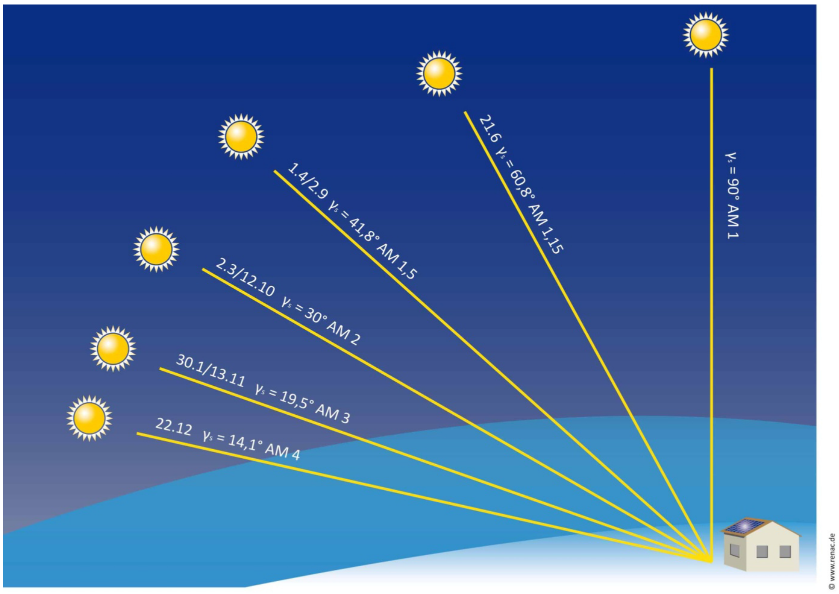
Aerosol…………………..……... **Scatter and Absorption (∅ ca. 15%, max. 100%)**

Clouds……………..……….. **Reflection, Scatter, Absorption (max. 100%)**

Water Vapor…….……..…..……… **Absorption (ca. 15%)**

Direct normal irradiance at ground

Irradiance reduction through atmosphere
Air Mass (AM)



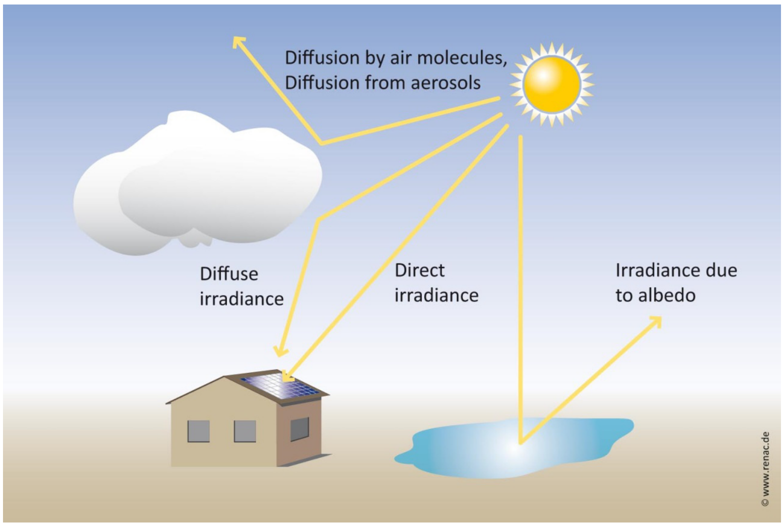
Graph: RENAC

Beware of the trap: solar irradiance vs. irradiation

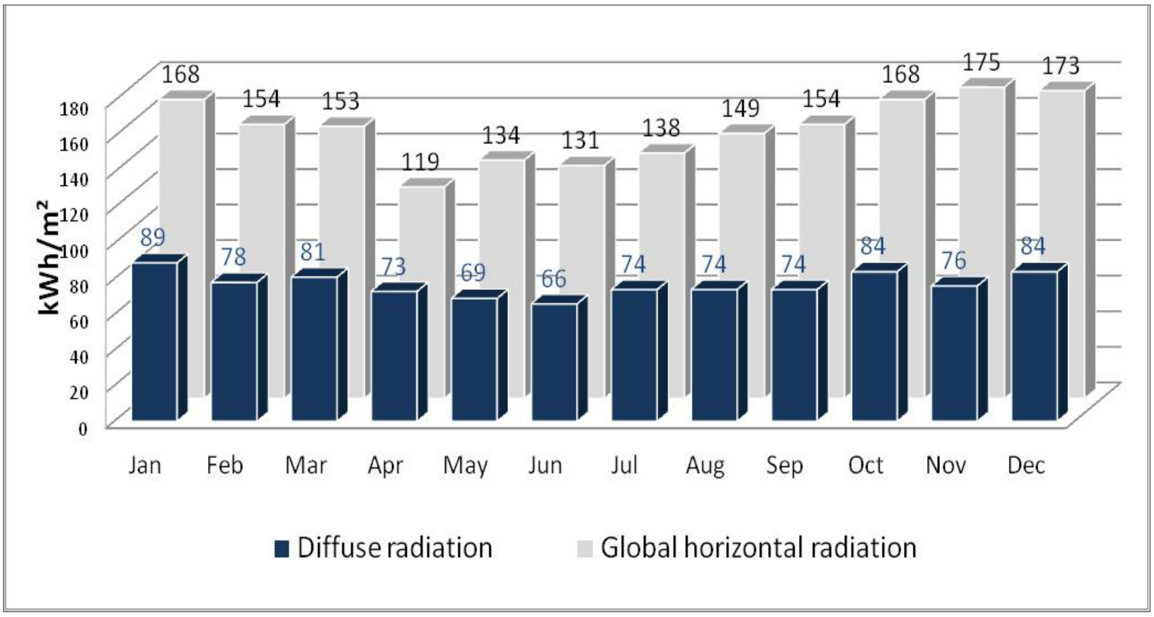
- Solar irradi**ance**
  - Instantaneous power of sunlight on a defined surface; e.g. in W/m^2
- Solar irradi**ation**
  - Solar energy received during a specified time period on a defined surface; e.g. in kWh/(m^2*day) or MJ/(m^2*year)

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).



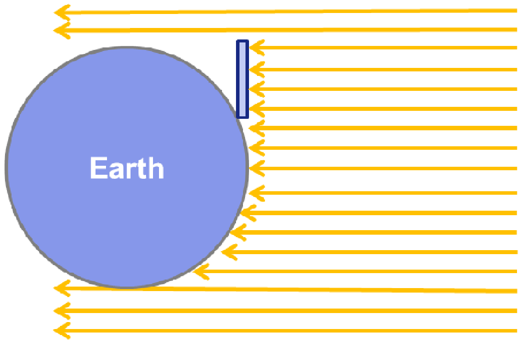
Solar radiation – Dar Es Salaam, TZ



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.

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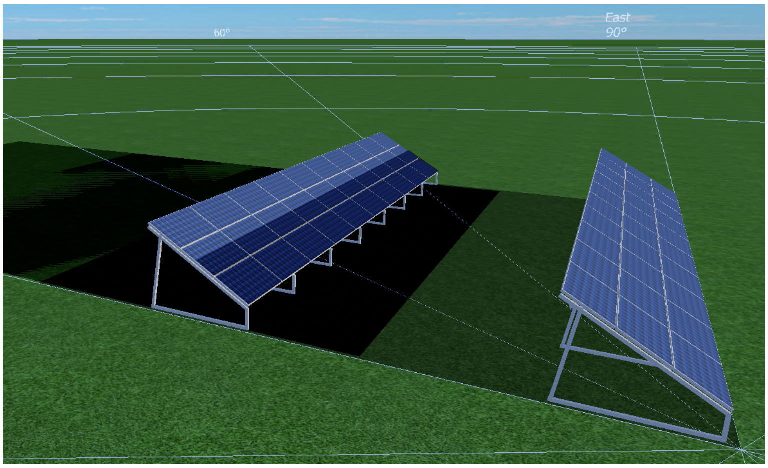
3. SPATIAL SETUP OF LARGE-SCALE PV PLANTS

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

Source: Albrecht Tiedemann

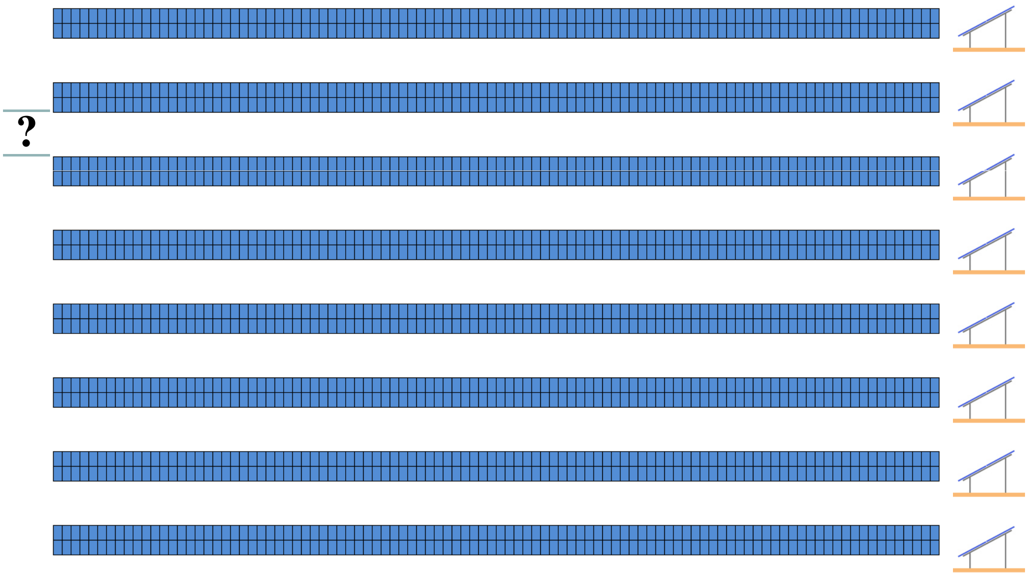
…and limit excessive shading?

- 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)

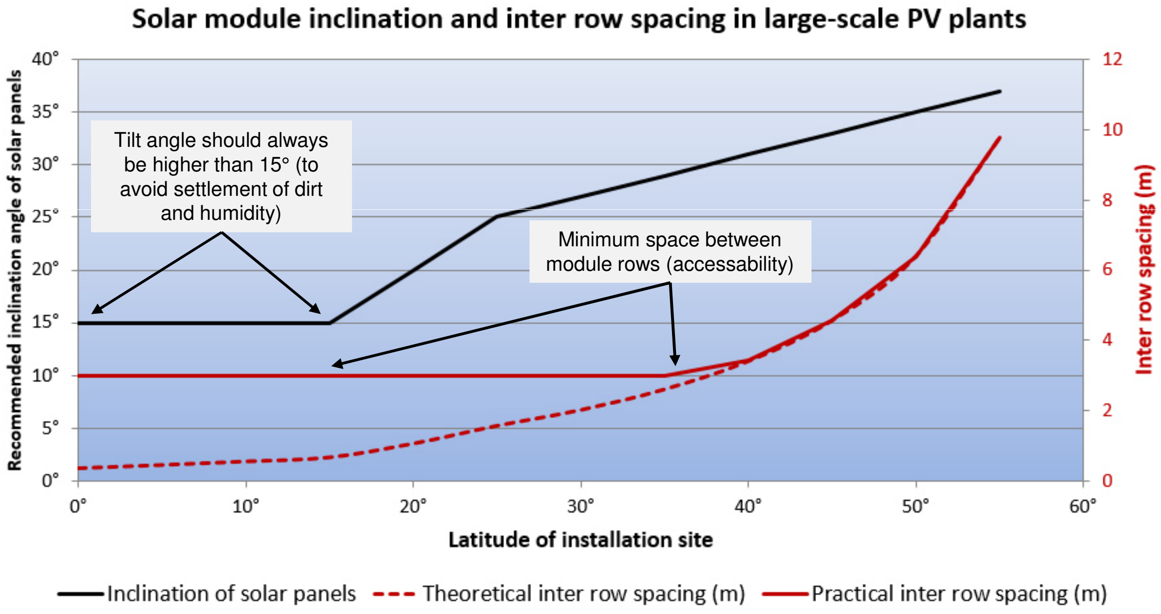
Which space between rows is needed?



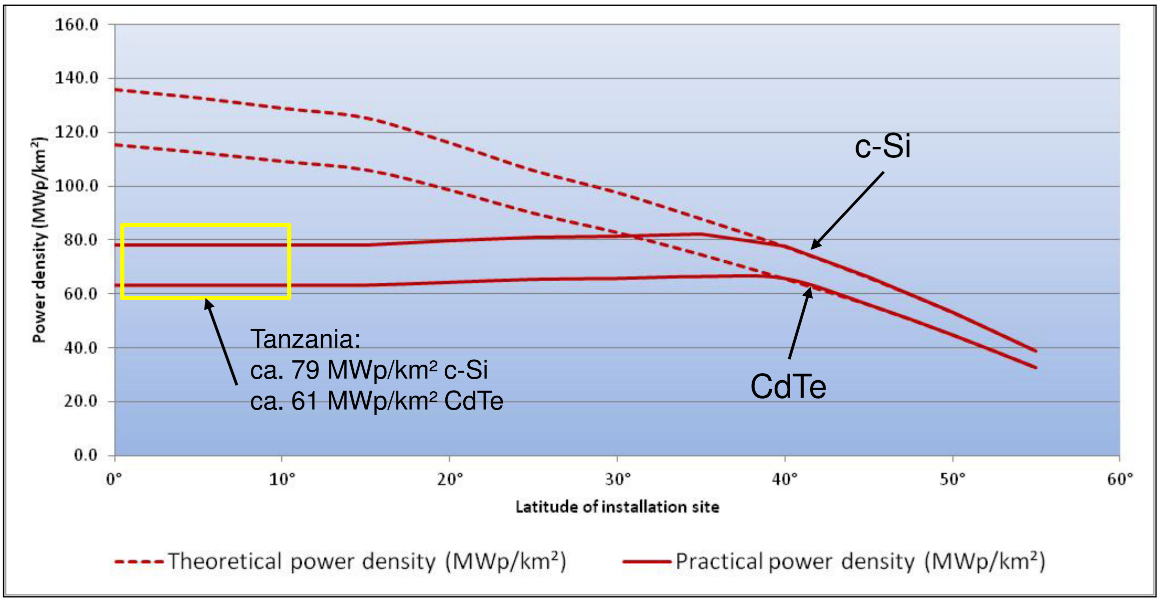
Which space between rows is needed?

- 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)

Solar panel inclination and inter-row spacing



Power density of large-scale PV plants



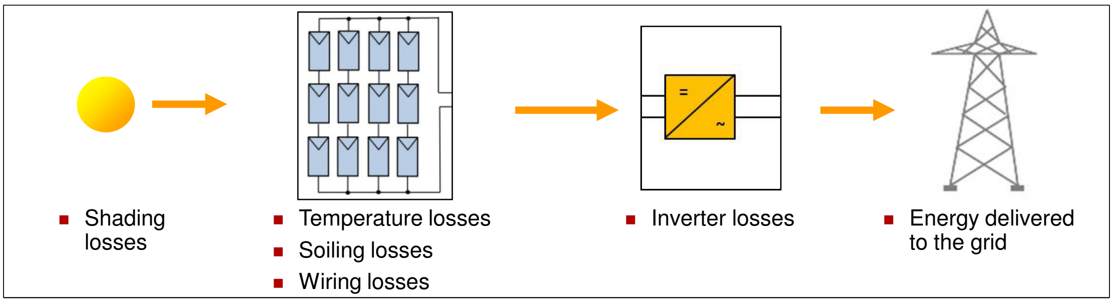
4. ESTIMATING PV ELECTRICITY YIELD

Photovoltaic electricity yield

- Our input is the solar radiation received, the solar resource
- We are using a technical system – i.e. the PV system – to convert light to useful electricity;
- Any technical system has physical limitations (module efficiency) and will create losses
- Our useful electricity is alternating current (in the case of grid-tied systems)

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



- Shading losses

- Temperature losses
- Soiling losses
- Wiring losses

- Inverter losses

- Energy delivered to the grid

Reasons for losses (simplified)

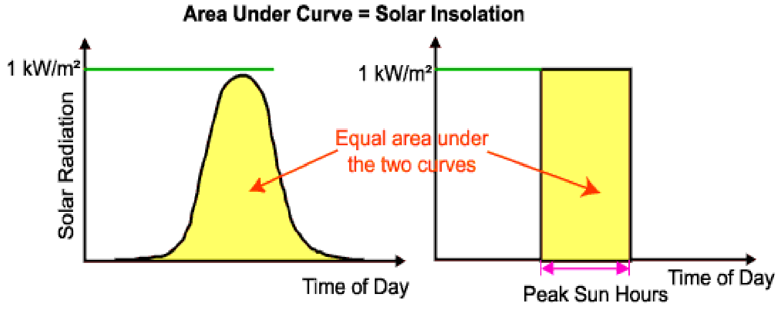
- Losses before module (Pre-conversion losses)
    - Module tolerance
    - Shadows
    - Dirt – 5 % - more than 20% in arid regions with little rain (maintenance dependent)
- Module losses due to deviation from standard conditions and temperature-related losses
- System Losses (~10-15%)
    - Wiring
    - Inverter
    - Transformer (if applicable)
- O&M downtimes
- Losses are added up and result in the so-called Performance Ratio (in %); PR is improving with technological development, currently: 75 - 85%

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} ?
  - Remember the 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

What is the capacity factor?

- The capacity factor of a PV plant is the ratio of its actual output over a period of time, to its potential hypothetical output if it were possible for it to operate at full nameplate capacity forever.
- Example:
    - PV plant: 1 MWp
    - Potential hypothetical output = 1 MWp x 8,760 h = 8,760 MWh
    - Actual output: 1,600 MWh/MWp
    - **Capacity factor**: 1,600 MWh/8,760 MWh **= 18.3%**

- Not to be confused with the capacity credit!

Worked example:

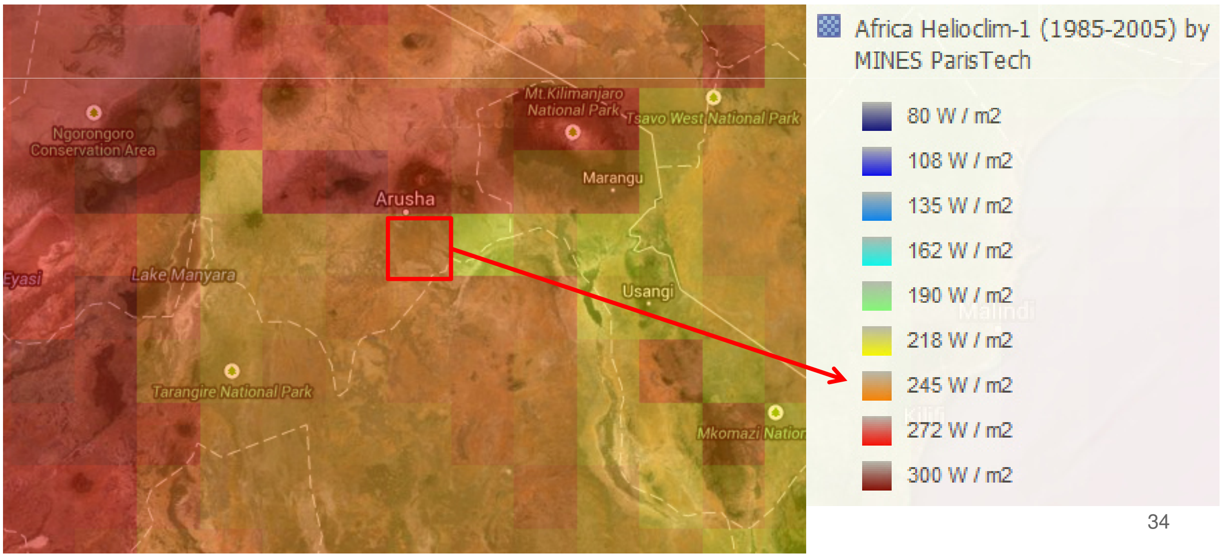
5. ESTIMATING PV CAPACITY AND YIELD AT A GIVEN SITE

PV energy yield estimation near Arusha

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

Retrieving global horizontal irradiation

- Daily average global horizontal irradiance of 245 W/m²
  → 8760h * 245 W/m² = 2,146 kWh/m²/a



Adjusting horizontal irradiation to irradiation on tilted plane

- Arusha is very close to the equator (latitude: 3°S); the theoretical optimum tilt angle is very close to 0° at this location. Since PV modules should never be placed flat, we choose a tilt angle of 15° in order to avoid too strong settlement of dust.
- Tilting the module ‘away’ from its optimum means that we have to adjust irradiation on the tilted plane.
- Online tools like PVGIS (http://re.jrc.ec.europa.eu/pvgis/) or professional database meteonorm produce 3% less irradiance per year on the tilted module plane (15°):

  2146 kWh/m²/a global horizontal irradiation – 3% = **2082 kWh/m²/a** (tilted module plane)

- **Note**: In locations which are located further away from the equator (approximately between 5°N and 5°S), tilting the modules to 15° or a higher optimal angle will produce solar irradiation **gains**.

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 = (2,082 kWh/m²/a) / (1,000 W/m²) = 2,082 h/a

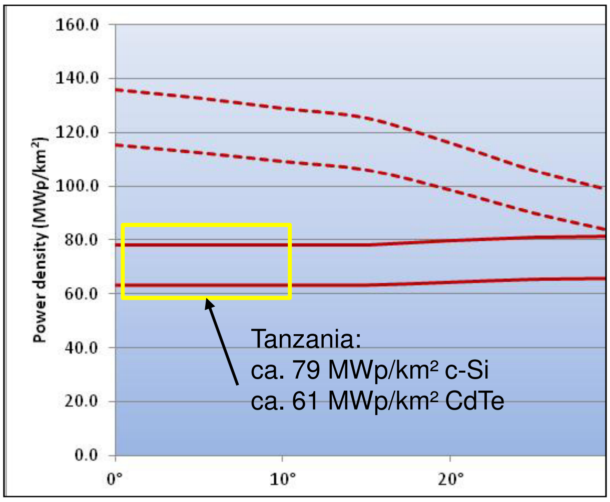
- Electricity yield estimation:
  - c-Si: 1kWp * 75% * 2,082 h/a = **1,562 kWh/kWp/a**
  - CdTe: 1kWp * 78% * 2,082 h/a = **1,624 kWh/kWp/a**

*PR: own estimates

Estimating energy per km^2 and capacity factor

- c-Si:
  - 79 MWp/km^2 * 1,562 MWh/MWp/a = **123 GWh/km^2/a**
- CdTe:
  - 61 MWp/km^2 * 1,624 MWh/MWp/a = **99 GWh/km^2/a**

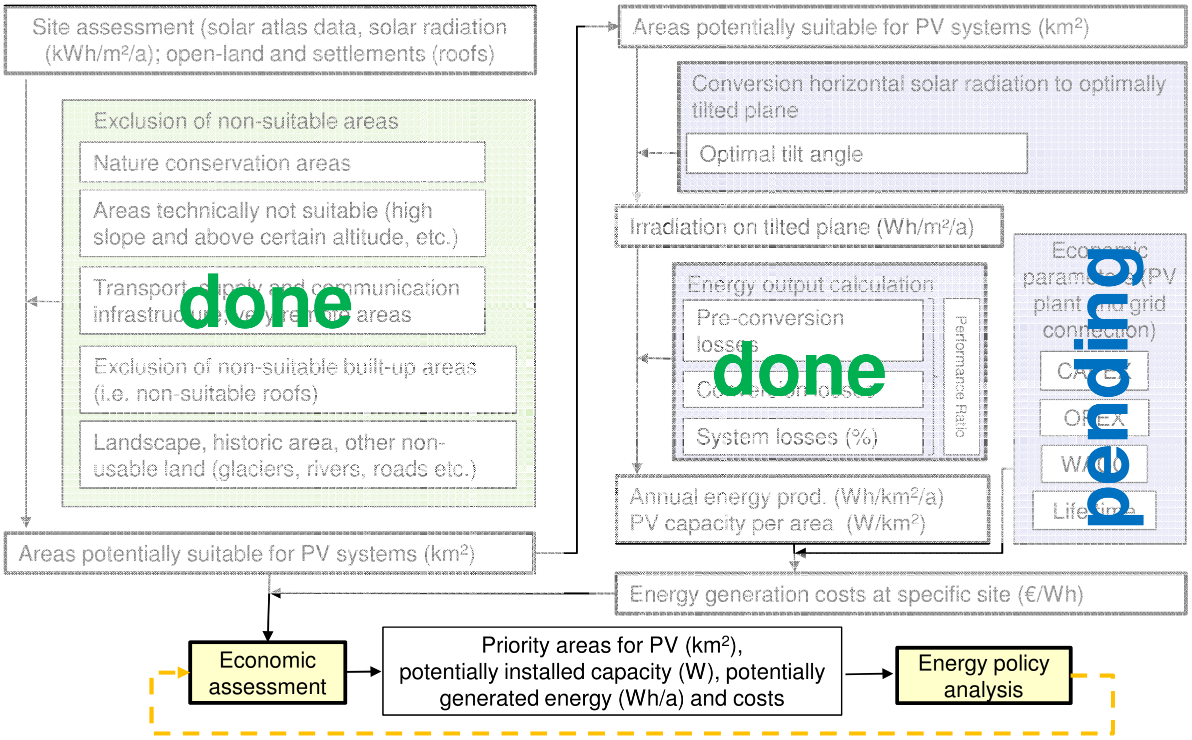
- Capacity factor: 1,562 MWh / 1 MWp = 1,562 h → 1,562 h / 8760 h = **17.8%**



Tanzania:
ca. 79 MWp/km^2 c-Si
ca. 61 MWp/km^2 CdTe

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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done

Areas potentially suitable for PV systems (km^2)

Conversion horizontal solar radiation to optimally tilted plane

Optimal tilt angle

Irradiation on tilted plane ($Wh/m^2/a$)

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done

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6. PECULIARITIES IN OFF-GRID APPLICATIONS

Off-grid solutions will play an important role.

- In view of low electrification rates, economic and population growth, and large geographic areas with dispersed population, IEA has estimated that 60% of the additional generation capacity to be installed by 2030 will be off-grid.

- **Technical solutions:**
  - Small off-grid: Individual **Solar Home Systems** / **Pico Systems**
  - **Mini-grids**: A mini-grid is a power system where produced electricity is fed into a small distribution network that provides a number of end-users with electricity in their premises. Mini-grids are typically less than 1 MW in capacity and utilize diesel, renewable (+storage) or hybrid (combined) fuel sources to produce electricity.

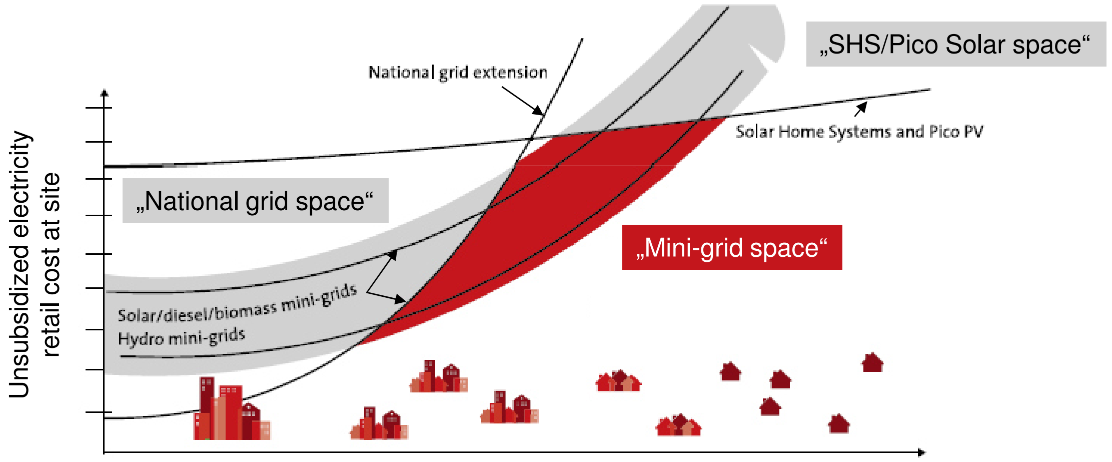
Source: Mini-grid Policy Toolkit, October 2014, African-EU RECP

Small hybrid (PV-Diesel-Battery) Mini-grid system

China (Yunnan province)

Picture:Lars Koerner

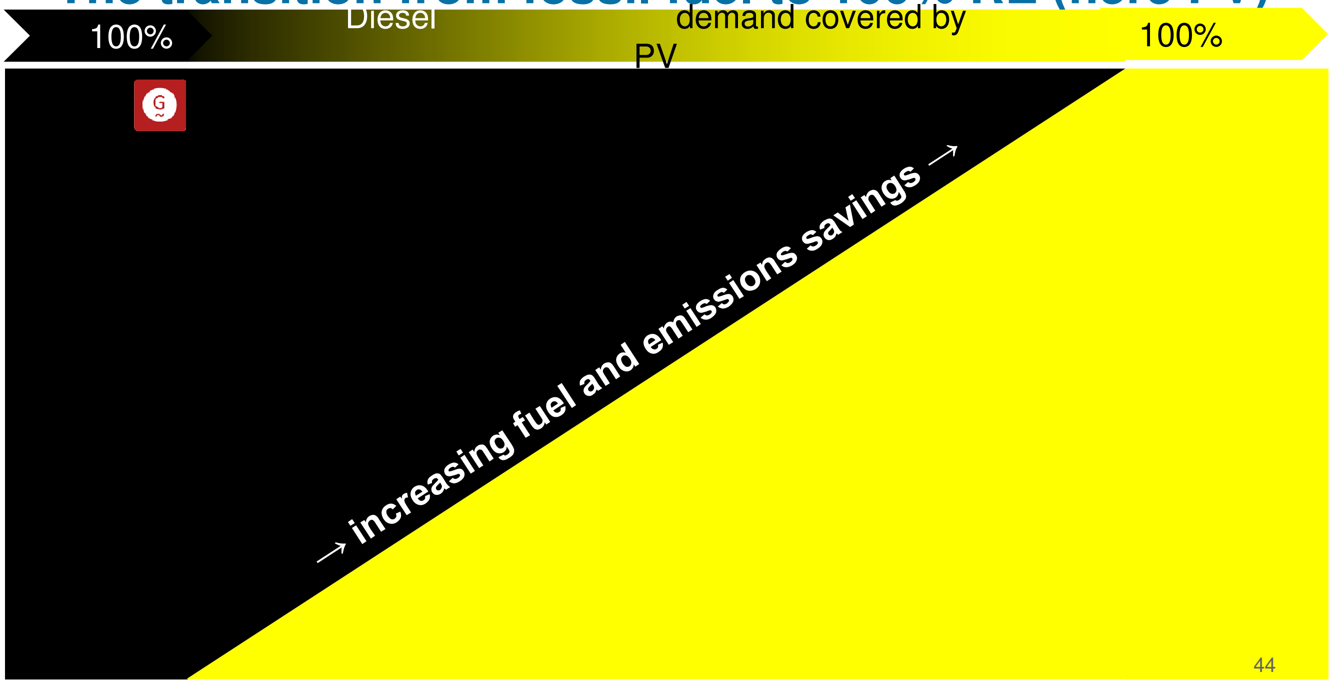
Where can off-grid solutions play a role?



Large……………………………………Size of community………………………………..Small
High……………………………………Density of population………………………………Low
Close………………………………......Distance to national grid……………………………..Far
Easy…………………………………....Complexity of terrain……………………………Complex
Strong……………………………….....Economic strength………………………………Weak

Source: Adapted from INENSUS
(taken from the Mini-grid Policy Toolkit, Oct. 2014, African-EU RECP)

The transition from fossil fuel to 100% RE (here PV)

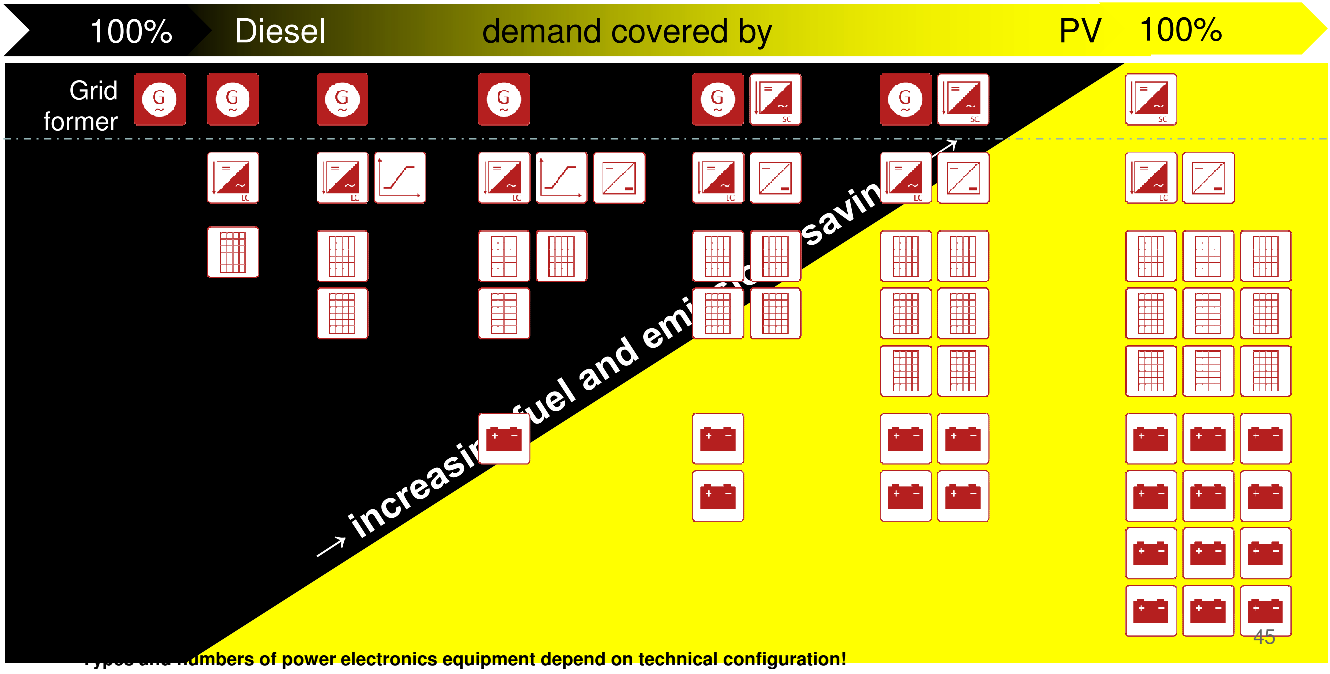


100% Diesel

demand covered by PV 100%

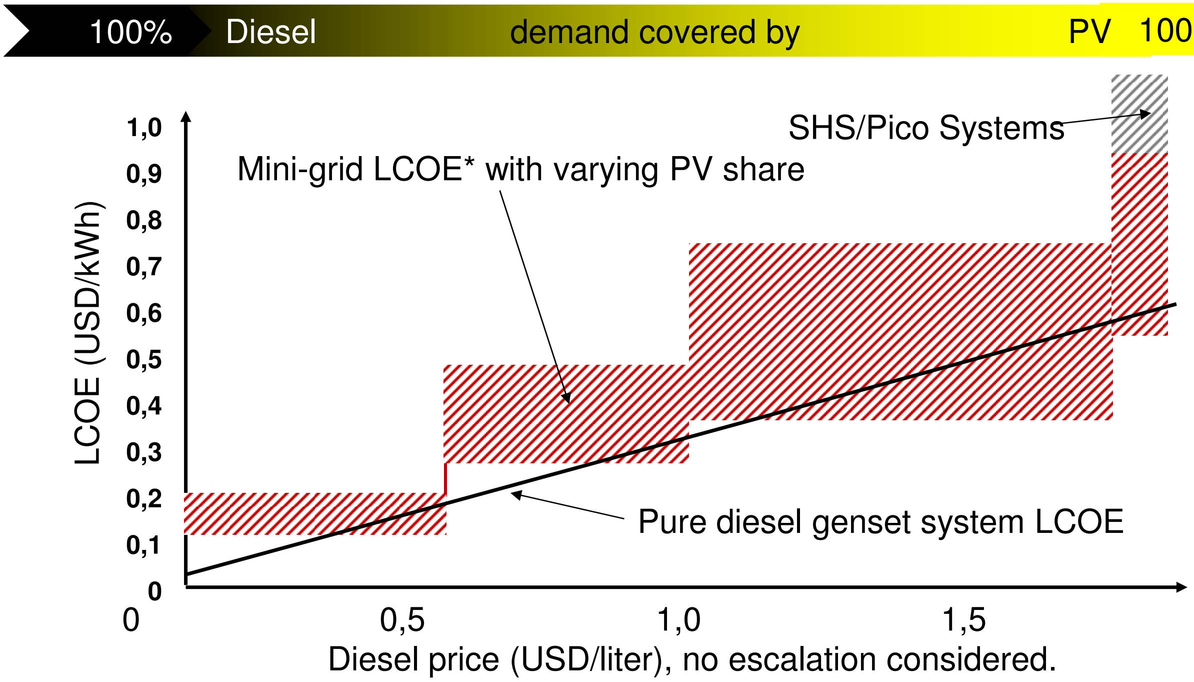
→ increasing fuel and emissions savings →

Complexity increases.



Types and numbers of power electronics equipment depend on technical configuration!

LCOE increases.



Source: RENAC Research 2014

*LCOE span might vary more for some markets.

Know your CAPEX leverage!

Increasing quality standards are required as power quality and energy supply depend increasingly on the PV system alone.

Do not try to cut down on CAPEX by lowering quality standards!

Instead implement energy efficiency measures on the demand side (DSM)!

The biggest challenge in rural electrification is..

- ...NOT the technology (if you have achieved certain quality standards) but the **management and operation of the system!**

- Involve the community.
- Know and manage the risks and be honest in your judgement.
- Be prepared to be on your own!
- Implement clear processes with clear responsibilities assigned to real persons/teams/companies.
- Manage accounts thoroughly.
- Avoid conflicts of interests.
- Avoid staff fluctuation.

Solar panels damaged by members from a neighboring community.
„They weren't electrified, too!"

Picture: Lars Koerner

What happens if the national grid arrives?

- New power generation sources will change or even threaten the business plan for off-grid rural electrification.
- Such risks need to be governed in the policy framework.
- A rural electrification masterplan must be developed, implemented and followed (Kenya example).
- As usual: No reliable policy framework → no investors.

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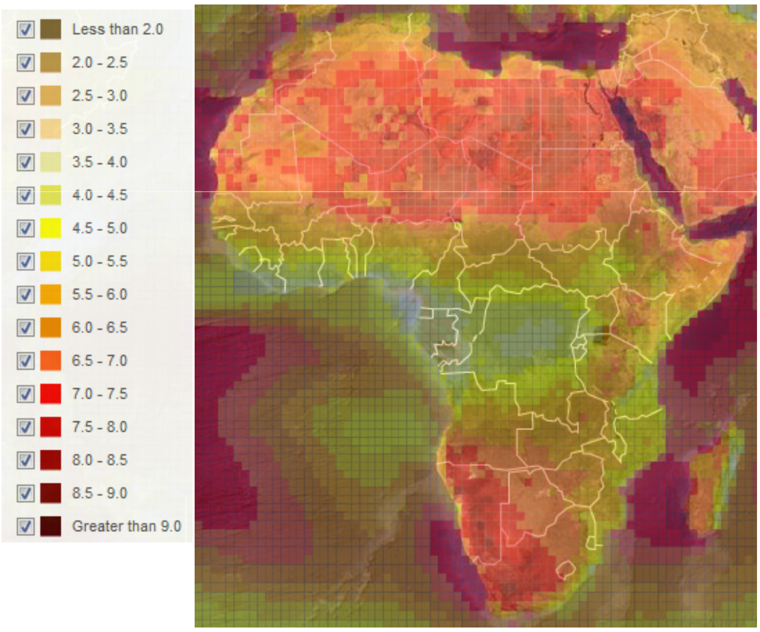
7. A FEW WORDS ON CSP

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

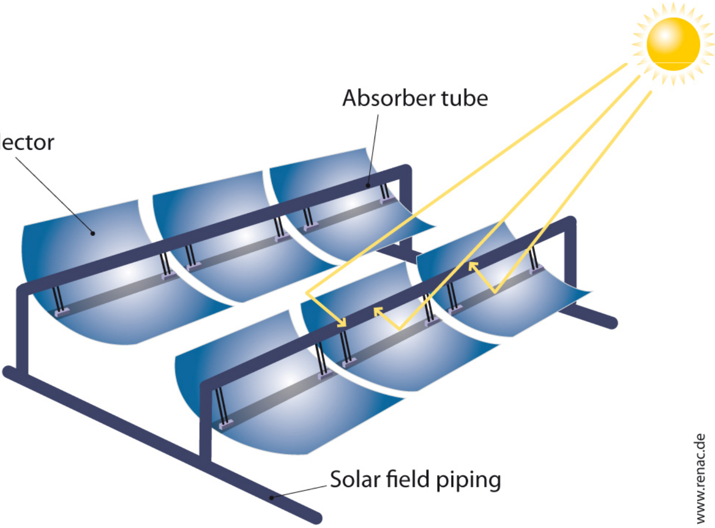
Parabolic trough power plant

- Operating temperature: 300°C to 500°C
- 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!

Photo: Solar Energy Generating System SEGS, California

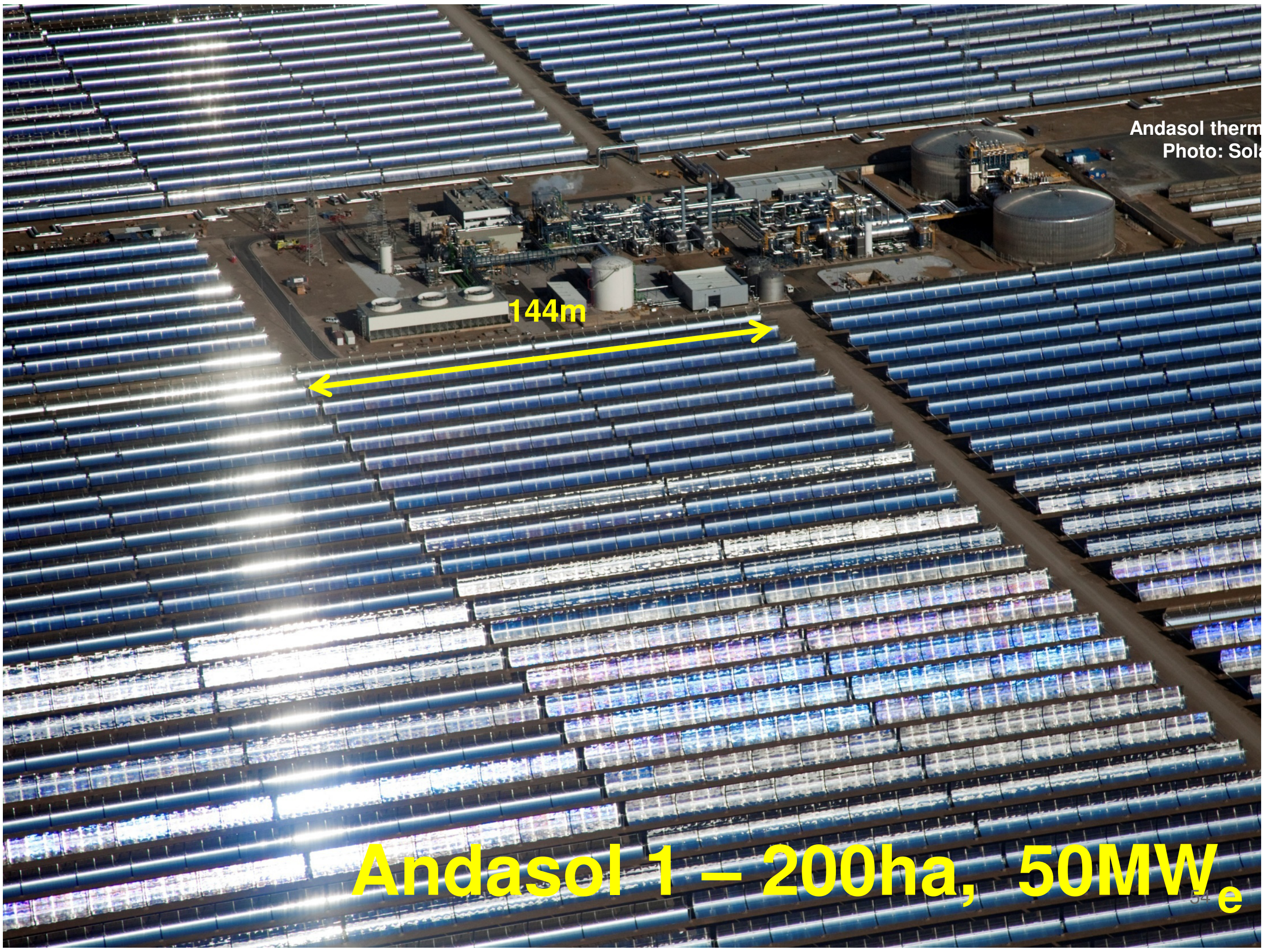
Parabolic trough collector - principle

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



© www.renac.de

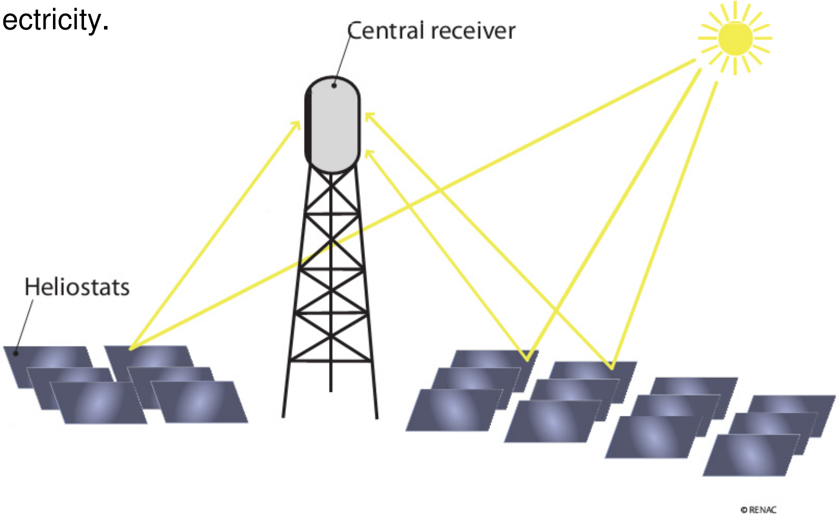
Graph: RENAC



Andasol 1 – 200ha, $50MW_e$

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

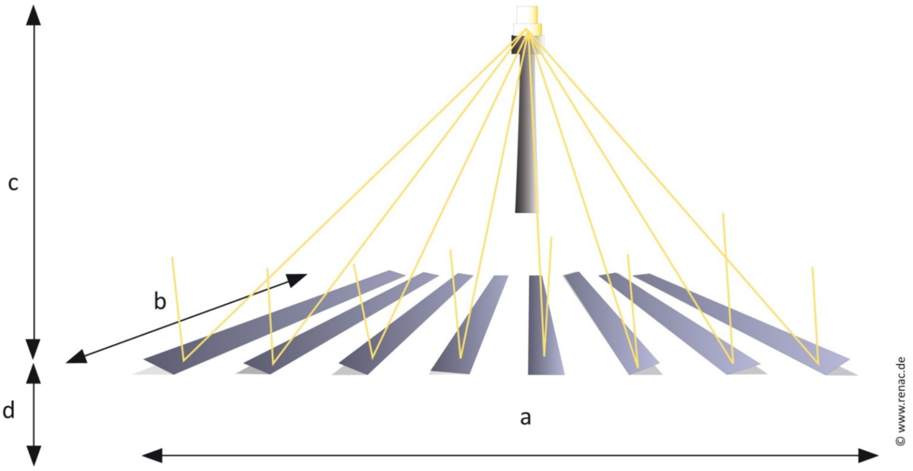
PS10 – 55ha, 11MW_e

Planta Solar 20 - Seville, Spain Source: Abengoa

PS20 – 80ha, 20MW_e

Linear Fresnel power plant

- Operation as for parabolic troughs.
- A series of mirror strips form a parabola shape. Low cost manufacturing.
- The mirror strips track the sun to optimise solar concentration onto receiver tube.
- Achieve lower temperatures. Suited to industrial heating applications.



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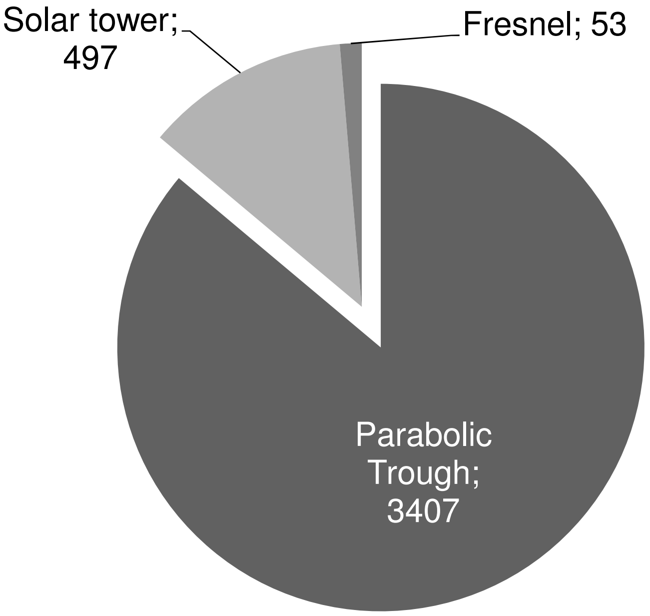
Puerto Errado 1- Murcia, Spain Source: Novatec

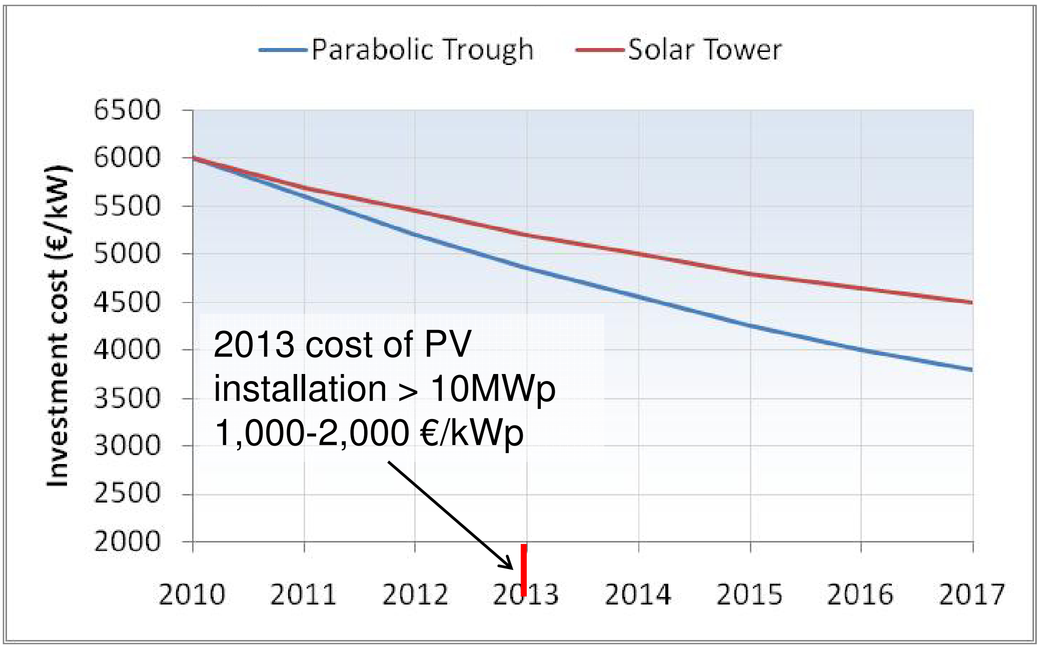
PE1 – 7ha, 1.4MW$_e$

CSP market



Source: CSP Today Global Tracker; as of April 2014

CSP Plants – Costs and cost trends



2013 cost of PV installation > 10MWp 1,000-2,000 €/kWp

Source: IRENA_CSP Cost Analysis, June 2012

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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