Photovoltaic Energy Introduction

ESMAP—SAR—EAP RENEWABLE ENERGY TRAINING
APRIL 23-25, 2014 THAILAND

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About the tutor

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- Degree in Industrial Engineering and Business Administration
- 4 years project manager with the German Energy Agency, focussing on solar technology; managed solar lighthouse projects abroad, did market research on foreign markets and co-ordinated the EU consortium ‘PV Policy Group’
- Since March 2009 scientific coordinator, lecturer and project director for RENAC’s solar training programmes:
  - Coordinates and develops the Masters Program Global Production Engineering in Solar Technology (GPE Solar) in cooperation with the Technical University Berlin
  - Teaches photovoltaic engineering, solar project financing and energy economics
  - Consults electric utilities, NGOs, national energy agencies a.o. on the development of own solar training activities
  - Author of technical studies about PV power plant design and grid integration of photovoltaics

Agenda (I)

5. Technology overview
   - The solar resource
   - Fundamentals of PV technology
   - Description of PV technologies: crystalline silicon and thin film (a-Si, CIGS, and CdTe)
   - Typical PV applications and components of grid-tied PV systems
   - Performance modelling and estimating the yield of a grid-tied PV power plant
6. Project planning and implementation
   - Overview on project phases
   - Solar resource assessment and site analysis
   - Engineering & construction
   - Testing and certification
   - Operation, maintenance and monitoring.

AGENDA

Agenda (II)

7. Financial modeling
   - Life-cycle cost analysis and LCOE evolution
   - Risk management; bankability of PV projects
8. Overview on off-grid photovoltaics
9. Introduction to Concentrating Solar Power (CSP)

AGENDA

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5 Technology overview
The solar resource

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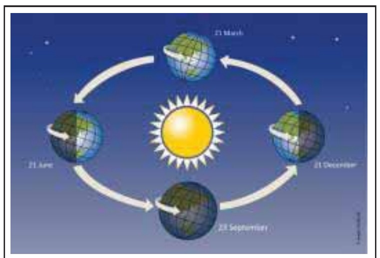
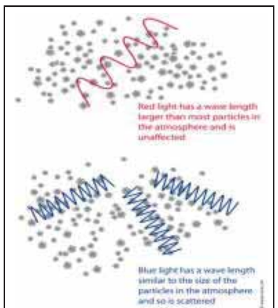
Solar radiation

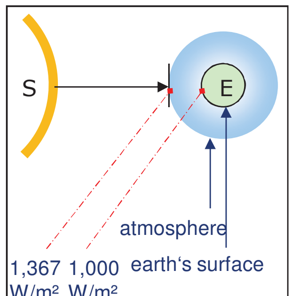
Solar constant E=1367 W/m²	Reflection, absorption	1000 W/m²	Annual Irradiation kWh/m²



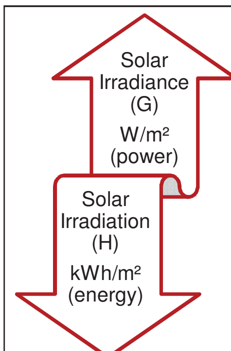
- The intensity of solar radiation outside the atmosphere depends upon the distance between the sun and the Earth
- The average value is referred as solar constant (1,367 W/m²)



- The Earth's atmosphere reduces the insolation through reflection, absorption and scattering



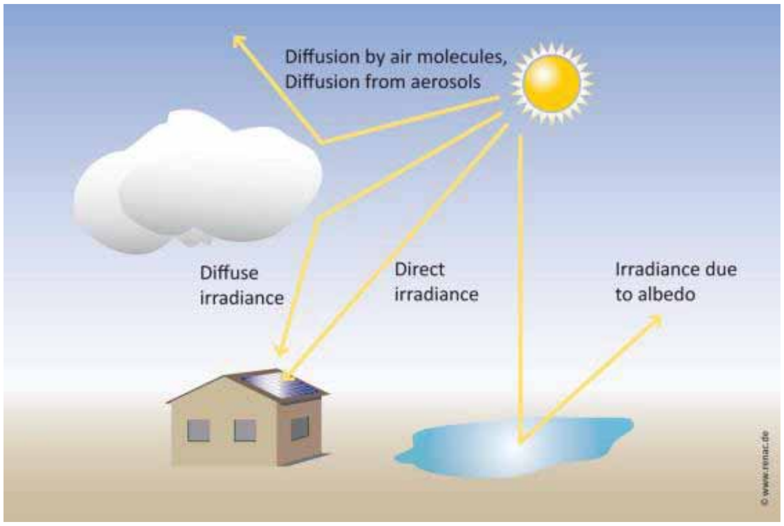
- In good weather at noon, irradiance reaches 1,000 W/m²



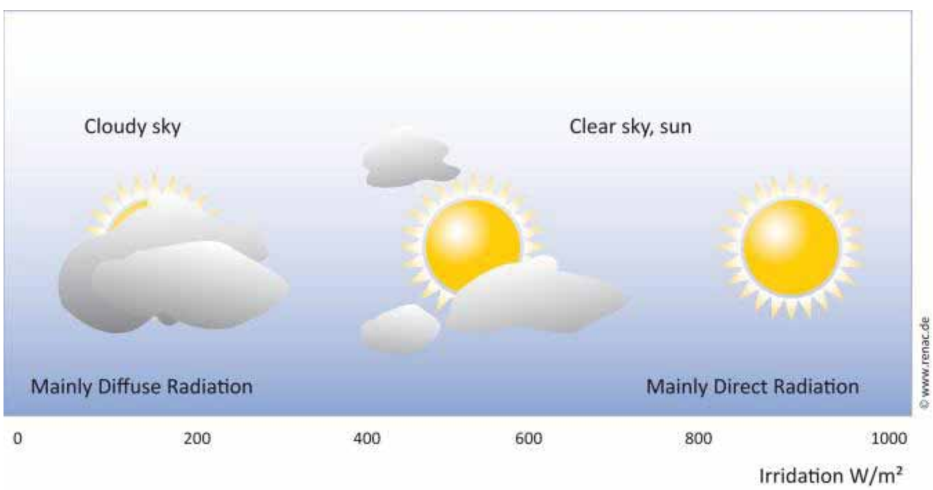
- If the energy content of solar irradiation is added up over a year, this gives the annual global radiation in kWh/m2

Correlation of irradiation and weather

- Global radiation is composed of:
  - direct radiation (coming directly from sun, casting shadows)
  - Diffuse radiation (scattered, without clear direction) and
  - Reflected radiation



- Depending upon the cloud conditions and the time of the day, both,
  - irradiation power and
  - proportion of direct and diffuse radiation can vary greatly



Global horizontal irradiation and irradiation on the tilted plane

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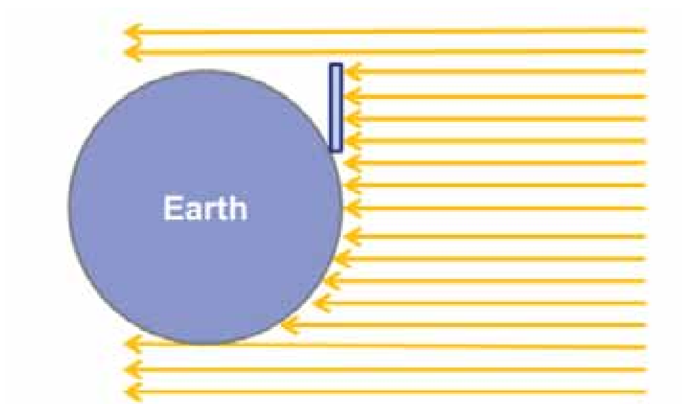
- Irradiation data is usually provided as global horizontal irradiation (GHI)
- If moving away from the equator, more irradiation can be received by tilting solar modules



Graph: RENAC

Sun path varies during a year

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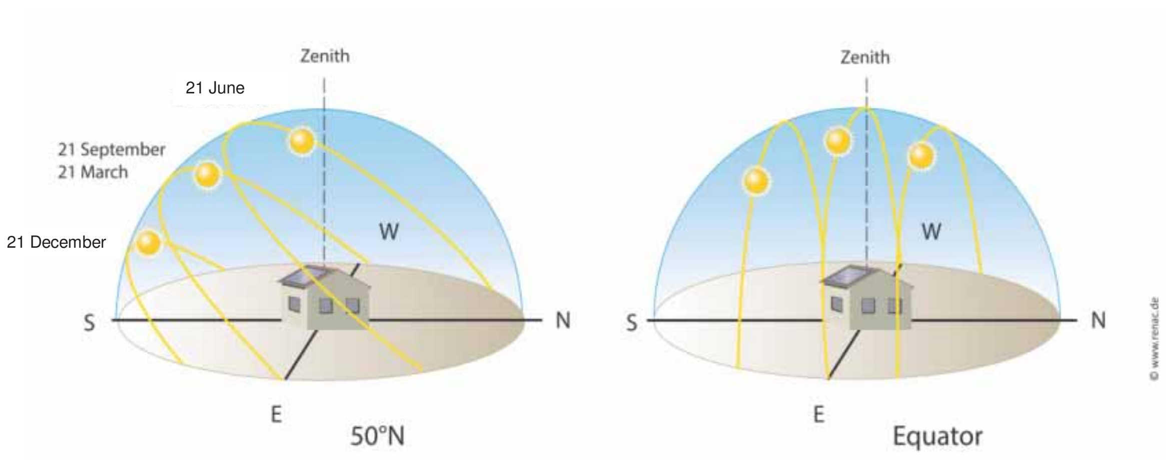
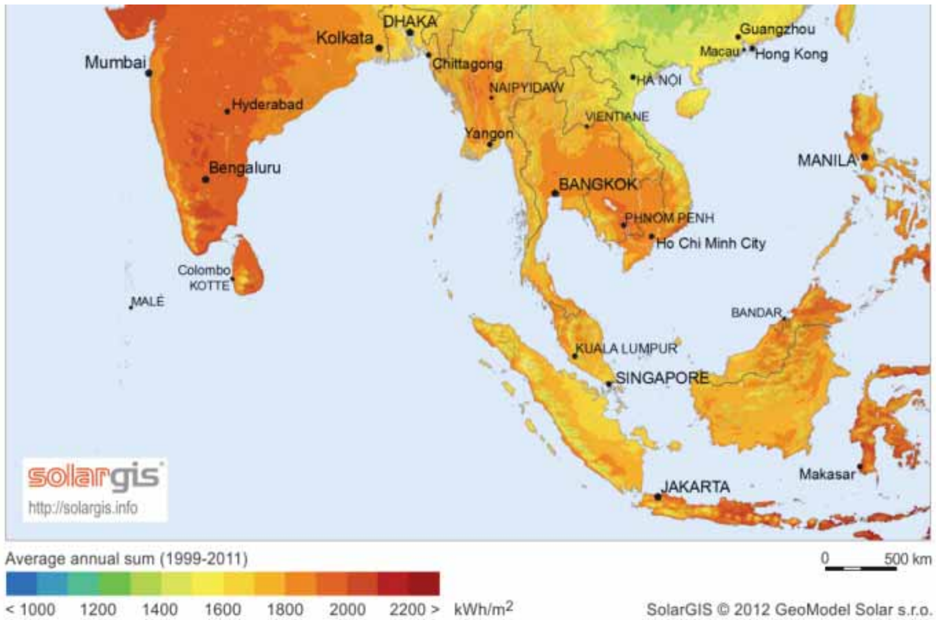
- Rule of thumb:
  Tilt angle against the horizontal = Latitude of the PV generator’s position
- **Attention**: PV modules should have a minimum tilt angle of 10-15° to avoid settlement of dirt



Graph: RENAC, indicative only

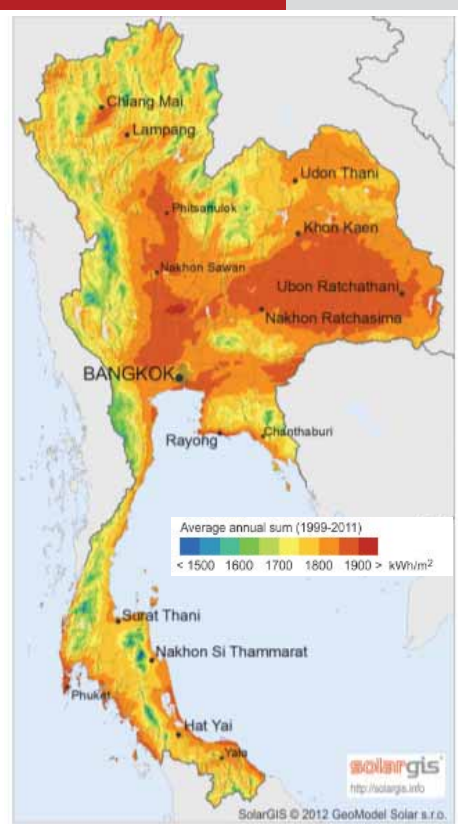
Global horizontal irradiation in South and Southeast Asia

- Color-coded maps show how irradiation is distributed in a certain area
- Data is usually provided as average global sum in kWh/m²



Global horizontal irradiation in Thailand

- In Thailand global horizontal irradiance widely exceeds 1,600 kWh/m² and reaches up to 2,000 kWh/m²
- Depending on the module technology a grid-tied PV plant in Bangkok could produce between 1,250 and 1,450 kWh electricity [1)] per annum
  other areas could produce higher or lower electricity output



Source: Irradiation map: http://solargis.info
1) Assumption: tilt angle: 15°, orientation: South
values calculated on http://valentin.de/calculation/pvonline/pv_system/

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5 Technology overview Fundamentals of PV technology

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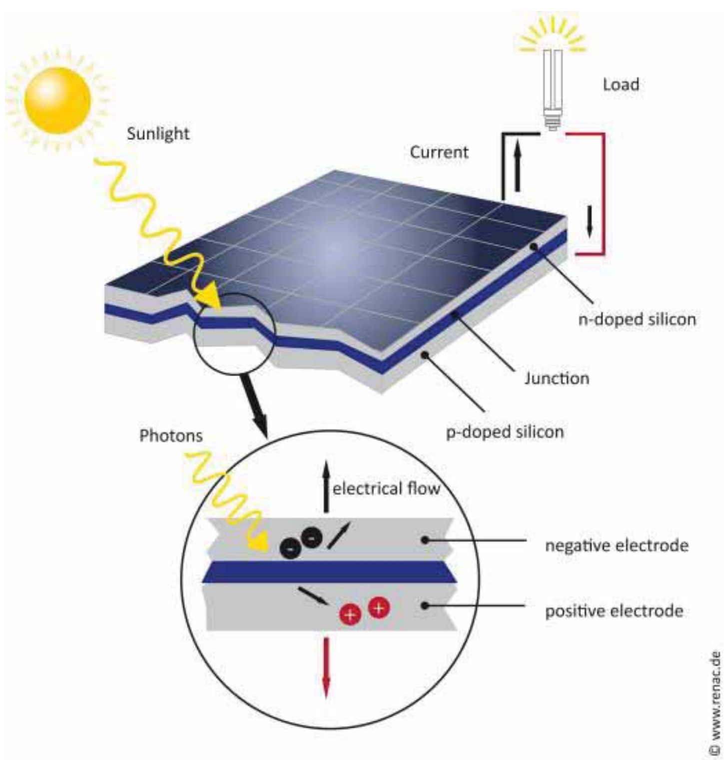
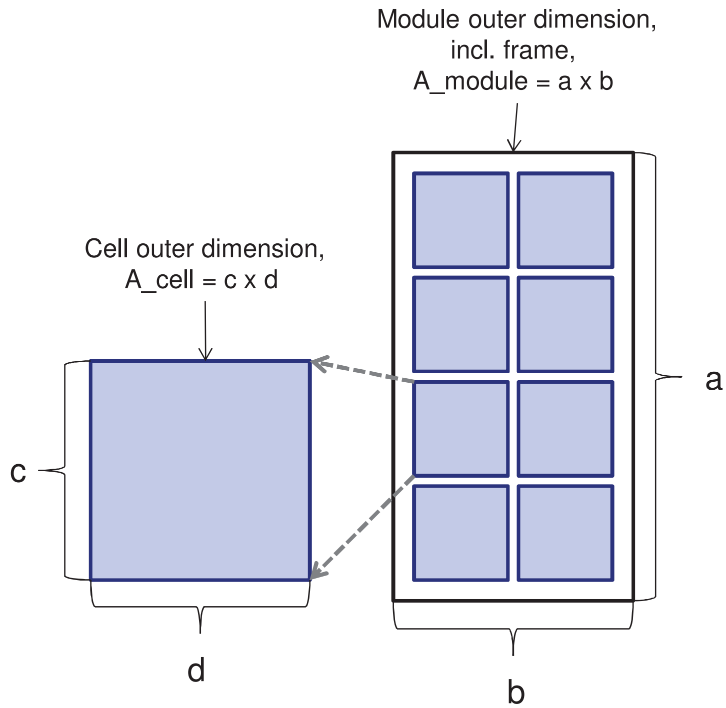
The photovoltaic effect



Cell and module efficiency

- Both efficiencies are measured under Standard Test Conditions STC (25°C, 1000 W/m², AM: 1.5)
- Cell efficiency refers to a single cell's surface only
- Module efficiency refers to the outer dimensions of the complete module AND considers all module related losses (e.g. ohmic losses, losses through the glass cover etc.)
- Cell eff. > Module eff.



Graph: RENAC

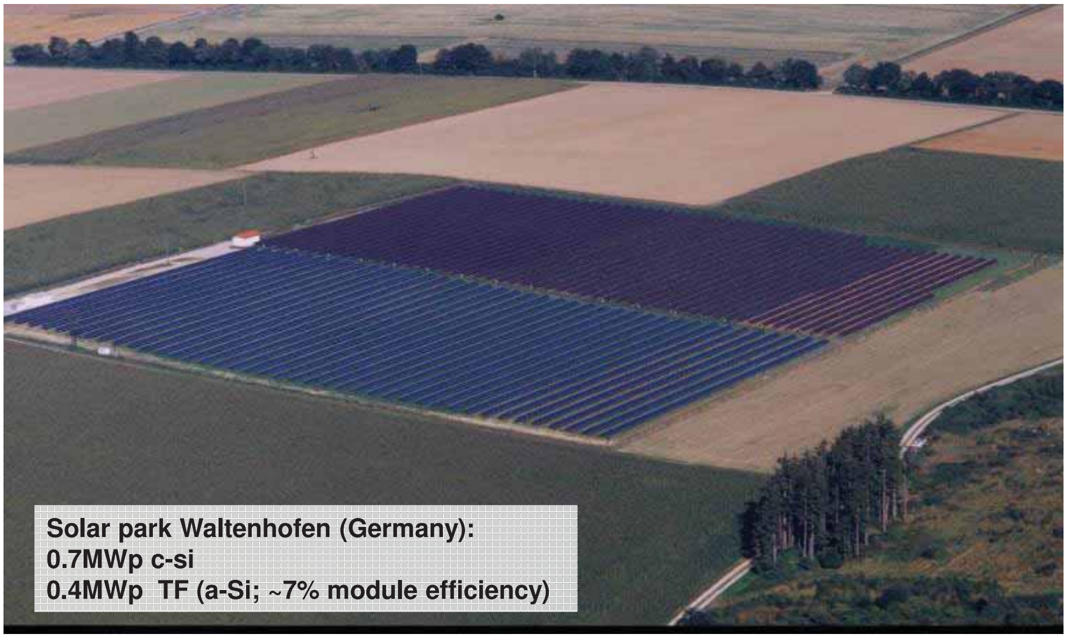
Module efficiencies and surface area need of typical solar cell materials

Cell material	Module Efficiency (serial production)	Surface area need for 1 kWp [m²]
High performance monocrystalline silicon (Si)	20.0%	5.0
Hybrid Si cell (HIT - Hetero-junction w. Intrinsic Thin Layer)	16.8%	6.0
Monocrystalline silicon	15.5%	6.5
Polycrystalline silicon	15.0%	6.7
CIS (Copper-Indium-Diselenide)	11.0%	9.1
CdTe (Cadmium-Telluride)	10.4%	9.6

- The lower the efficiency, the more space is needed to produce the same amount of energy under the same conditions

Source: Data: Deutsche Gesellschaft für Sonnenenergie DGS e.V.: Leitfaden Photovoltaische Anlagen, 2012; Graph: RENAC

Area needs c-si versus thin-film



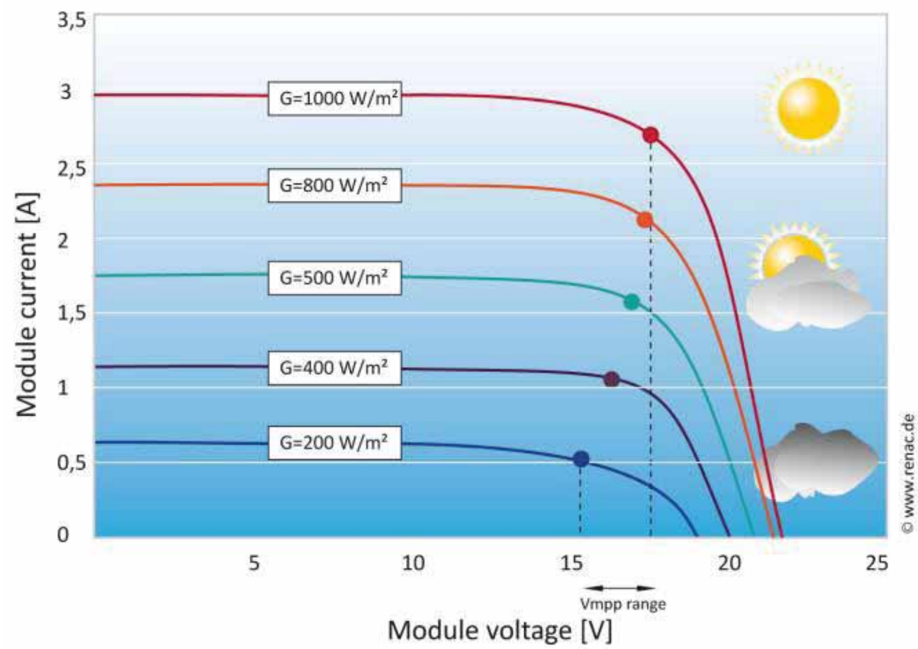
Power of a PV module

- Like efficiency, of course, power output of a PV module depends on cell material, temperature and irradiance

Power P in [W] = Current I in [A] x Voltage U in [V]

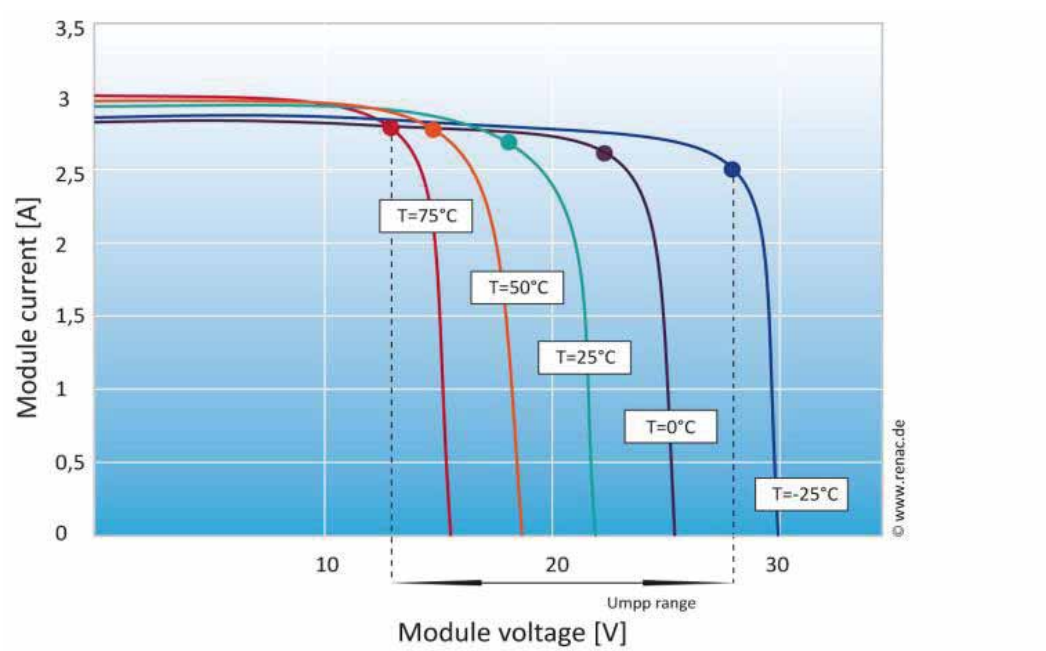
- Nominal (name plate) power is always measured under the internationally acknowledged Standard Test Conditions (STC):
  - Cell temperature: 25°C
  - Irradiance: 1000 W/m²
  - Air Mass: 1.5

Effect of light intensity on the electrical characteristics of PV modules



- Module current is proportional to irradiation E

Effect of temperature on the electrical characteristics of PV modules



- T is the cell temperature and not ambient temperature renac renewables academy

5 Technology overview Crystalline silicon and thin film PV

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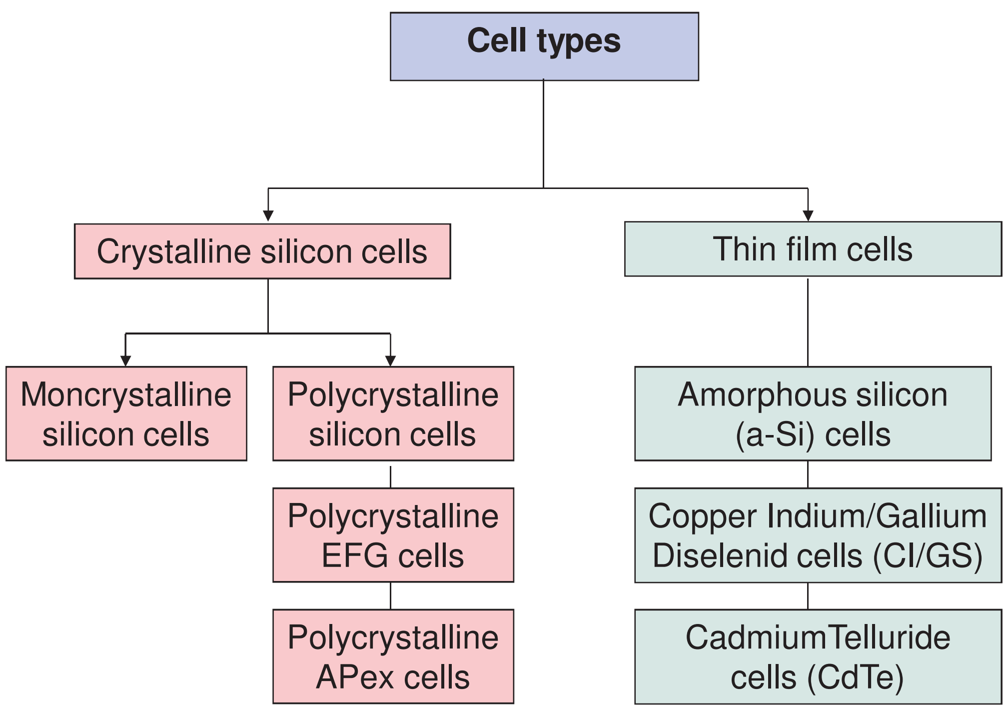
Main cell types



Source: solid GmbH

Main commercially available PV module technologies

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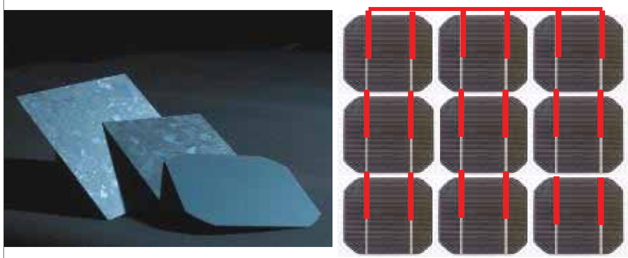
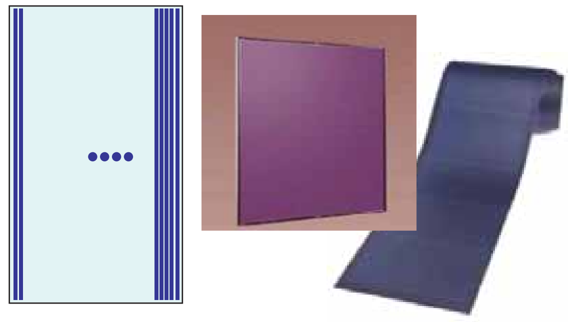
Silicon wafers



- Silicon wafers are processed and the obtained solar cells are connected in series
- Current module efficiencies: 14-21%
- Proven technology: global PV production in 2011 circa 33GW
- Potential for low cost high efficiency (20 - 25%)

Thin-film



- Depositions on large area substrates and "monolithic series integration" of the cells (typically by lasering)
- Current module efficiency 8-16%
- Emerging technology: global TF production in 2011 approx. 5GW
- Potential for ultra-low cost and medium efficiency (14-20%) but market share currently decreasing

Comparison of Si-wafer based and thin film modules

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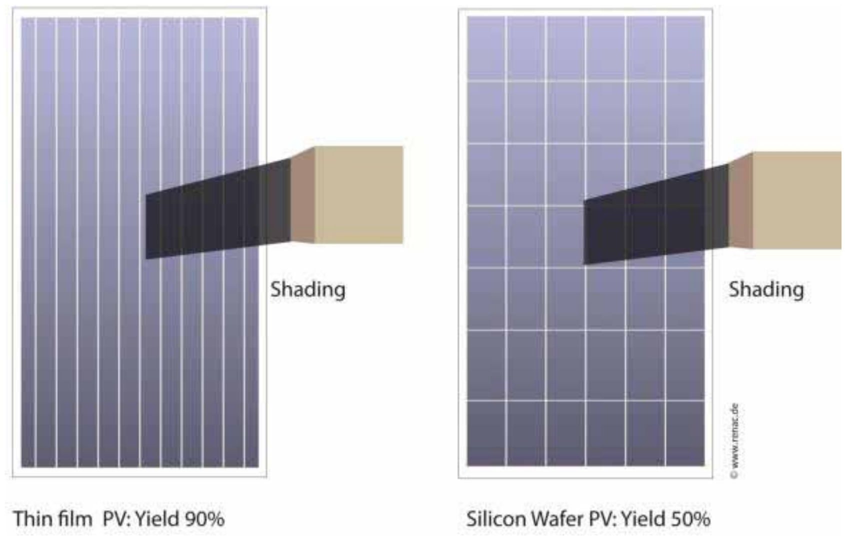
Characteristic	Mono-/ poly Si wafer based	a-Si thin film	CIS thin film	CdTe thin film
Module efficiency	15 – 21% / 13 – 20%	5 – 7%	9 - 11%	7 - 10.4%
Power temperature coefficient (STC)	-0.30 to -0.38 / -0.37 to -0.52 %/K	-0.1 to -0.29 %/K	-0.35 to -0.4 %/K	-0.25 to -0.36 %/K

Sources: Deutsche Gesellschaft für Sonnenenergie DGS e.V.: Leitfaden Photovoltaische Anlagen, 2012;

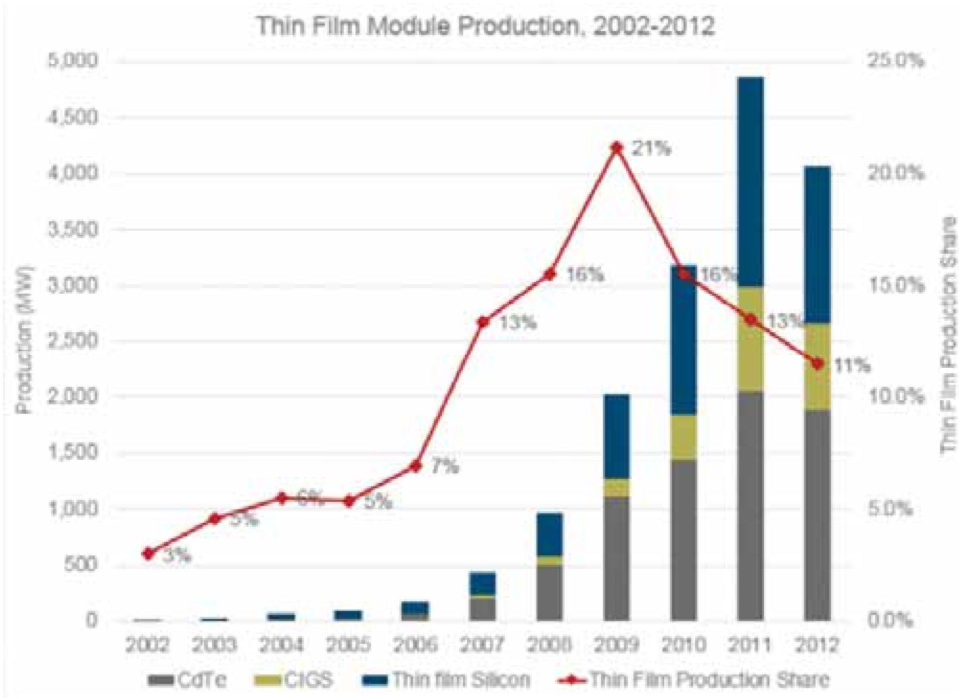
Advantage of thin film modules in case of shading



Comparison thin-film and Si-wafer based PV

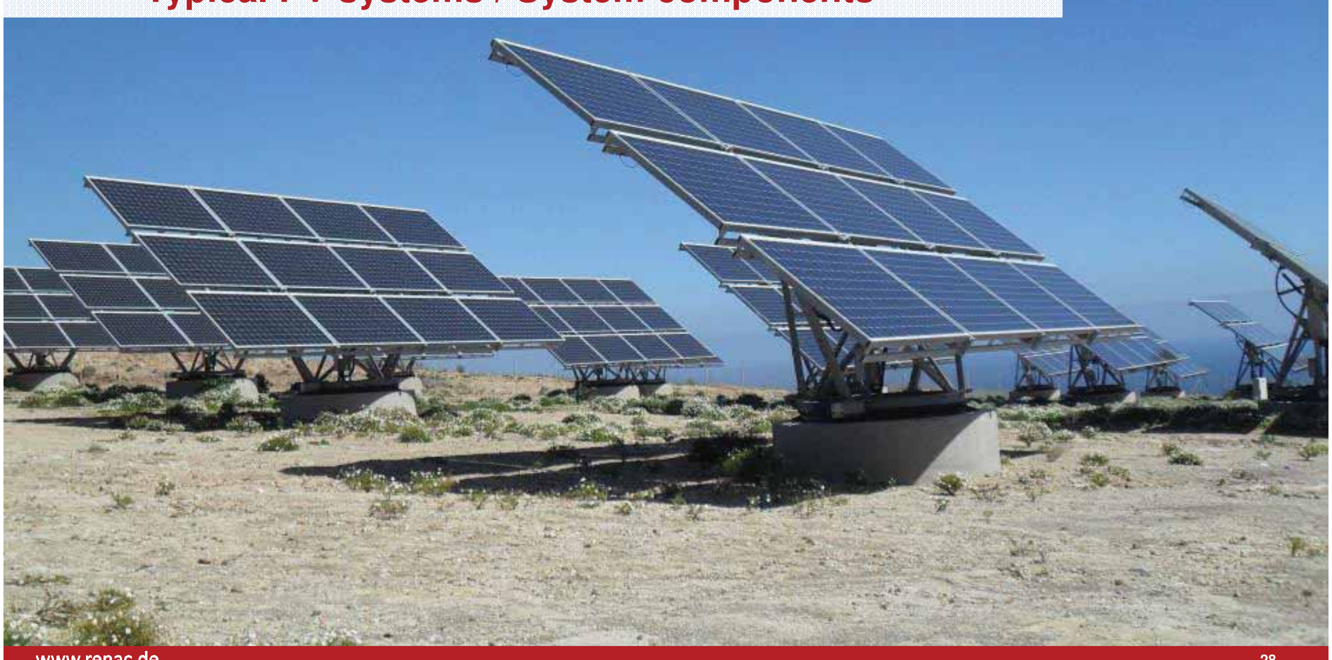
- Thin-film generally with lower efficiency than Si-wafer based PV
- Thin-film usually less temperature sensitive than Si-wafer based
- Thin-film can have lower losses in diffuse radiation or shaded conditions
- Thin-film is the technology being developed more recently and not yet "proven" in all conditions
- Thin-film can be cheaper (less material needed) but more surface is needed thus bigger mounting structure and more space

Thin film module production 2002-2012



Source: Online: http://www.greentechmedia.com/articles/read/Yingli-Gains-Crown-As-Top-Producer-in-a-36-GW-Global-PV-Market; retrieved on 2 April 2014

5 Technology overview
Typical PV systems / System components



Grid-tied PV systems on domestic properties

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- Especially suitable for densely populated areas
- Proximity to electricity consumption
- Typically 1 – several kW

PV array on suburban house in Germany
Photo: SMA Solar Technology AG

Grid-tied PV systems on non-domestic properties

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- Can often be found on industrial flat roofs with large area
- Statics of the building to be taken into account
- Covering peak loads also an option
- Up to hundreds of kW

Grid-tied PV systems as 'solar power stations'

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- Economies of scale
- Power suppliers' interest on the rise
- Free-standing mounting
- MW's
- Germany
  - Old airfields
  - Arrays sold off as investments

www.schletter.de

Components of PV systems

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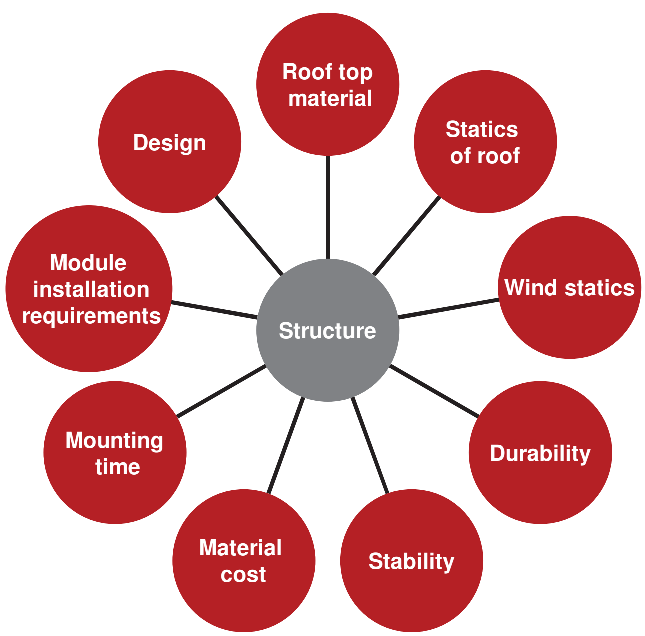
Module ⇔ Structure ⇒ Inverter ⇔ Monitoring /Power M. ⇒ Transformer ⇒ Grid Connection

Standard support rack

- A support rack is a standardized mounted system that will be replicated many times in a large scale plant
- Racks are composed of
  - PV modules interconnected in series/parallel
  - Junction box
  - Standard mounting structure
    - Typically hot dipped galvanized steel – in marine conditions 316 stainless steel is used
    - Aluminum is 3-times lighter, but also expensive
    - Connections bolted

Source: Schletter

Choice of mounting structure



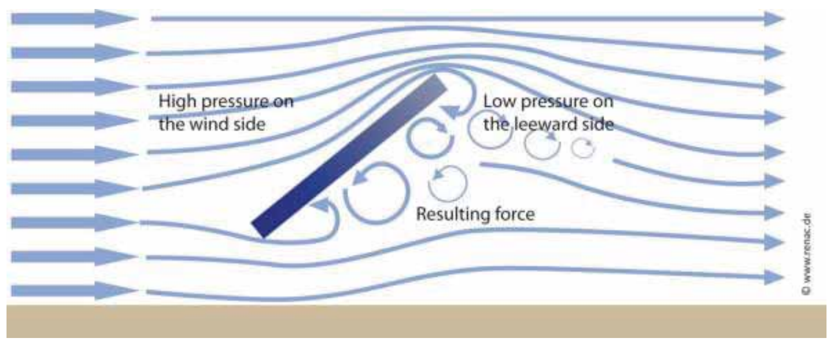
Static calculation and Wind loads!

- Wind causes high pressure on the front side of the PV module, whereas low pressure is created at the near side due to recirculation current
- According to DIN 1055-4 the wind load depends on the shape of a module and wind's velocity. The wind force is then calculated with $F_w = C_f \cdot v \cdot A$

C_f = aerodynamical coefficient (1,26 for vertical, 1,2 for tilted modules)

V = wind's velocity

A = reference area



Graph: RENAC

Ground mounted PV systems - Structure

Source: www.schletter.de

Factory-made mounting structures

- Fixed either with concrete or with steel profiles

Source: Left: Array Solar; right: Schletter GmbH

Mounting on a flat roof without penetration

- Avoiding roof penetration reduces humidity penetration issues
- Common PV array tilting angles in Thailand (between 10° and 20°) produce significant uplift forces => it is recommended to use wind shields on the back of the array rows in order to reduce depression loads

Source: www.prweb.com

Mounting on a flat roof without structural binding

- Flat roof mounting

Weight!

Disadvantage: At wind speed above 150 km/h the mounting systems could move or tip over!

Source: 2010 SchaefferTC for RENAC

Mounting on a flat roof with structural binding

- Flat roof mounting

Advantage: At wind speed above 150 km/h the mounting systems could not move or tip over!
Disadvantage: Panels may increase potential for roof damage during strong winds.

No Weight!

Source: 2010 Oekogeno / Schaeffer

Fixing methods for different roof coverings

- Flat roof mounting

Profiled sheeting

Plate fold clamps

Source: www.schletter.de

Grid-tied inverters definition

- Inverters convert DC electricity from the PV array to AC electricity suitable for feeding into the grid

Photo: RENAC (Grid-tied inverters on the roof of Berlin water treatment plant)

Main inverter types

String inverter

- 1 – 10 kW
- 1-2 MPP tracker
- efficiency 96-98%
- 1 phase

Mini central inverter

- 10 – 30 kWp
- Multi MPP
- efficiency 97%
- 3 phases

Central inverter

- 30 – 1.200 kWp
- 1 MPP tracker
- efficiency 97%
- 3 phases

Source: SMA

Important inverter manufacturers

SMA

REFU Elektronik

Fronius

LTi REENERGY

KACO new energy

Satcon

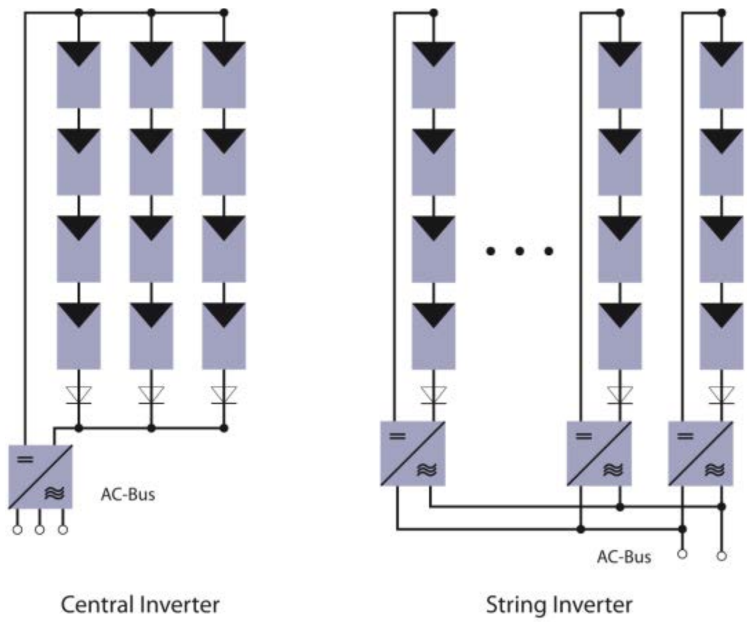
CONERGY

KOSTAL

SolarMax by Sputnik Engineering

sunways Photovoltaic Technology

Central and string inverter concepts



Graph: RENAC

String vs. central inverter: Installation

	String Inverter
	Installation
+	Flexible design: Single phase and three phase inverter
+	Shadowing effects easy to minimize
+	1 inverter: Quick installation (behind the modules) No transmission station
-	Hundreds of inverter: Complex installation **Higher installation costs**
+	**Low inverter prices** due to high production volume
+	String monitoring included
+	No additional junction box needed
?	Smaller DC losses (according to wire cross section)
?	A lot of MPP Tracker

	Central Inverter
	Installation
+	Three phases inverter, fix design
-	Shadows not easy to minimize
-	Transmission station
+	**Lower installation costs**
-	**Higher inverter prices** due to low production volume
-	String monitoring in addition
-	Generation junction box in addition
?	Higher DC losses (according to wire cross section)
?	Only several MPP Tracker

String vs. central inverter: Installation

	String Inverter
	Operation
+	**Easy maintenance and exchange of inverter**
+	No warranty contract with the inverter company necessary
?	Faults: If one inverter drops out, a small part of the PV array is involved, but the probability of a fault is higher

	Central Inverter
	Operation
-	**Maintenance and exchange of inverter more complex**
-	Warranty contract with the inverter company necessary
?	Faults: If one inverter drops out, a big part of the PV array is involved, but the probability of a fault is very small

5 Technology overview
Performance modelling and yield estimation

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)

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
- The losses are added up and result in the so-called Performance Ratio (in %); PR is improving with technological development, currently: 75 - 80%

Losses in a PV system (example)

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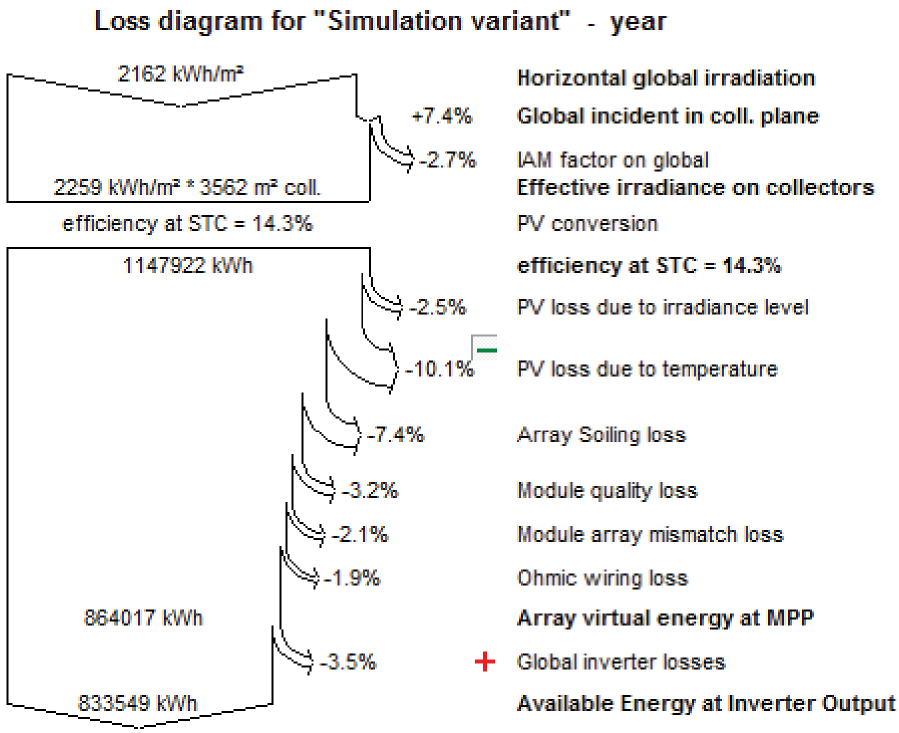

Source: Loss diagram produced with simulation software PVSyst

Estimating PV plant electricity yield

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- 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

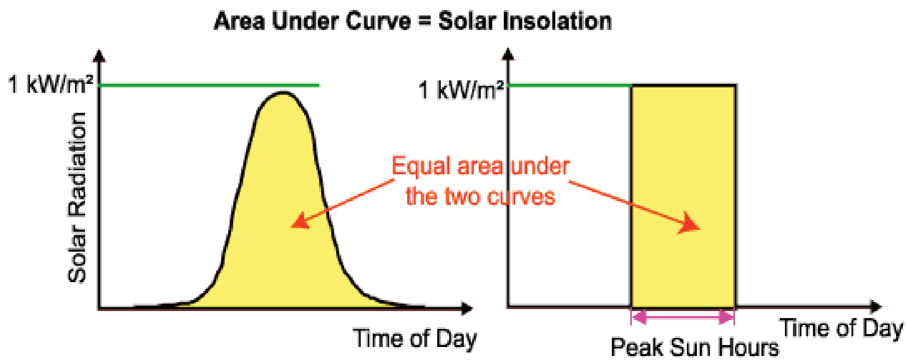
- '*h*' is Peak Sun Hours, unit: hrs (do not confuse with sunshine hours!)

  Peak Sun Hours = Annual irradiation in [kWh/m²*a] / 1000 W / m²

  Interpretation:
  If the sun shone permanently at 1000 W/m², how many hours would it shine to reach the annual irradiation?

Peak Sun Hours PSH

- PSH (h) refers to the solar irradiance at a particular location if the sun was shining at its maximum value of 1kW/m2 for a certain time (e.g. a day or a year)

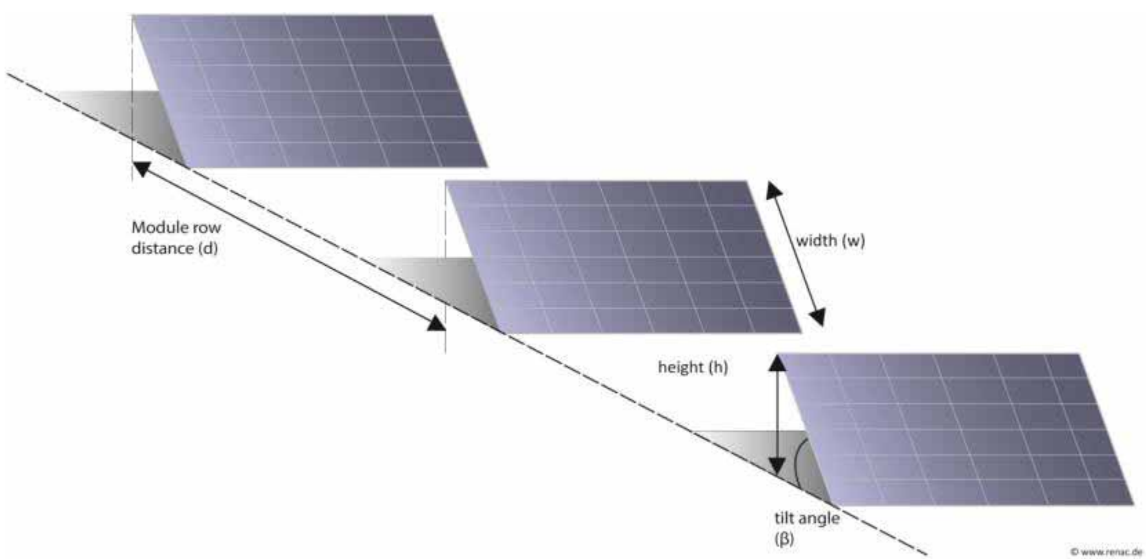


Ex: A location that receives 8 kWh/m² per day can be said to have received 8 PSH per day at 1 kW/m².

Source: Graph: http://pvcdrom.pveducation.org/

How much PV power can be put on a given area?

- Commonly calculated by shadow projection at noon on Dec 21st



Graph: RENAC

6 Project planning and implementation Overview on project phases

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Overview on all project phases

Project Development
- Site surveying
- Preliminary planning
- Cost calculation
- Licenses & Permitting
- Contracting of site
- Grid Connection
- Due Diligence
- Environmental Impact
- Output simulation

Engineering
- Technical planning
- Construction drawing
- Construction timetable
- Performance optimization

Financing
- Economic efficiency calc.
- Investment
- Revenues
- O + M costs
- Financing
- Pre-financing
- Debt/Equity planning

Procurement & Construction
- Procurement / Assembly
- Commissioning / acceptance
- Construction coordination
- Grid connection
- Quality inspections

Operation
- Plant monitoring
- Fault analysis
- Reporting
- Operations and maintenance
- Contract management
- Accounting

Disinvestment
- Equity transfer
- Dismantling

Sample timeline PV projects (ground mounted)

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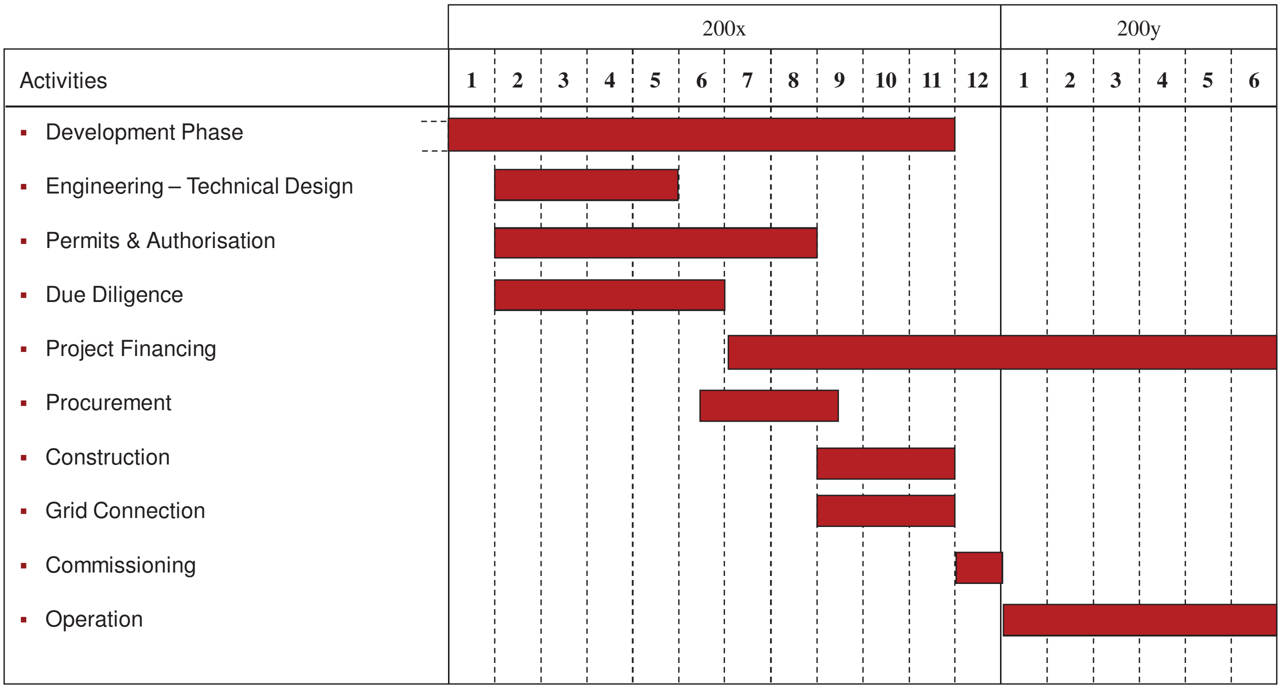

Main processes during project development

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Technical	• **Pre-feasibility study** • **Feasibility study (including solar yield prognosis)** • **Basic design**
Economical	• **Economic efficiency calculation** • **Bank credit and equity**
Administrative	• **Government** • **Municipalities** • **Environmental (birds, landscape, dazzling effects etc.)** • **Grid access/connection** • **Public information** • **Land owners** • **Use of resources and infrastructure (water, roads, affected plots etc.)**
Contractual	• **Tendering process** • **EPC and O&M contracts** • **Shareholders and financing agreements** • **Land Lease Agreement** • **Power Purchase Agreement** • **Main supplier agreements**
Consulting	• **Consulting and advisory (legal, technical, insurance, market, financial)** • **Due Diligence (legal, technical, insurance, market, financial)**

Main processes during construction

Start	• Leveling • Road building • Forest clearance
Engineering	• Review of basic engineering (re-evaluation) • Detailed engineering
Procurement	• Issuing of request for quotation • Purchase orders • Manufacturing (monitoring of manufacturing procedures- QA) • Delivery (check at reception of equipment condition and packing lists)
Construction	• Civil works • Electrical works • Mechanical works • Instrumentation and control works • Pre-commissioning of components and sub-systems
Start-up	• Commissioning • Provisional acceptance

6 Project planning and implementation Solar resource assessment and site analysis

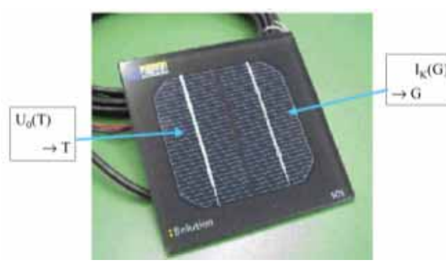
Ground measurements Vs Satellite data

- Ground measurement
  - **Advantages**
    - High accuracy (depending on sensors)
    - High time resolution
  - **Disadvantages**
    - High costs for installation and O&M
    - Soiling of the sensors
    - Sometimes sensors fail
- Satellite data
  - **Advantages**
    - Higher spatial resolution
    - Long-term data (more than 20 years)
    - Effectively no failures
    - No soiling
    - No ground site necessary
    - Low costs
  - **Disadvantages**
    - Lower time resolution
    - Low accuracy in particular at high time

Radiation data for yield estimations

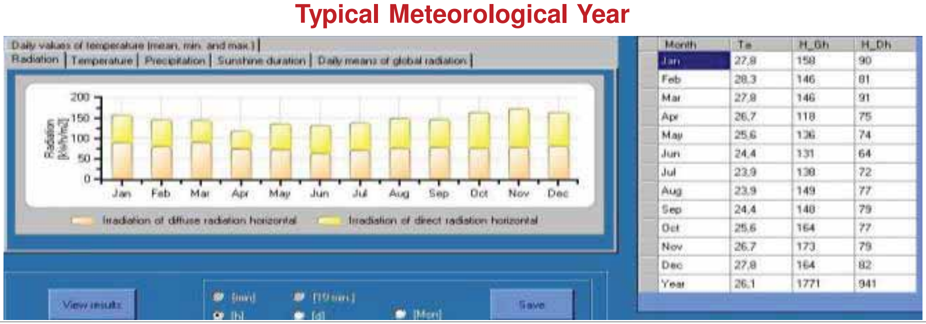
Field measurements

- Accuracy 1% – 5%



- Accuracy 5% – 10%

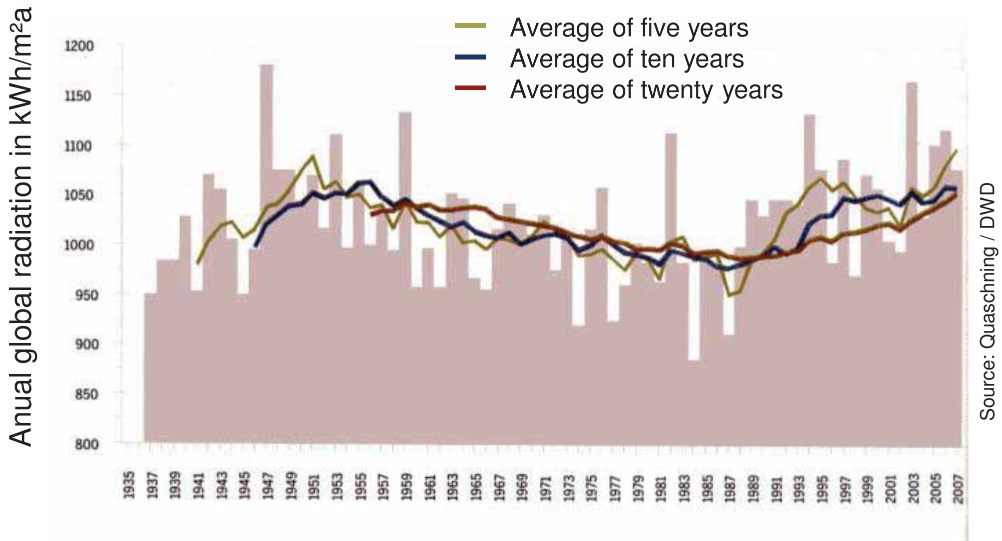
Typical Meteorological Year



Month	Ta	H_Gh	H_Dh
Jan	27,8	158	90
Feb	28,3	146	81
Mar	27,8	146	91
Apr	26,7	118	75
May	25,6	136	74
Jun	24,4	131	64
Jul	23,9	138	72
Aug	23,9	149	77
Sep	24,4	148	79
Oct	25,6	164	77
Nov	26,7	173	79
Dec	27,8	164	82
Year	26,1	1771	941

www.meteonorm.com

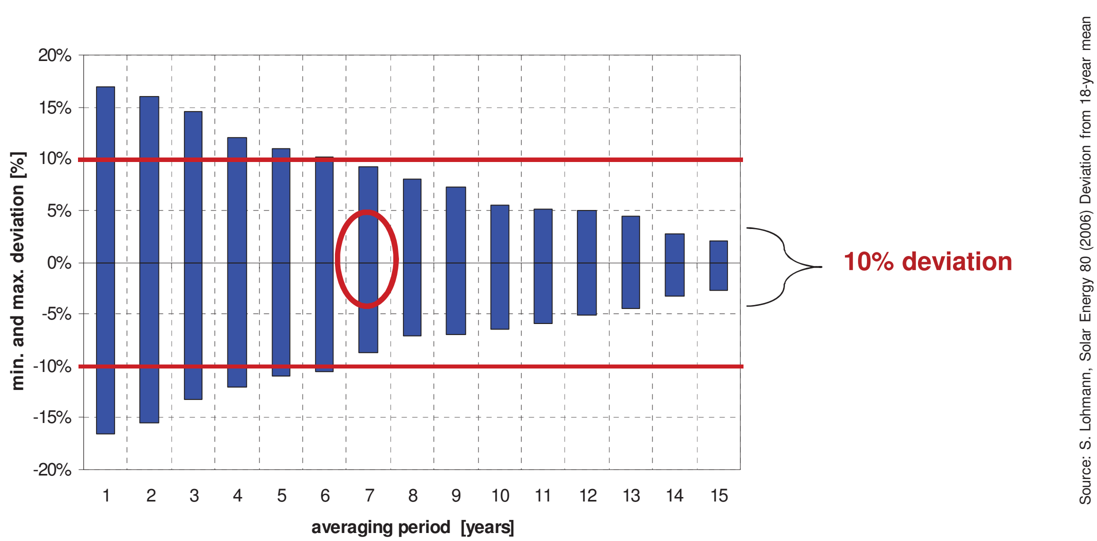
Longtime averages must be used to build typical meteorological years



Variation of anual global radiation in Potsdam, Germany over the last 70 years

Site radiation contribution to yield

- Starting point for an energy yield assessment is the average solar radiation at the planned site
- The basis are long duration measurements from ground stations or satellite

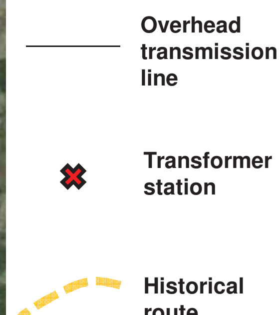


Sources of radiation data

- PVGIS, EU
  - http://re.jrc.ec.europa.eu/pvgis/solres/solrespvgis.htm
- National Renewable Energy Laboratory, USA
  - http://www.nrel.gov/csp/troughnet/solar_data.html
- NASA – horizontal only
  - http://eosweb.larc.nasa.gov/sse/
- Digital data bases (e.g. Meteonorm)
  - http://www.meteonorm/com/pages/en/meteonorm.php
- Simulation software (selection)
  - PV*Sol: http://www.valentin.de/ and PVsyst: http://www.pvsyst.com/

Measuring solar radiation

Analysis of the surrounding area (I)



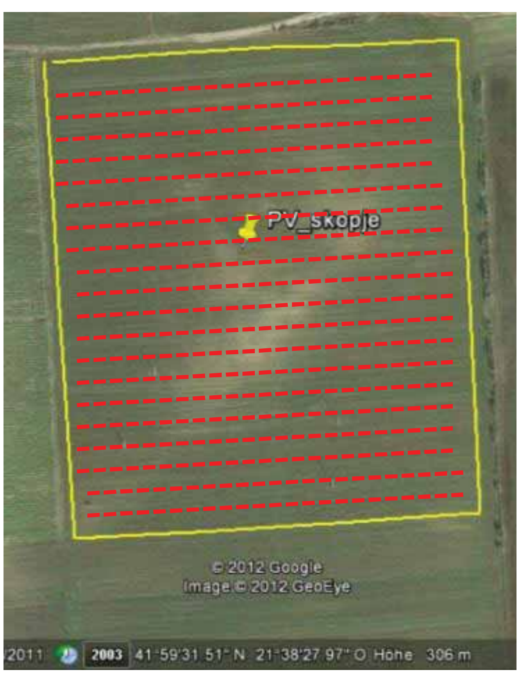
Analysis of the surrounding area (II)

Overhead transmission line

Transformer station

Planned earth cable PV plant – grid

Analysis of the installation site

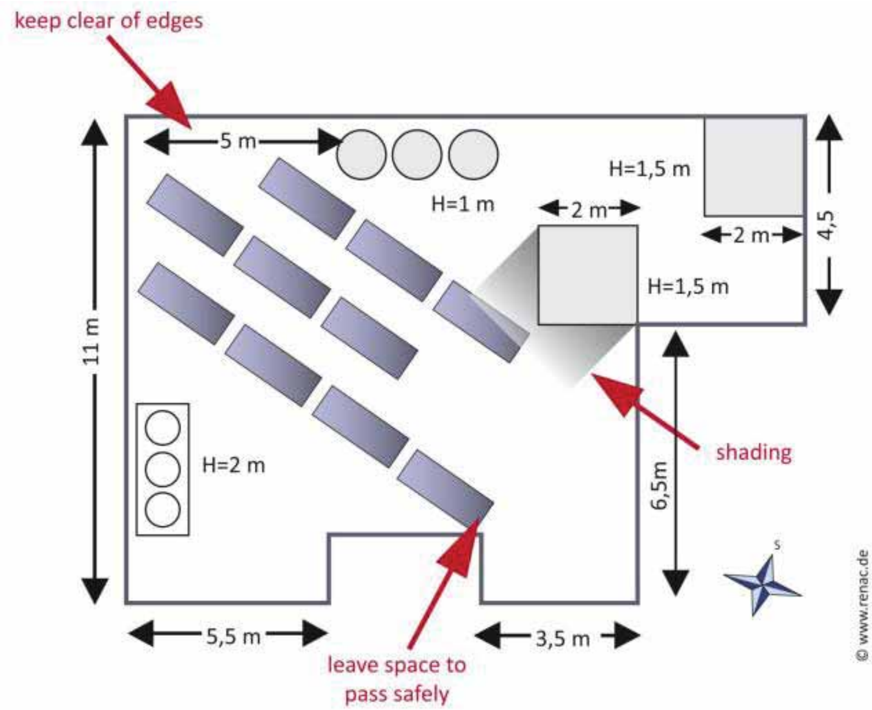


Ramming: potential danger through military objects; archeological artefacts?

Protected species on site?

Source: www.wageningenur.nl

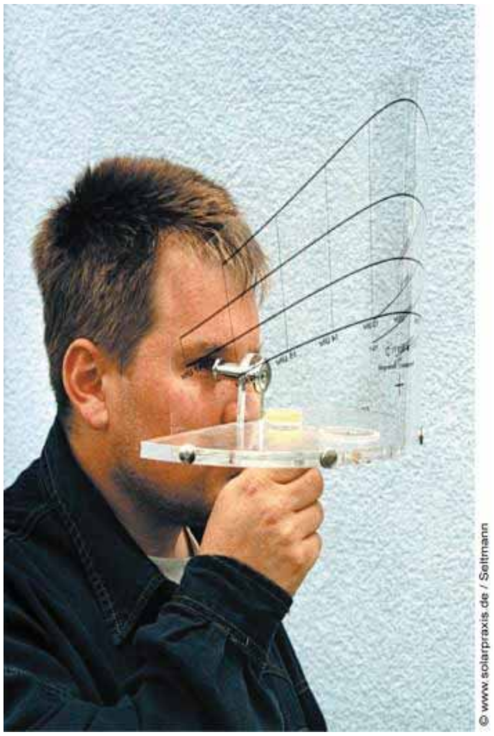
Analysis of roofs (e.g. industrial roofs)

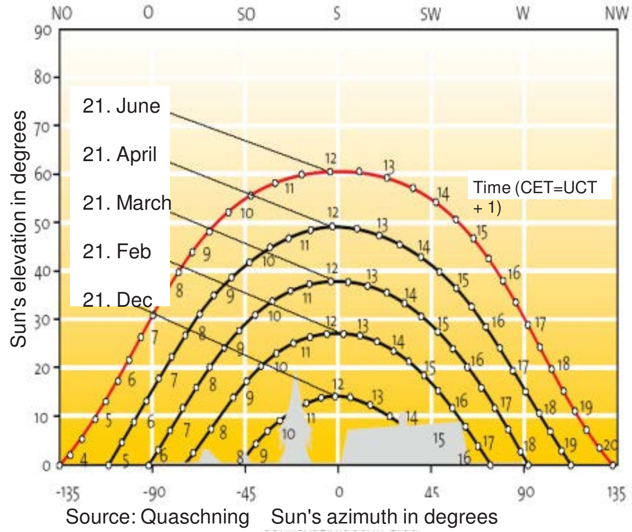


Shading analysis

Source: www.azsolarcenter.org, www.solarpraxis .de / Schubert (3x)

Shading analysis



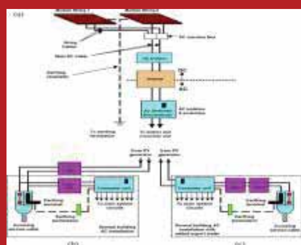


6 Project planning and implementation Engineering and construction

Engineering

Detailed technical design

- Components
- Norms & codes
- Electrical engineering
- …



Engineering

Civil engineering

- fixed installation / one or two-axis tracker systems?
- Statics
- Costs: Mounting time and material

- Plant layout
- Shadowing
- Efficient use of space
- Grid connection
- Wiring losses
- …

Source: www.sciencedirect.com

Procurement

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- Road building
- Foundation
- Transport and installation
- PV power plant (modules, inverters, cables etc.)
- Grid-connection
- Compensatory measures
- Others (e.g. construction management)

EPC contractor or different partners??

- Important requirements for successful procurement:
  - Detailed and completed planning
  - Defined cut surface
  - Complete tendering
  - All-embracing contracts

Logistic aspects

- PV is modular, therefore special transport is not required
  - Standard trucks
- Since no very large items are being transported, no special preparation of the roads is needed
- Largest items are:
  - Transformers
  - Standard housings for inverters
  - DC cable drums

Source: SMA Solar Technology AG

Source: Betonbau

Source A. Tiedemann, RENAC

Construction of a PV plant

Source: KWA Eviva GmbH

Forest clearance – sometimes necessary to prepare site

Construction of a PV plant

Unprocessed | After forest clearance | After leveling



Source: KWA Eviva GmbH

Leveling of the site – calculate, if advantages of leveling justify the costs

Construction of a PV plant

First tests

Source: KWA Eviva GmbH

First complete rows

Source: KWA Eviva GmbH

Rows with module frames

Source: KWA Eviva GmbH

Source: Suntex GmbH

Static foundations - usually pile driven profiles, in special cases concrete

Construction of a PV plant

Fence and first modules

Module installation

Finished module rows

Module installation

Source: KWA Eviva GmbH

Construction of a PV plant

Inverter and transformer

Medium voltage transmission station

Cable laying with cable runs

Inverters, transformers, cables…

Source: KWA Eviva GmbH

Construction of a PV plant

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…and the whole PV power plant (2 MWp)

Source: KWA Eviva GmbH

Grid connection

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Grid installation with plow and/or digger

Source: KWA Eviva GmbH

Commissioning of a PV power plant

- Commissioning of grid connection (electricity needed for running PV power plant)
- Commissioning of different parts of PV power plant (electric, static, etc.)
- Commissioning of complete PV power plant
- Monitoring
- Important: coordination of cut surfaces, time planning, one person in charge! - > 90 % of successful commissioning
- **Target: commissioning and acceptance in time!**

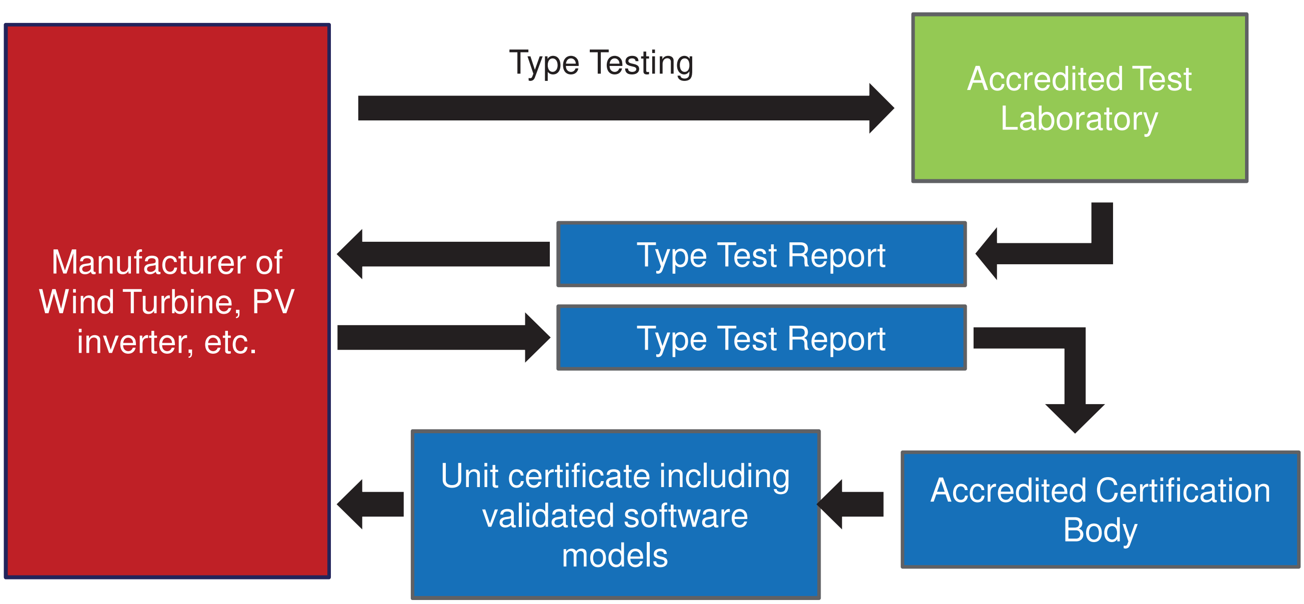
(First four points:) EPC contractor or different partners??

6 Project planning and implementation Testing and certification

Overview of grid-related issues

- **The loading capacity of network equipment**
  (Is the grid able to absorb the electrical power of the PV plant at all times?),
- **Voltage changes in the undisturbed grid**
  (Is the voltage change due to the PV plant within defined limits, how can it be limited?),
- **Potential network disturbances caused by the PV plant**
  (What kind of disturbances could be caused by a PV system, what are acceptable limits?), and,
- **The behaviour of PV plants in case of grid disturbances**
  (If there is a grid disturbance, which automatic and active control features does the PV system have to have to be able to support the grid or to avoid further adverse effects?).

Unit Certification of Renewables



Duration: approximately 4-6 months

System Certification of Renewables

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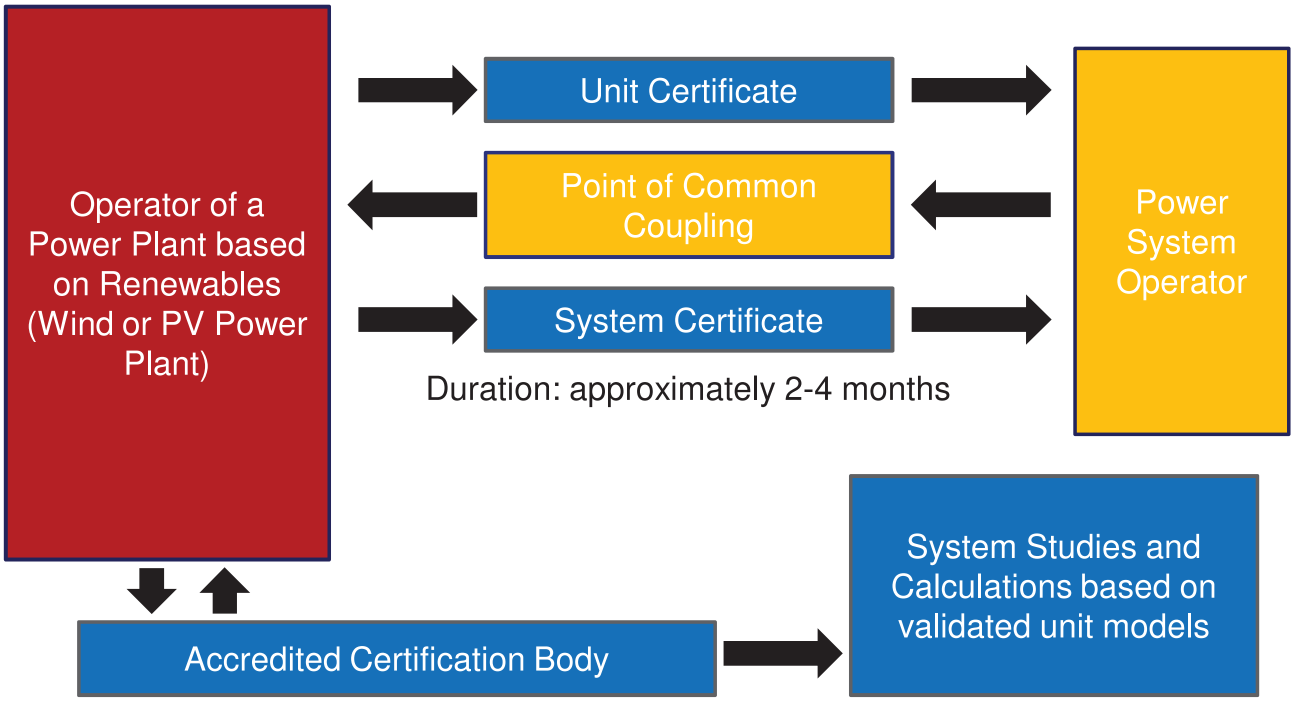

Further reading

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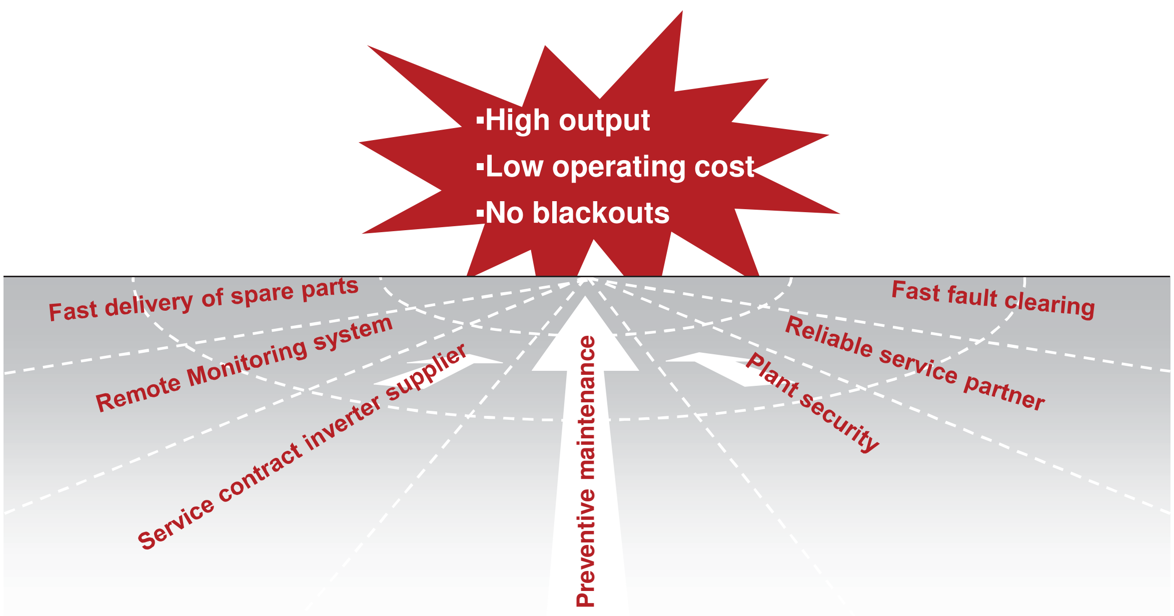
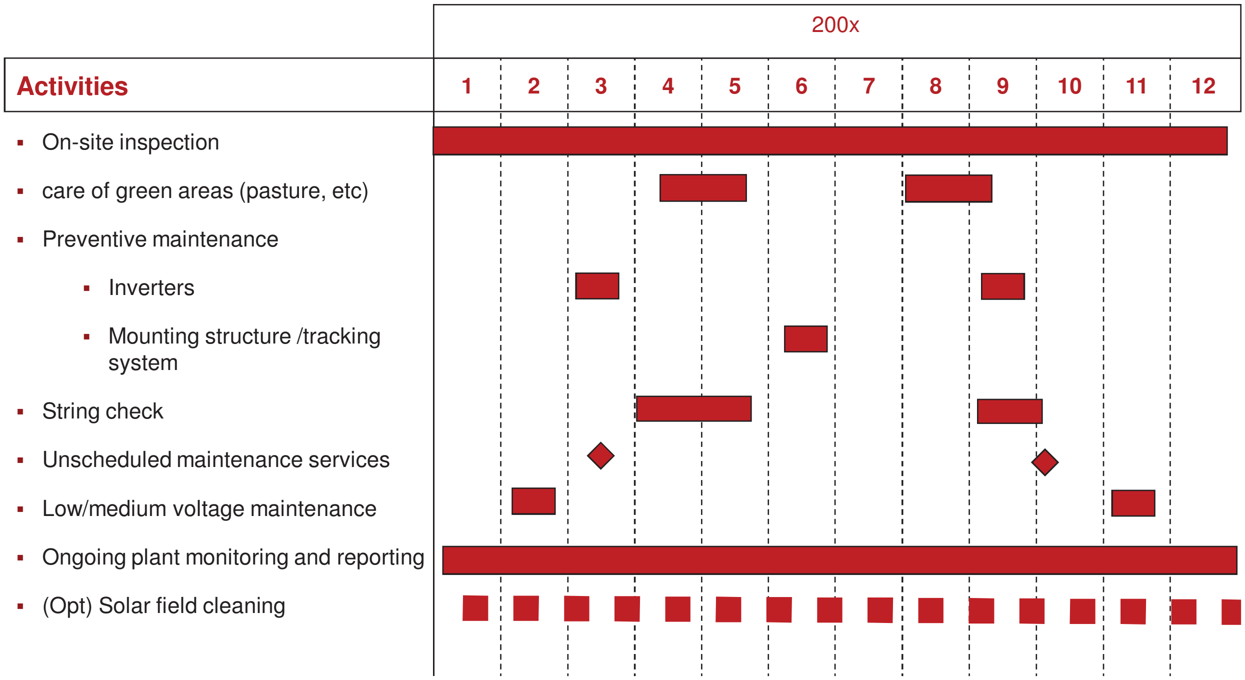
- German 'Technical Guideline: Generating plants connected to the medium-voltage network' (BDEW, 2008). This guideline is available free of charge in English. It can be downloaded from http://www.bdew.de/internet.nsf/id/A2A0475F2FAE8F44C12578300047C92F/$file/BDEW_RL_EA-am-MS-Netz_engl.pdf
- International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), especially Task 14: High Penetration of PV systems in Electricity Grids: http://http://iea-pvps.org (very interesting presentations can be found in the section 'Utility Workshops')

6 Project planning and implementation Operation, maintenance and monitoring

PV plant operation & maintenance



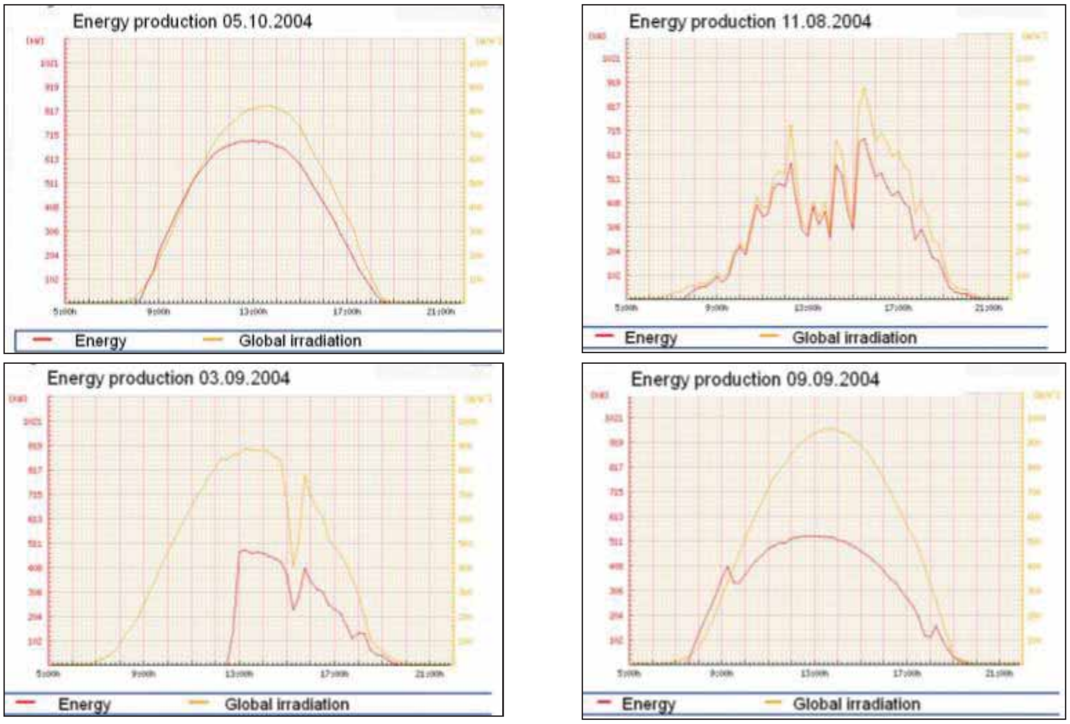
Operation and maintenance: activities overview



Dust on the modules due to pollution (location!)

Source: Schaeffer TC for RENAC

Energy Yield monitoring, which graph might show a failure?



Source: Siemens

7 Financial modeling
Life-cycle cost analysis and LCOE evolution

What does €/Wp mean?

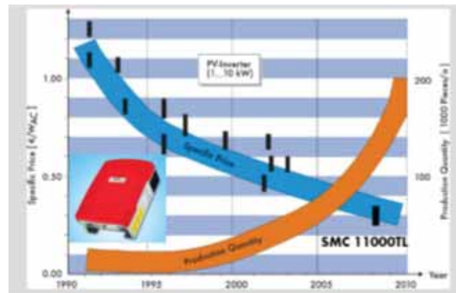
- In solar industry costs are often referred to the installed capacity.
- Wp = Watt peak => this is the installed capacity at Standard Test Conditions
- Example:
  - The specific cost of PV modules shall be 0.70 €/Wp
  - How much do 10 kWp of PV modules cost?

PV modules spot market in Europe (Feb 2014)

Module type. provenance	€ / Wp Apr 2010	€ / Wp Apr 2011	€ / Wp Jul 2013	€ / Wp Oct 2013	€ / Wp Feb 2014	Trend since Apr 2010	Trend since Oct 2013
Crystalline Germany	1.97	1.61	0.76	0.71	0.7	-64%	-1%
Crystalline China	1.52	1.32	0.56	0.58	0.59	-61%	2%
Crystalline Japan	1.94	1.54	0.78	0.73	0.69	-64%	-5%
Thin-film CdS/CdTe	1.57	1.09	0.57	0.58	no data		1%
Thin-film a-Si/µ-Si	1.41	1.19	0.47	0.45	no data		-2%
net prices in € per Wp; Source: www.pvXchange.com; Feb 2014							

Inverters

- 2010: 300 - 400 €/kW
- Q3 2011: 200 €/kW
  (Source: Photon profi, 9-2011; note that this price is an average, prices show large variety; spot market prices)
- 2013:
  for MV central inverters: 150 €/kW
  for 3-phase string inverters: 175 €/kW
  (Source: interviews with two international project developers conducted by RENAC, March 2013)
- Sep 2013:
  Single phase: 210 €/kW
  Three-phase <= 35 kW : 150 €/kW
  Three-phase 36 – 100 kW : 130 €/kW
  (Source: IHS Inc., published in pv magazine 12/2013)



Source: SMA Technologies AG

Direct / indirect investment costs (sample)

Project Development costs

- Project acquisition
  - Own development
  - Buying projects rights
- Pricing
  - Depends on market situation
  - Germany 50 – 150 €/kWp
  - RO Europe 100 – 1.000 €/kWp

Construction costs

- Components
  - Module: 700 €/kWp
  - Inverter: 150 €/kWp
  - Structure: 100 – 200 €/kWp
  - DC Cable: 50 – 75 €/kWp
- Mounting
  - Mechanical: 100 – 150 €/kWp
  - Electrical: 100 – 150 €/kWp
- Grid connection
  - Transformer: > 30.000€
  - Grid connection: 20 – 50 €/kWp
- Remote Control/ Monitoring
- Protection
  - Lightning protection
  - Theft and vandalism protection

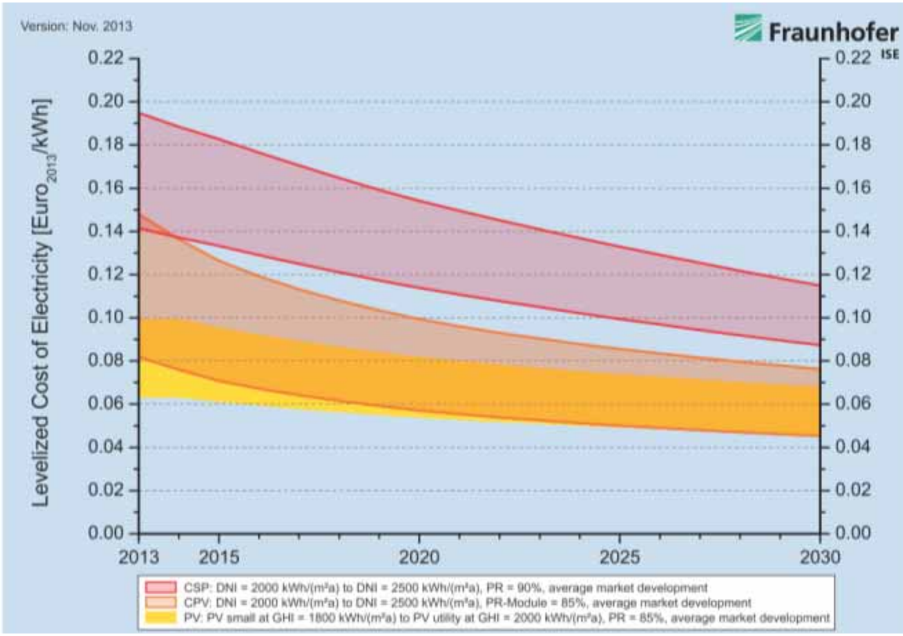
Sales Costs

- Cost of equity acquisition
  - Prospect
  - Mailings
  - Events
  - Advertisement
- Sales fee
  - Own employees
  - External sales partners

Other costs:

- Civil engineer
- Static of rooftop
- Static of ground
- Lawyer
  - Contracts
  - Foundation of company
- Ground registry
- Upfront lease rate
- Bank fee
- Independent output prognosis
- Bridge financing

Development of the LCOE of PV at location with high solar irradiation



Source: Fraunhofer Institute for Solar Energy Systems ISE: Levelized cost of electricity - renewable energy technologies, November 2013

Revenues components

PV electricity (Energy Yield)

- Should be performed by experienced technicians as yield depends on a large number of technical parameters
- Be careful if the same person who is selling you the projects also calculates yield! Especially in medium-scale projects. plausibility should be checked!
- Determination by means of simulation software
  - Time step simulation programs: Greenius. PV*Express. PV*Sol. PVSYST, RETScreen, etc.
  - Others: PVKalk, PVProfit, SolINVEST, etc.

Revenues

Sales price

- Electricity sales and
- Incentives:
  - Feed-in-tariffs
  - Electricity sales contract
  - Net metering (sales price = savings of own electricity costs)
  - Certificates – in most cases not relevant for PV

PV project profitability

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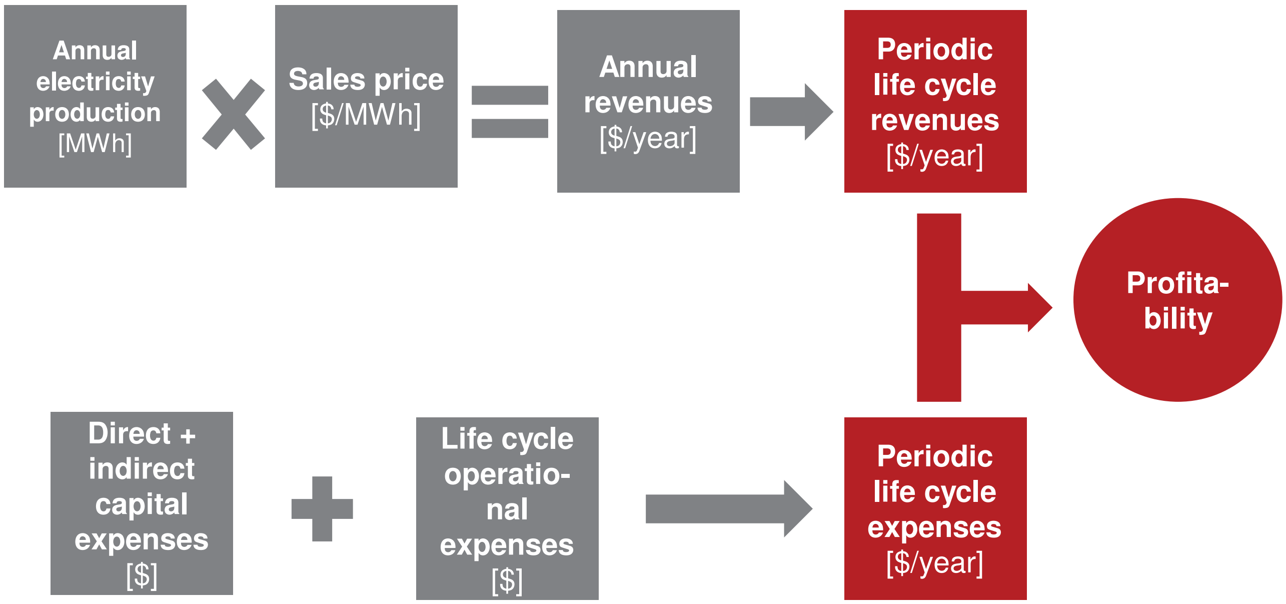

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7 Financial modeling
Risk management; bankability of PV projects

Completion risk (I)

Risks	Mitigation
▪ Late completion	▪ Contract incl. penalties for late completion with competent + experienced subcontractor(s)
▪ Completion with higher costs	▪ Fixed price contract with contractor(s)
▪ Underperformance of completed plant	▪ Performance guarantees (electricity yield), with responsible contractor ▪ Use of bankable components
▪ Non-completion	▪ Turn-key contract including completion guarantee and respective penalties with contractor ▪ Insurances are available to cover costs of late completion

Completion risk (II)

Risk	Causes	Mitigation
Lack of contractor availability	▪ high workload ▪ Capabilities do not fit the project pipeline	▪ assess market situation ▪ check contractors' capabilities ▪ liquidated damages ▪ diversify if possible
Delayed progress	▪ time schedule does not fit the project requirements ▪ delayed component supply ▪ missing or insufficient permits and licenses ▪ complicated tendering	▪ appropriate time schedules ▪ systematic project development ▪ professional consultation ▪ set milestones and deadlines ▪ define liquidated damages ▪ simplify tendering procedure
Conflict of interests	▪ participation of partners in other projects or joint ventures	▪ market screening ▪ check contractors indication of references

Risks examples – What can go wrong during completion?






Operational risk

Description	Mitigation
▪ All risks during operation which might lead to under-performance ▪ Interruption or standstill of the PV plant or parts of it	▪ Operation & maintenance (O&M) contract with an experienced company – preferably with one of the project's participants ▪ Project life time O&M contract ▪ Plant monitoring ▪ Yield definition through two or more independent yield assessment studies ▪ Insurances (damage, financial loss of revenue caused by down-times) ▪ Building up of reserves for scheduled and un-scheduled replacement of components

Ground movement (e.g. due to heavy rain)

www.solarpraos-de / Quednow

Damages caused by wind – inadequate fixation

Source: Mannheimer AG

Inadequate cabling

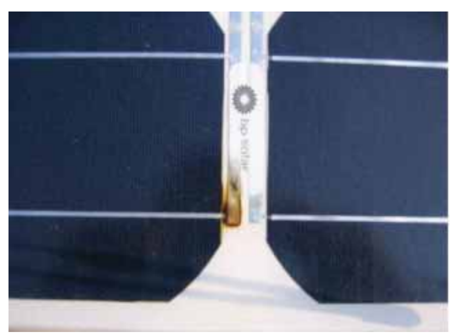
Eva Schubert, Solarpraxis AG

www. Solarpraxis.de

www.solarpraxis.de / Schubert

Module failures

Burnt junction box

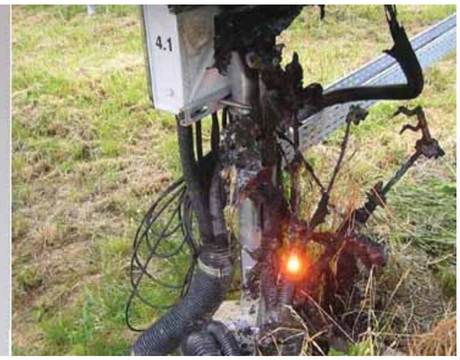


Arcs due to bad solder connectors may cause damage to modules or even fire

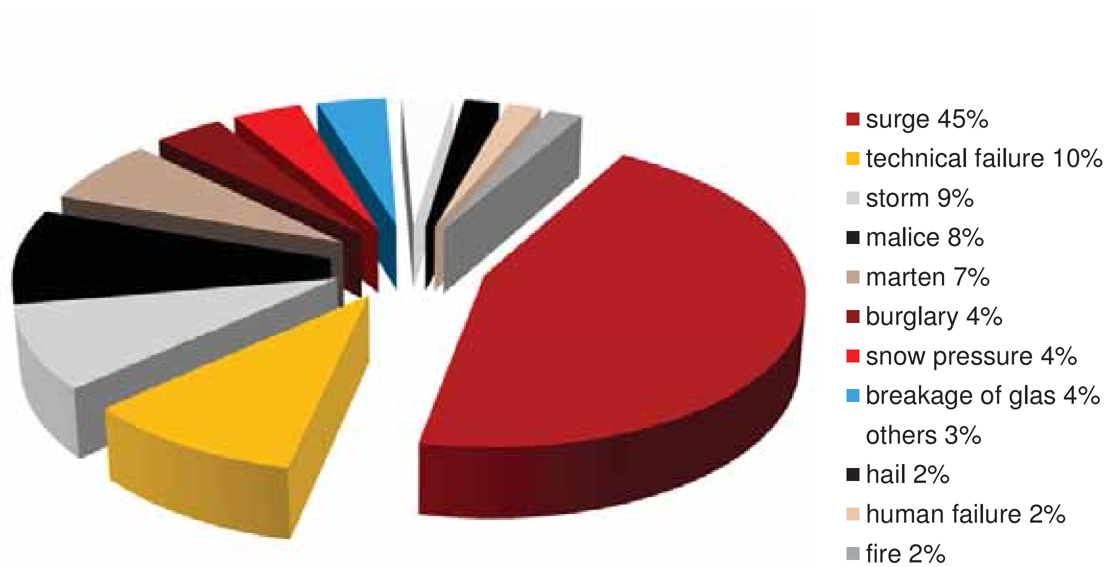
Broken cell, similar behavior as a shaded cell

DC failures

- All DC components (such as fuses and fuse holders) must be applicable for PV
- All DC connections have to be done very precisely.



Damage caused to PV systems between 2003 and 2005 according to a German insurance agency



Source: Mannheimer Versicherung 2006

Technology (functional) risk

Description	Mitigation
▪ Technology might not achieve the expected performance parameters (performance ratio too low)	▪ Only proven technology with a good track record should be chosen ▪ Performance warranties on equipment ▪ Certified modules and inverters according to IEC and/or UL standards ▪ Certification carried out only by an independently certified testing laboratory

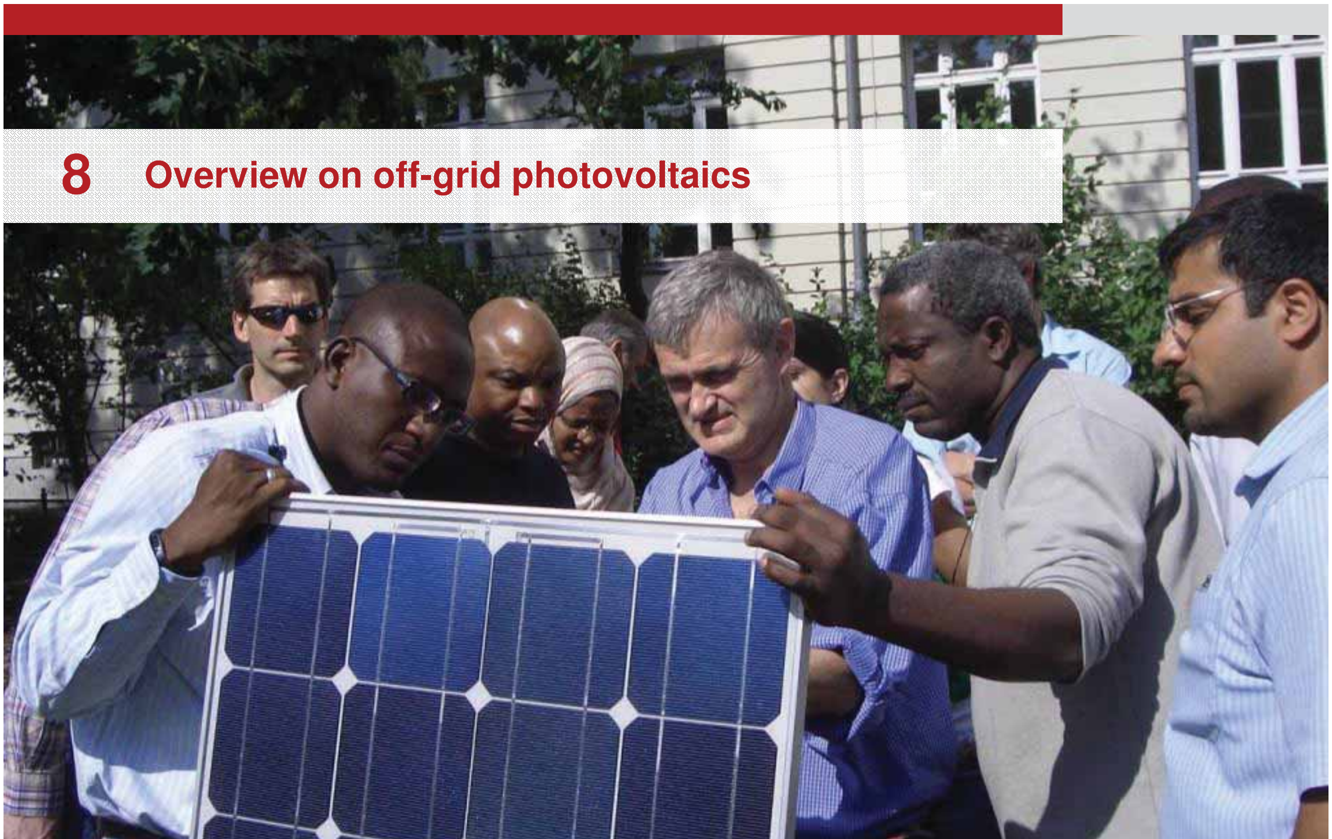
Quality marks, seals and standards

- IEC (International Electrotechnical Commission)
  - There is a range of IEC standards covering modules and other system components (e.g. IEC 61215 (Crystalline), IEC 61646 (Thin film), IEC 61730 (Safety))
- CEC (Commission of the European Community) Joint Research Center in Ispra, Italy
- UL (Underwriters Laboratory), USA
- ASTM (American Society for Testing and Materials)

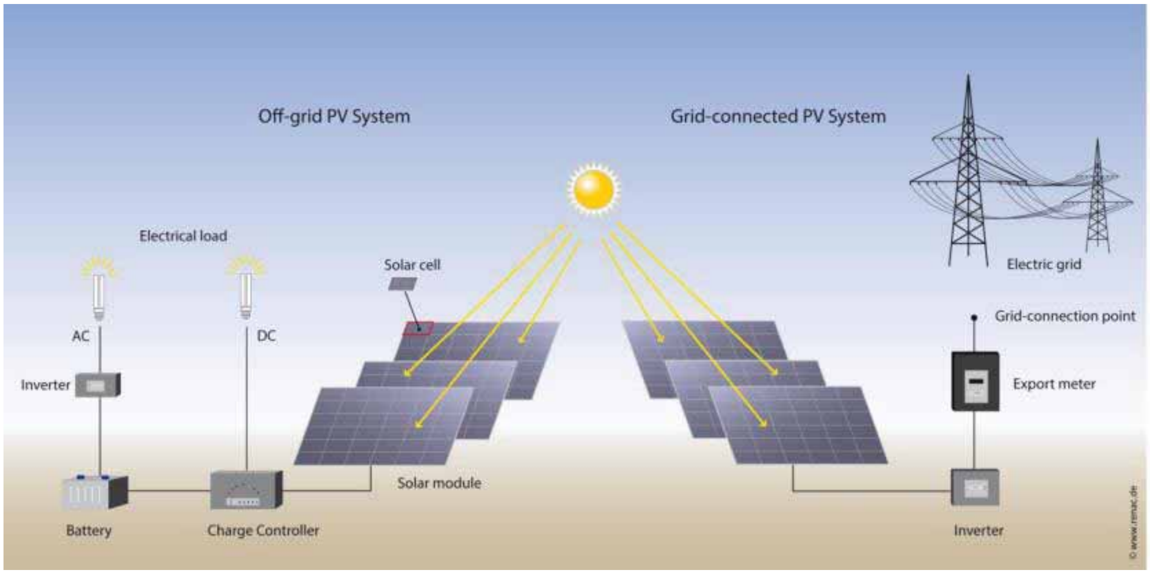
Market and distribution risk

Description	Mitigation
▪ The electricity cannot be sold in the expected amount and/or price ▪ Downtime of transmission lines ▪ Transmission line overload, congestion and curtailment of production (rare in PV) ▪ Resource availability reduces firm capacity ▪ Value of green certificates changes ▪ Inflation risk	▪ Long-term contracts with solvent buyer ▪ Fixed feed-in tariff (lowest risk) ▪ Own consumption ▪ Virtual power station, pooling with other RE

8 Overview on off-grid photovoltaics



Grid-tied vs. off-grid photovoltaics



Graph: RENAC

PV off-grid system configurations

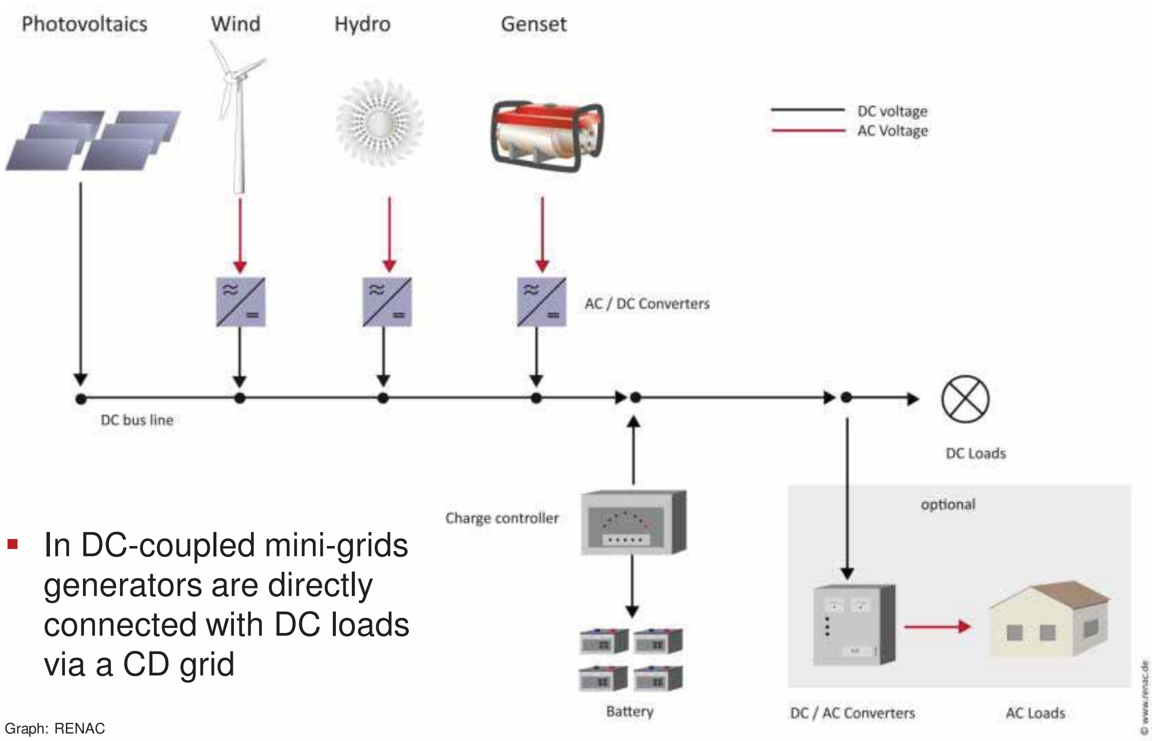
- Off-grid PV and grid-tied PV
- PV only off-grid systems
- Hybrid off-grid systems
- DC-coupled micro-grids
- AC-coupled mini-grids

Centre for Alternative Technology Wales, UK, part of large PV-hybrid system

Lighting system for boarding school, East Africa

Photos: Frank Jackson

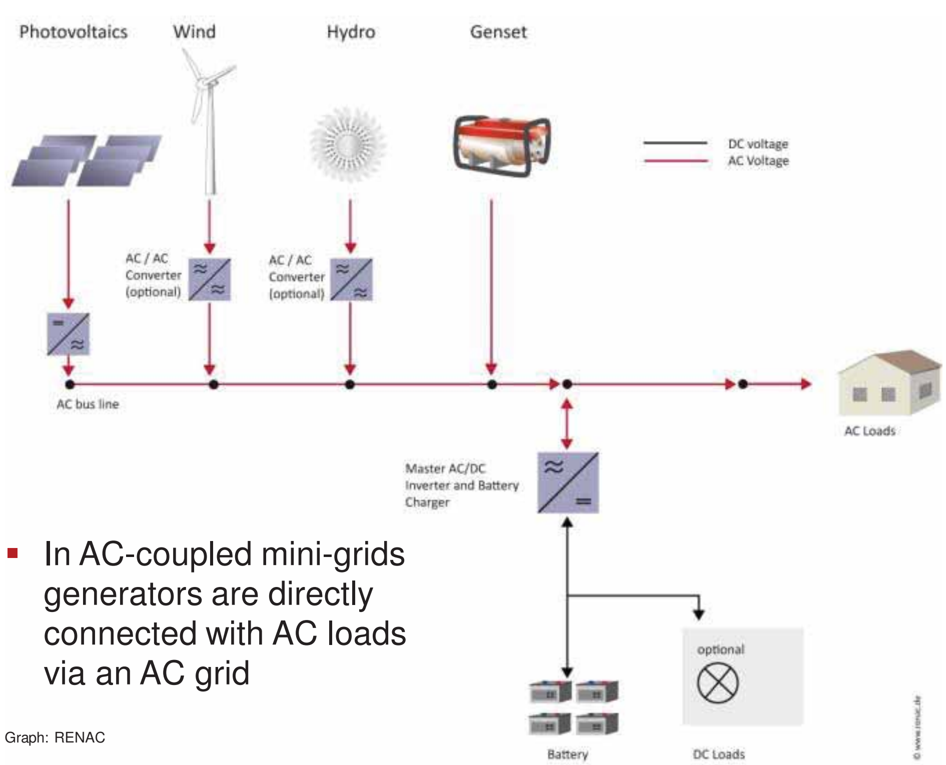
Direct current (DC)-coupled hybrid mini-grids



- In DC-coupled mini-grids generators are directly connected with DC loads via a CD grid

Graph: RENAC

Alternating current (AC)-coupled hybrid mini-grids



- In AC-coupled mini-grids generators are directly connected with AC loads via an AC grid

Graph: RENAC

Range of batteries for stand-alone PV systems

- Lead-acid batteries
- What types of batteries are available locally?
  - Locally manufactured?
  - Imported?
- Automotive (SLI) batteries are *not* recommended, but *are* used in SHS where they are the only option
  - 2 year maximum life if properly sized

Figure 4.9 *Types of battery: Sunset flat plate solar battery (top left); local Kenyan SLI batteries, not generally recommended but often the only option (top right); Hoppecke 2 volt cell, flooded, tubular plates, deep cycle, recommended for larger systems (bottom left); Surrette 6 volt batteries, deep cycle (bottom right)*

Photos: Mark Hankins: Stand-alone Solar Electric Systems, Earthscan Expert series; ISBN: 1849776504, 9781849776509

Batteries - important points

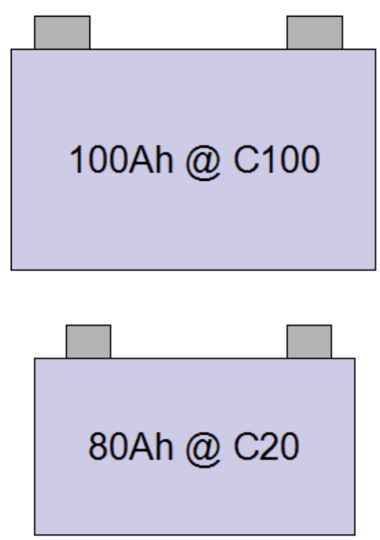
- Batteries should never be discharged completely to insure battery lifetime
  - 50% - 80 % is recommended for a deep-cycle battery
- The battery should be able to deliver the energy required in one cycle
  - in a solar system this is one day
- There should also be storage capacity for the days on which there is not enough sun or wind
- Every make of battery has different specifications

Battery capacity

- Batteries are sized in amp-hours (Ah)
  - A battery which can deliver 1 amp for 100 hours has a capacity of 1 x 100 amp-hours or 100Ah
  - A battery which can deliver 10 amp for 10 hours has a capacity of 10 x 10 amp-hours or 100Ah
- The capacity of lead-acid batteries is reduced with decreasing temperature – a typical battery will hold about 20 % less charge at 0°C than one at 40°C
- For basic capacity calculations it can be converted to watt-hours (Wh): **Wh = Ah x V_{system}**
  Example: a 100 Ah, 12 V battery = 1200 Wh

Battery C-rates

- The Ah capacity of a battery varies according to the rate at which it is discharged
- A battery discharged at a rate of 1 amp will have a higher Ah capacity than a battery discharged at a rate of 4 amps
- Example: a battery which can deliver 1 amp for **100 hours has a capacity of 100Ah @ C100**
- Example: the same battery may only deliver 4 amps for **20 hours. Then its capacity is 80Ah @ C20**
- C100 means discharged over 100 hours, C20 means discharged over 20 hours



Flooded Lead Acid (FLA) deep-cycle battery

- Specially developed for remote applications
- Tubular cells
- Expected life: 5-10 years
- Recommended DoD: 50%
- Maximum DoD: 80%
- Maintenance: topping up distilled water

Photo: Frank Jackson

Sealed deep cycle

- Maintenance free
- Shorter life

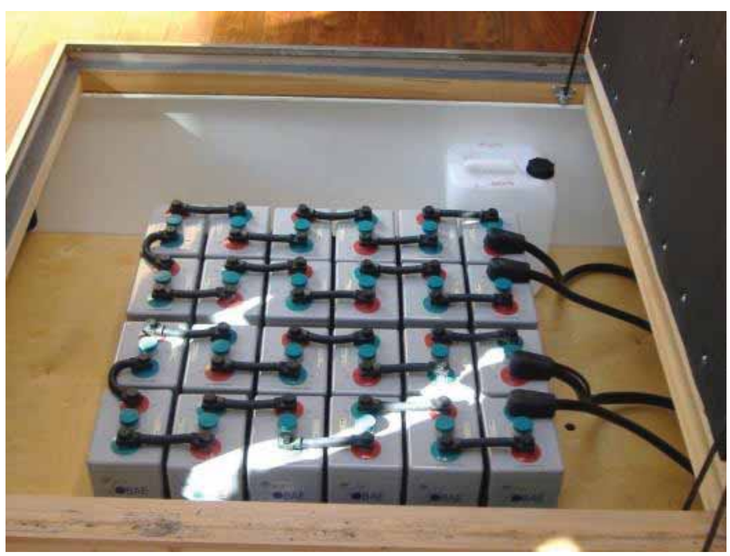


Photo: Frank Jackson; Sealed 2 V BAE deep cycle cells for solar system on house boat, Berlin, Germany

Properties of batteries for PV off-grid systems

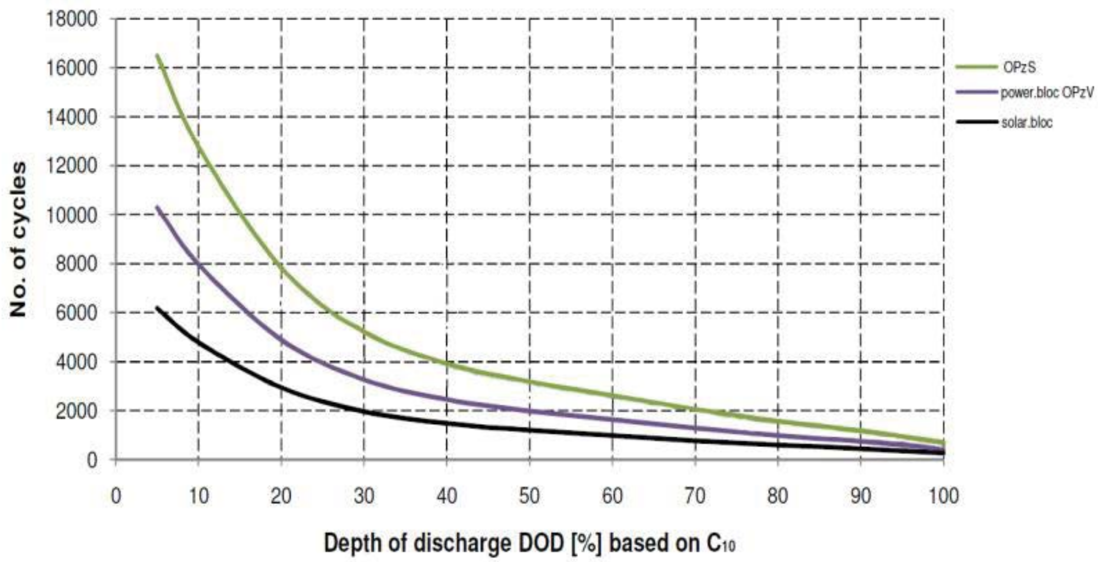
Usual type description	Modified SLI	Gel cells, maintenance-free	Maintenance-free deep cycle	Flooded deep cycle
Construction	Thicker plates than SLI (automotive)	Maintenance-free, sealed	Gel electrolyte, tubular plates	Liquid electrolyte, tubular plates, transparent containers
Properties	Moderate to low water loss, low self-discharge rate	No maintenance	Low maintenance, can withstand deep discharge	Low maintenance, robust construction, charge well with low currents, can withstand deep discharge
Unit voltages	12 V	12 V	2 V – 6 V	2 V – 6 V
Capacity range in Ah	60 – 260 Ah	10 – 130 Ah	200 – 12,000 Ah	20 – 2,000 Ah
Self-discharge rate – monthly	2 – 4 %	3 – 4 %	< 3 %	2 – 4 %
% DOD – cycle life (approximate)	20 % – 1000 40 % – 500	30 % – 800 50 % – 300 (can be less)	30 % – 3000 80 % > 1000	30 % – 4500 80 % > 1200
Maintenance periods	3 months approx.	None	Monitoring & yearly cleaning	3 month approx.

Large battery banks

- Large battery banks are installed in a locked ventilated room
- Separate rooms for batteries & inverters/switchgear etc. if the batteries are not sealed
- No sunlight permitted
- Comply with regulations!
- Access for authorised persons only

Photo: Frank Jackson, RENAC

Batteries cycle life



Source: Hoppecke

Planning off-grid systems

Current electricity consumption analysis

- Existing electricity infrastructure assessment
- Current level of electricity access
- Current demand level of demand for different sectors (different household types, tourism, retail, public sector, etc.)
- List of consumers (AC/DC, operating hours, seasonal changes)

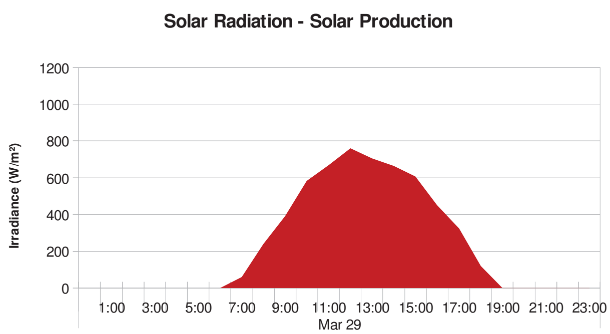
Electricity demand evolution forecast

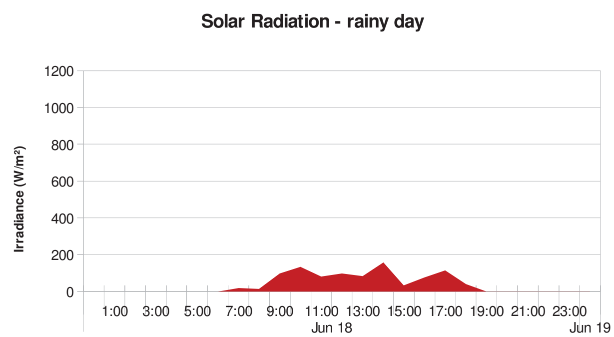
- Analysis of existing consumption patterns (surveys, measurements)
- Segmentation across consumer categories (household, commercial, institutions, etc.)

Energy efficiency provisions

- Electricity savings have a multiple impact (less consumption but also lower investment costs for the microgrid)
- Efficient appliances (lighting, efficient energy classes A, A++, etc.)

Fluctuation solar production



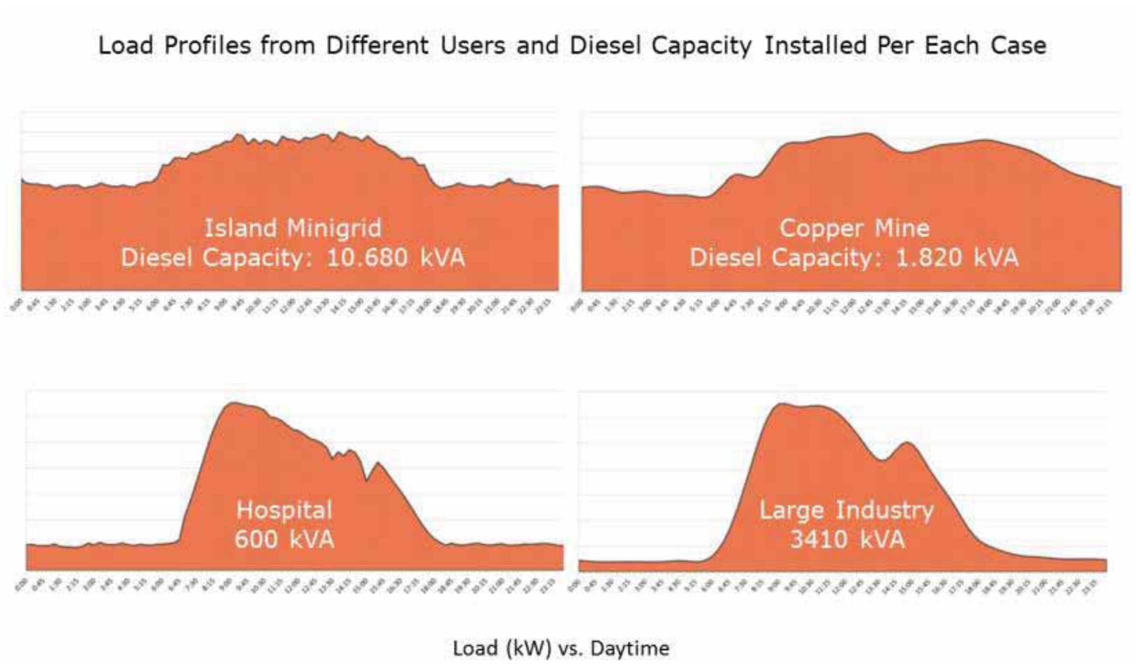


Sunny day: 4-5 kWh/kWp

Rainy day: 1-2 kWh/kWp

Source: Relitec-energy

Load profiles

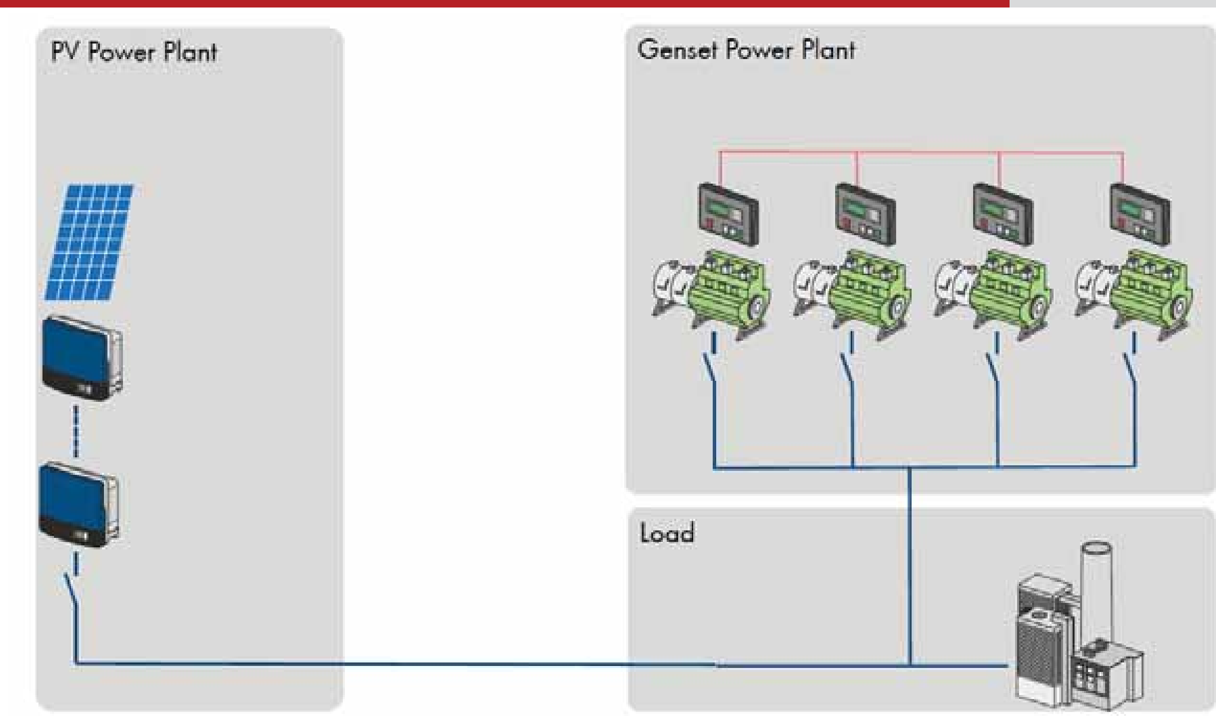


Source: RENAC

Summary load profile

- Detailed load analysis is very important for system simulation and sizing
- Take into account future development
- Off grid systems, especially battery banks are not easily expandable
- Main design criteria:
  - Peak power => inverter-charge size
  - daily energy requirement => battery size
  - solar radiation profile => PV generator size

PV-Diesel Hybrid System – PV Penetration < 20 %



Graph: with friendly permission of SMA Solar Technology AG

PV-Diesel Hybrid System – PV Penetration > 20 %

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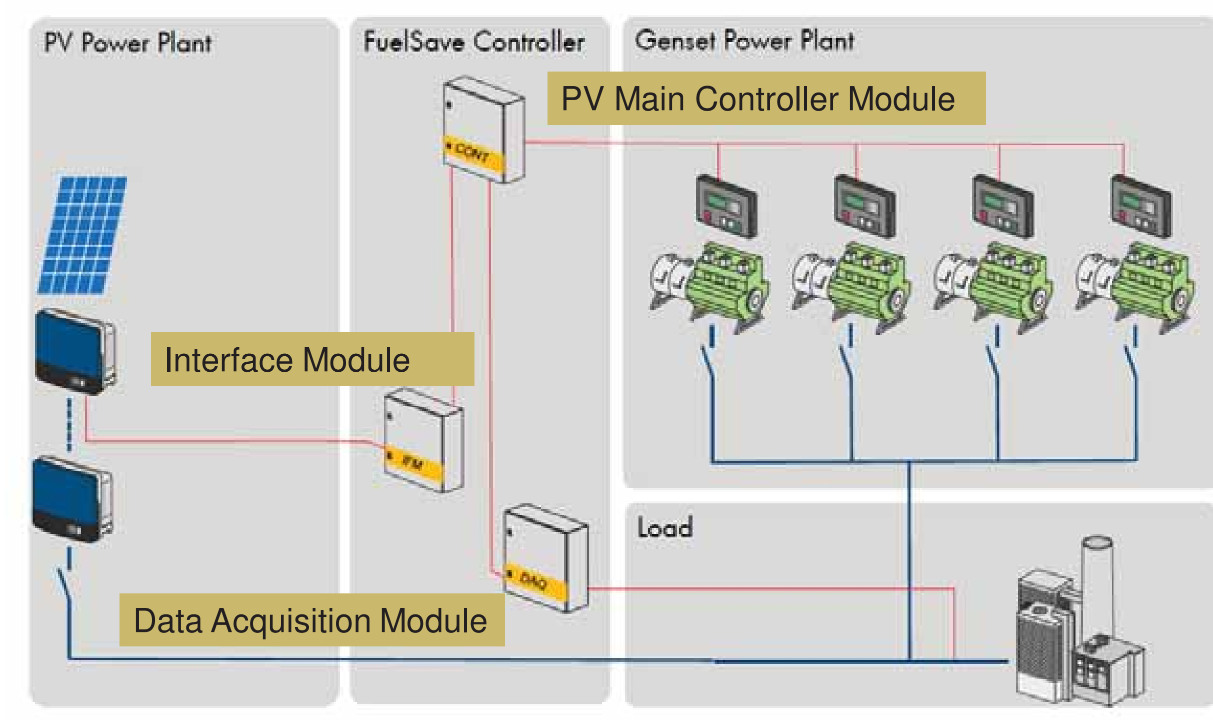

Graph: with friendly permission of SMA Solar Technology AG

Typical cost structure of an off-grid system

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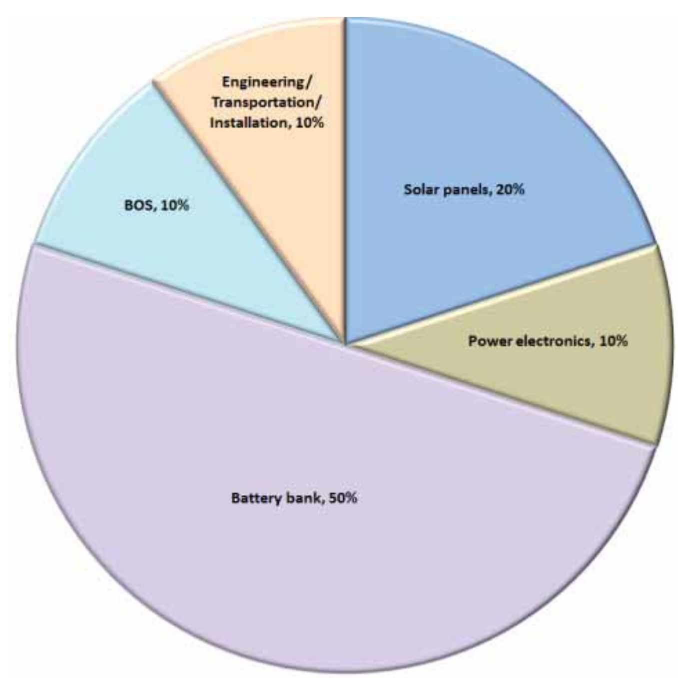
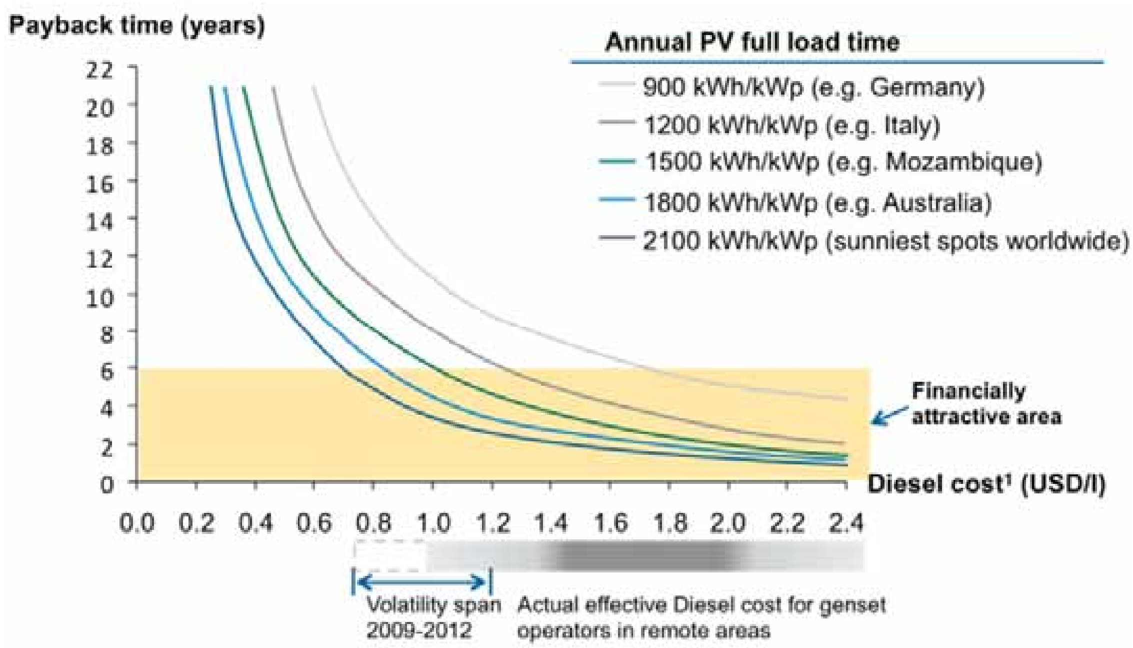
- Typical cost structure of off-grid systems



PV-Diesel-Hybrid is already a real business case



Graph: with friendly permission of SMA Solar Technology AG

1. Effective cost at point of consumption including fuel transportation and storage cost etc.
Assumptions : 1 MW PV plant; 100% consumption of PV power possible; CapEx=2,000 USD/kWp; OpEx= 2% of CapEx p.a.; PV financing with 30% equity/70% debt with 7% interest rate and amortization time of 5 years; Genset efficiency 3.5 kWh/l (net electricity production); CapEx and Maintenance cost for Diesel genset not included, since PV is considered as add-on here, not as genset hardware substitution Source: Web search, SMA analysis

9 Introduction to Concentrating Solar Power (CSP)

Geographical and irradiation requirements for CSP

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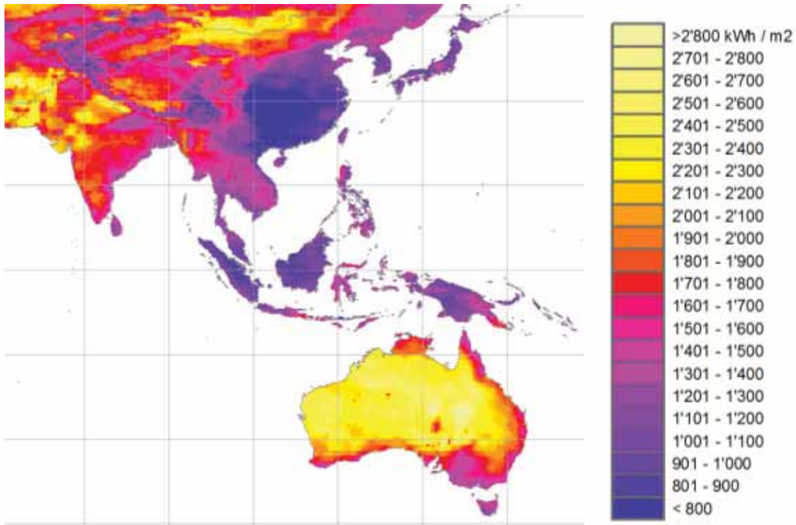

- Map shows annual Direct Normal Irradiation (DNI) in kWh/m² * year
- CSP needs not only high levels of DNI (>= 2,000 kWh/m² * year considered economically viable) but also flat ground and sufficient water supply

Source: Map extract from: Meteonorm 7.0 (www.meteonorm.com)

Basic principle of CSP plants with storage

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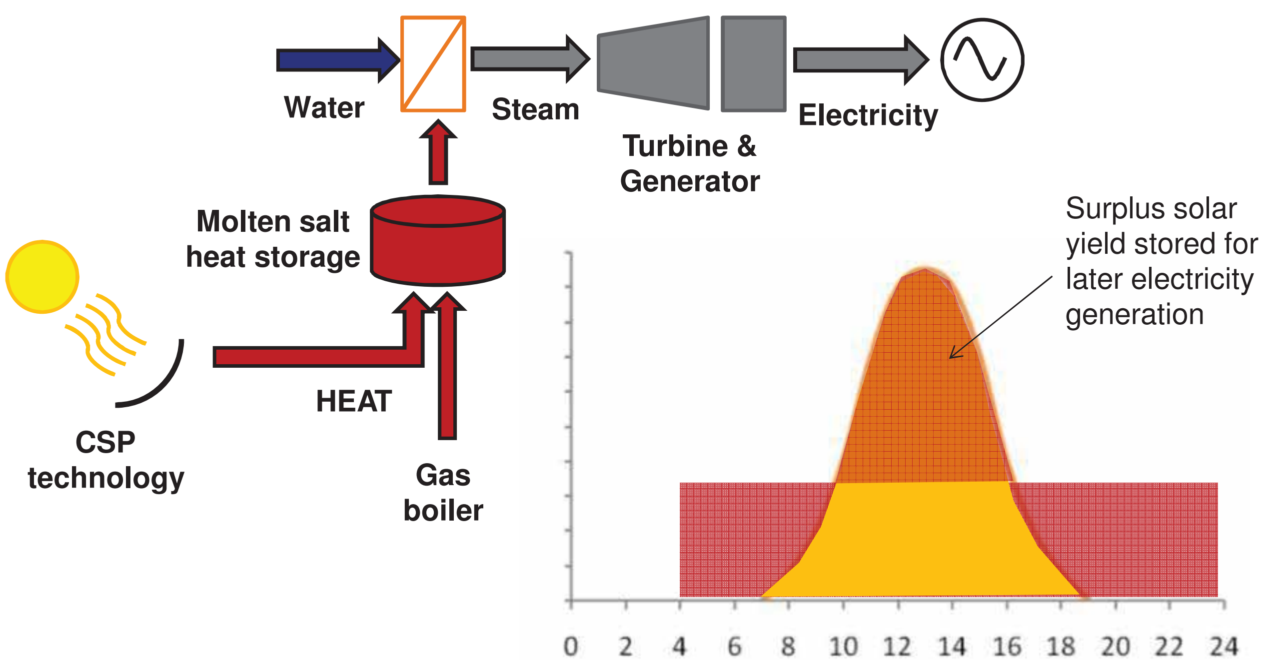


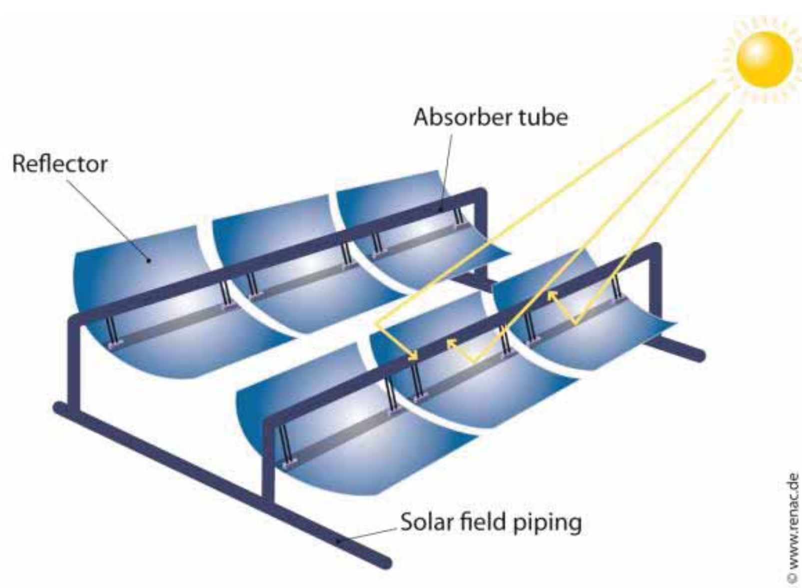
Use of heat storage to improve plant performance

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!

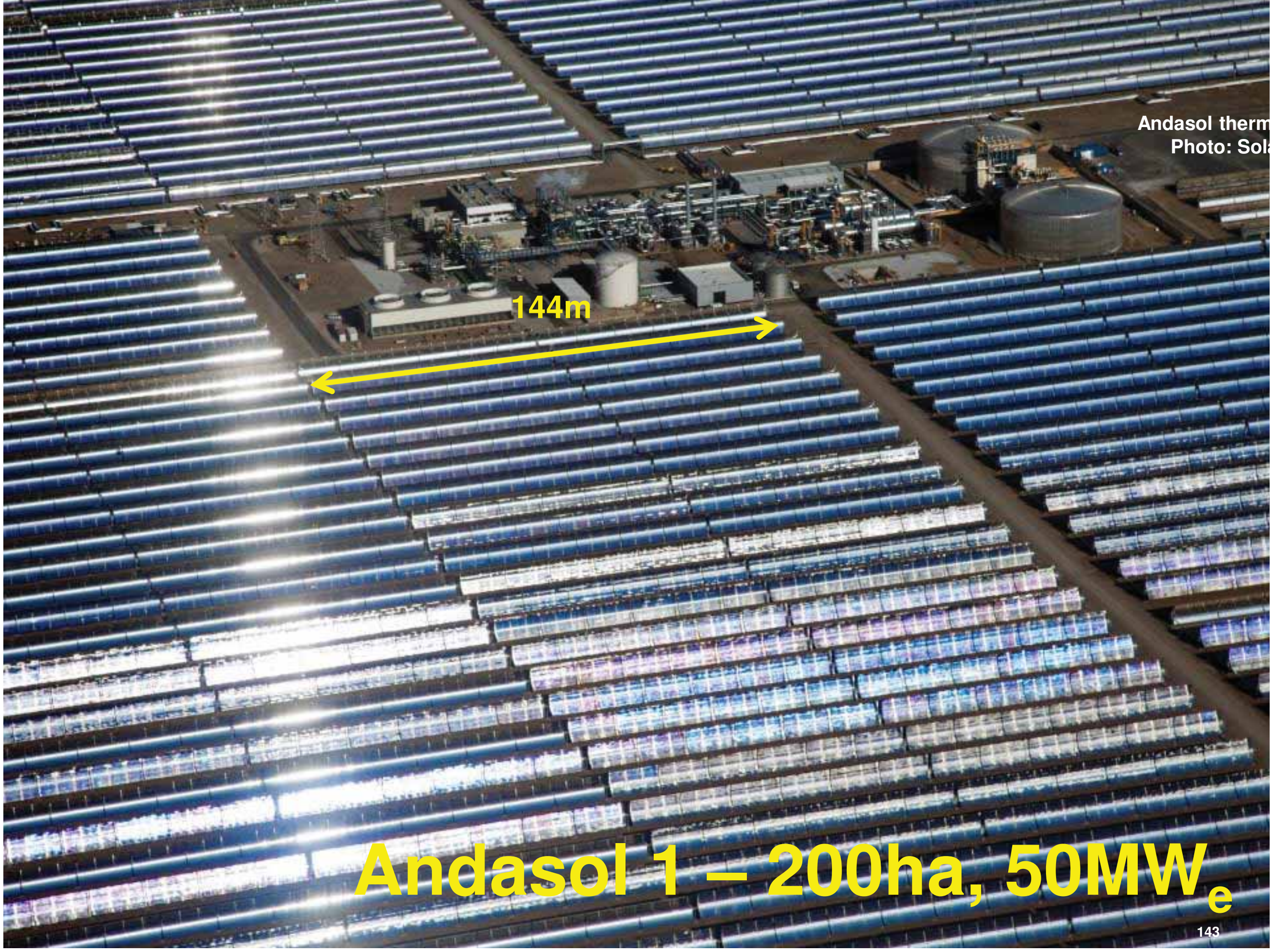
Photo: Solar Energy Generating System SEGS, California; © SANDIA

Parabolic trough collector - principle



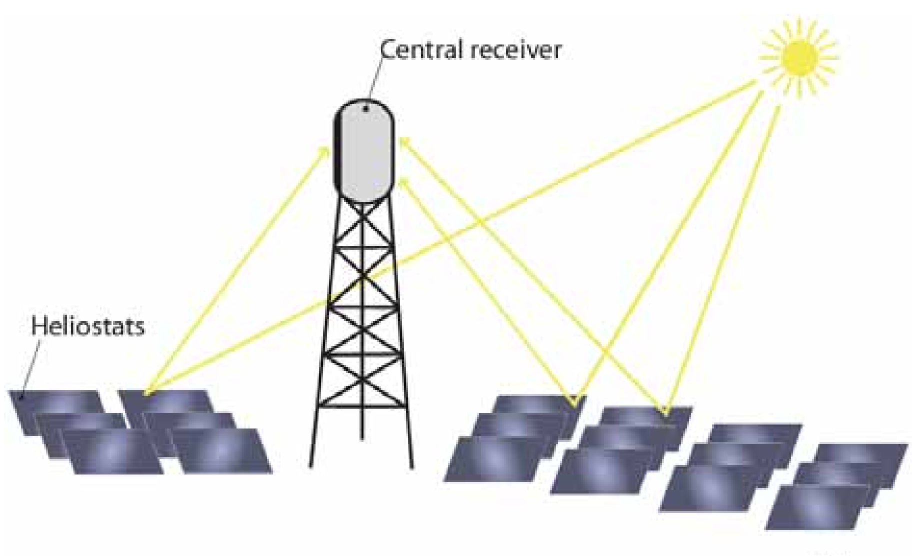
- Parabolic mirror tracks the sun in one axis and reflects Direct Normal Irradiation (DNI) on Heat Collecting Element (HCE)

Graph: RENAC



Andasol 1 – 200ha, $50MW_e$

Solar tower



Graph: RENAC

- 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.

Linear Fresnel power plant

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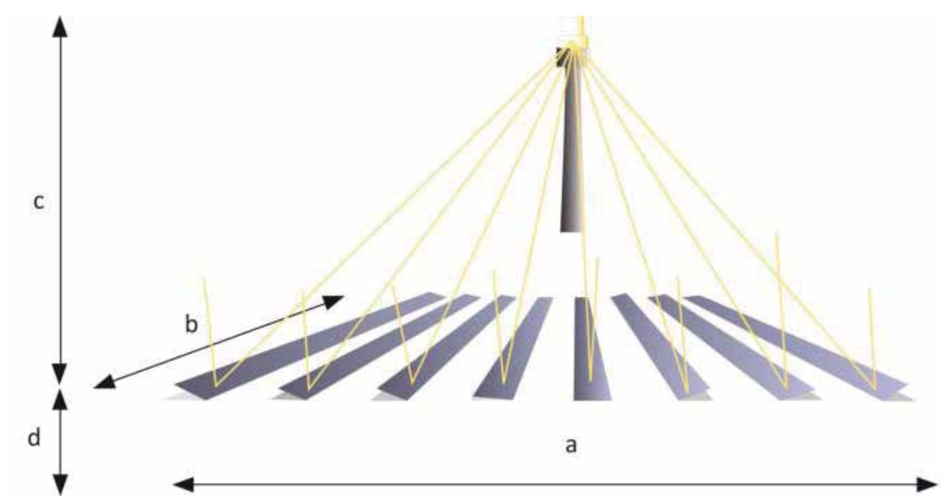
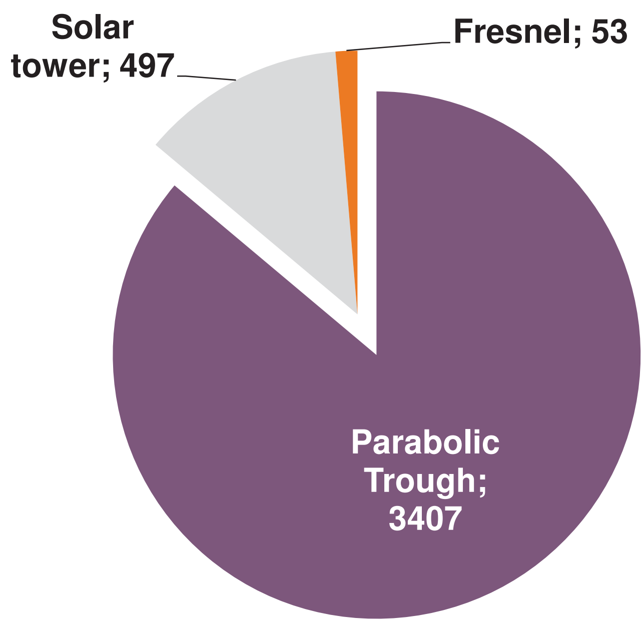
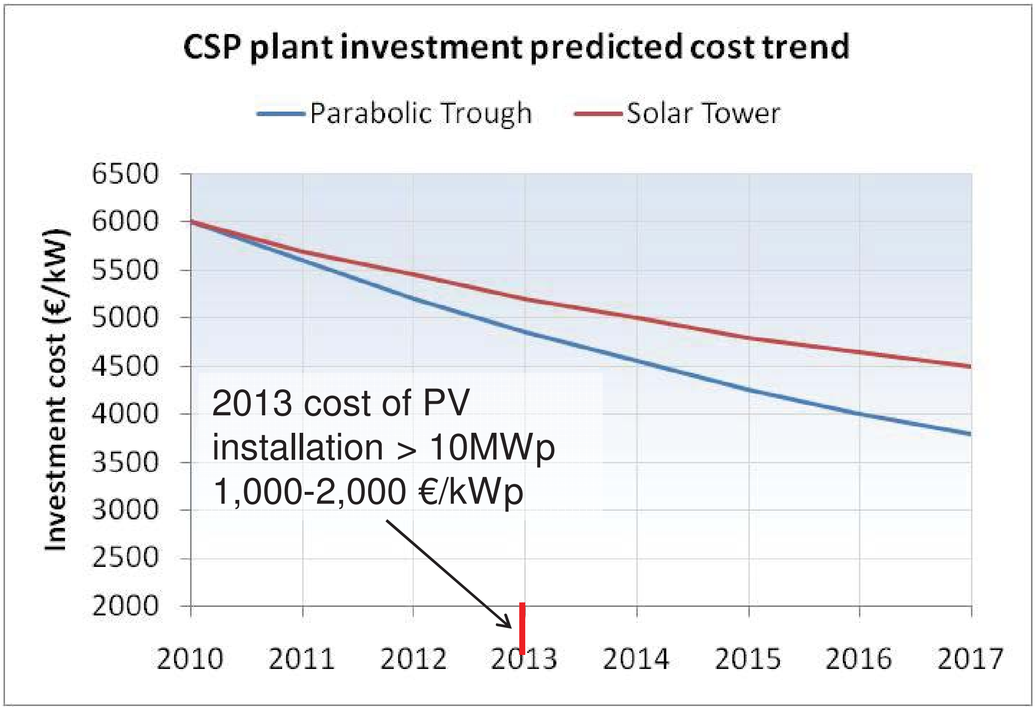


- Operation as for parabolic troughs.
- A series of mirror strips form a parabola shape. Low cost manufacturing.
- The mirror strips track the sun to optimise solar concentration onto receiver tube.
- Achieve lower temperatures. Suited to industrial heating applications.

CSP market & market development



Source: CSP Today Global Tracker; as of April 2014



Source: IRENA_CSP Cost Analysis, June 2012

CSP Plants – Costs and cost trends

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

- 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.

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!

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