Photovoltaics for decentralized power supply

Central America and Germany in comparison

Prof. Dr. Stefan Krauter, 8th June 2016
Guatemala-City

Overview of presentation

1. Solar Energy Potential
2. Principle and Characteristics of Photovoltaics
3. Photovoltaic Systems: On- and Off-Grid
4. Decentralized photovoltaics for Germany & Guatemala
5. How to size an off-grid PV System
6. Cost comparison: Diesel vs. PV
7. Implementation aspects

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Prof. Dr.-Ing. habil. Stefan Krauter

1998	Dipl.-Ing. for EE at University of Technology Munich
1993	Ph.D. at University of Technology Berlin
1996	Founder of SOLON AG (manufacturer of PV modules)
1998	Habilitation at University of Technology Berlin
1999	Founder of Rio-Solar Ltd (set-up of PV systems)
1998-2006	Visiting Professor at Federal University of Rio de Janeiro (lectures, set-up RE-lab, chairman of events *RIO 02-15*)
2006	Co-Founder, CEO of Photovoltaic Institute Berlin SE (Testing of PV modules & Quality control of PV systems)
2008-2010	Professor at University of Applied Sciences Biberach
Since 2010	Professor & Chair at University of Paderborn, Vice-Director of Competence Center for Sustainable Energy Technology (KET)

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University of Paderborn (UPB)

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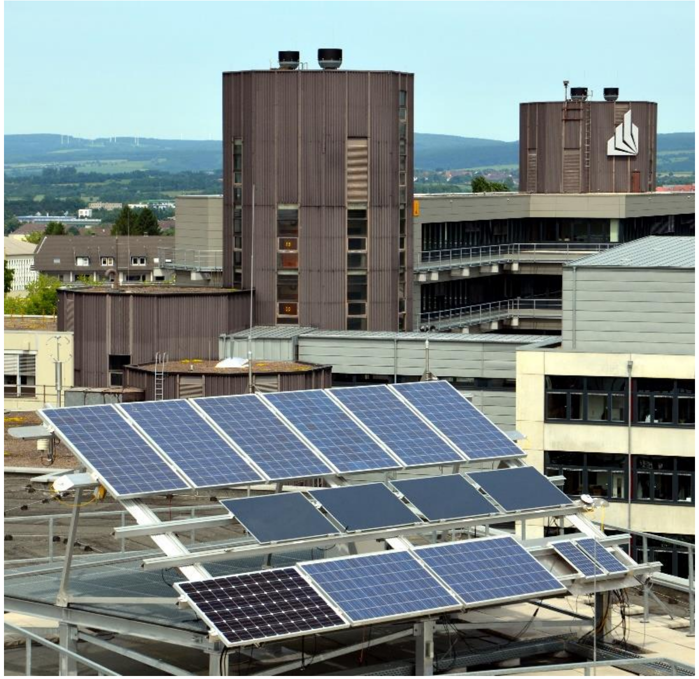
Electrical Energy Technology – Sustainable Energy Concepts



Research area:

Sustainable Generation and Use of Energy

- Energy efficient buildings
- Wind power monitoring
- Decentralized energy systems
- Virtual energy storage
- Load shifting via remote control of loads
- Yield prediction & optimization of PV

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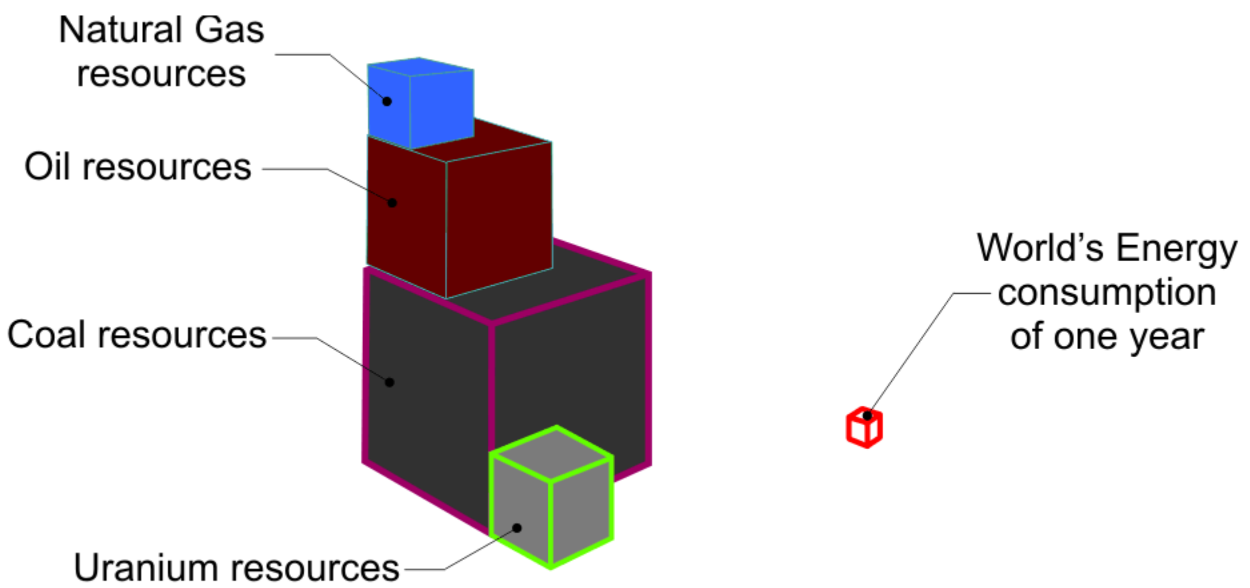
Energy consumption and resources



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Energy consumption and resources

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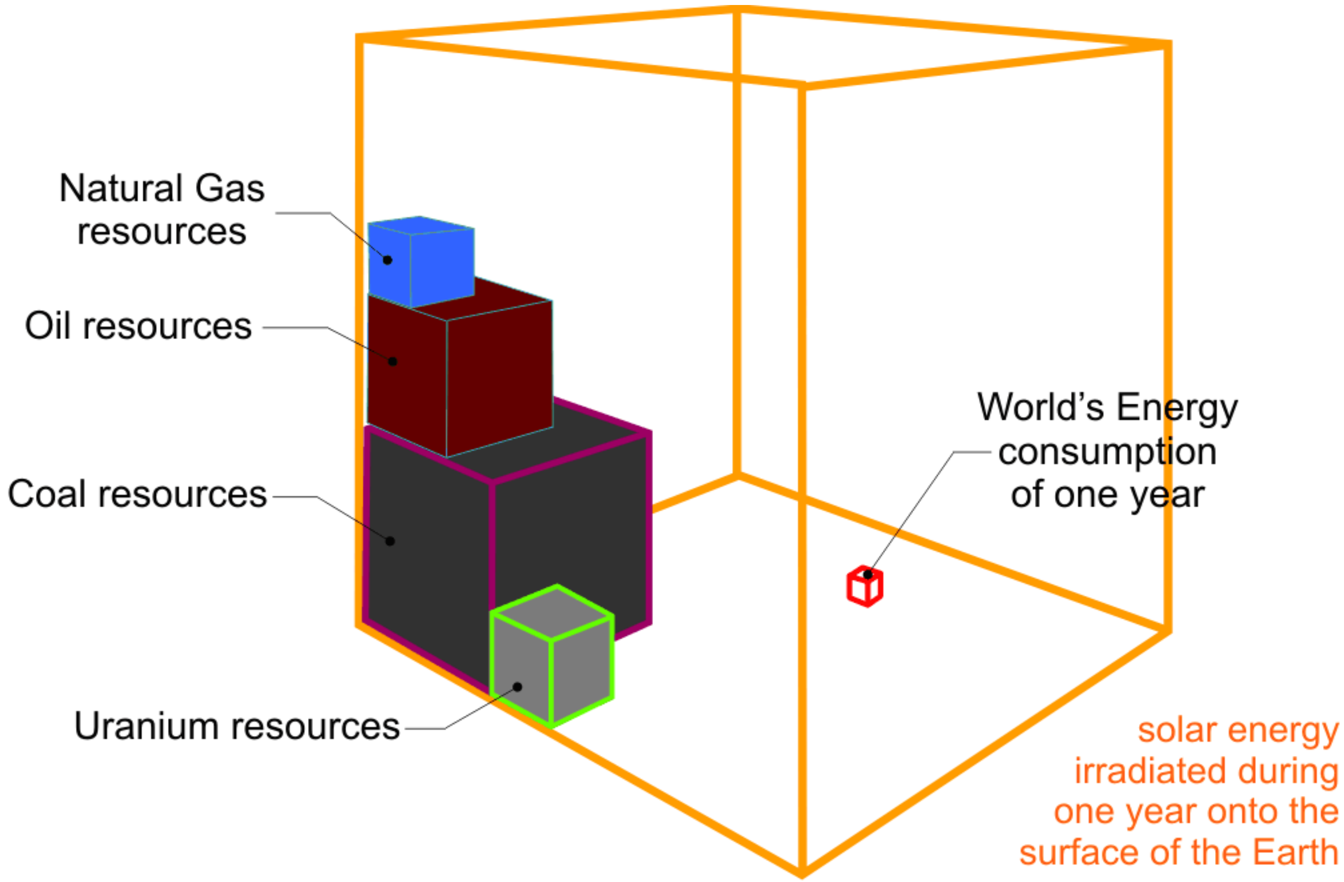

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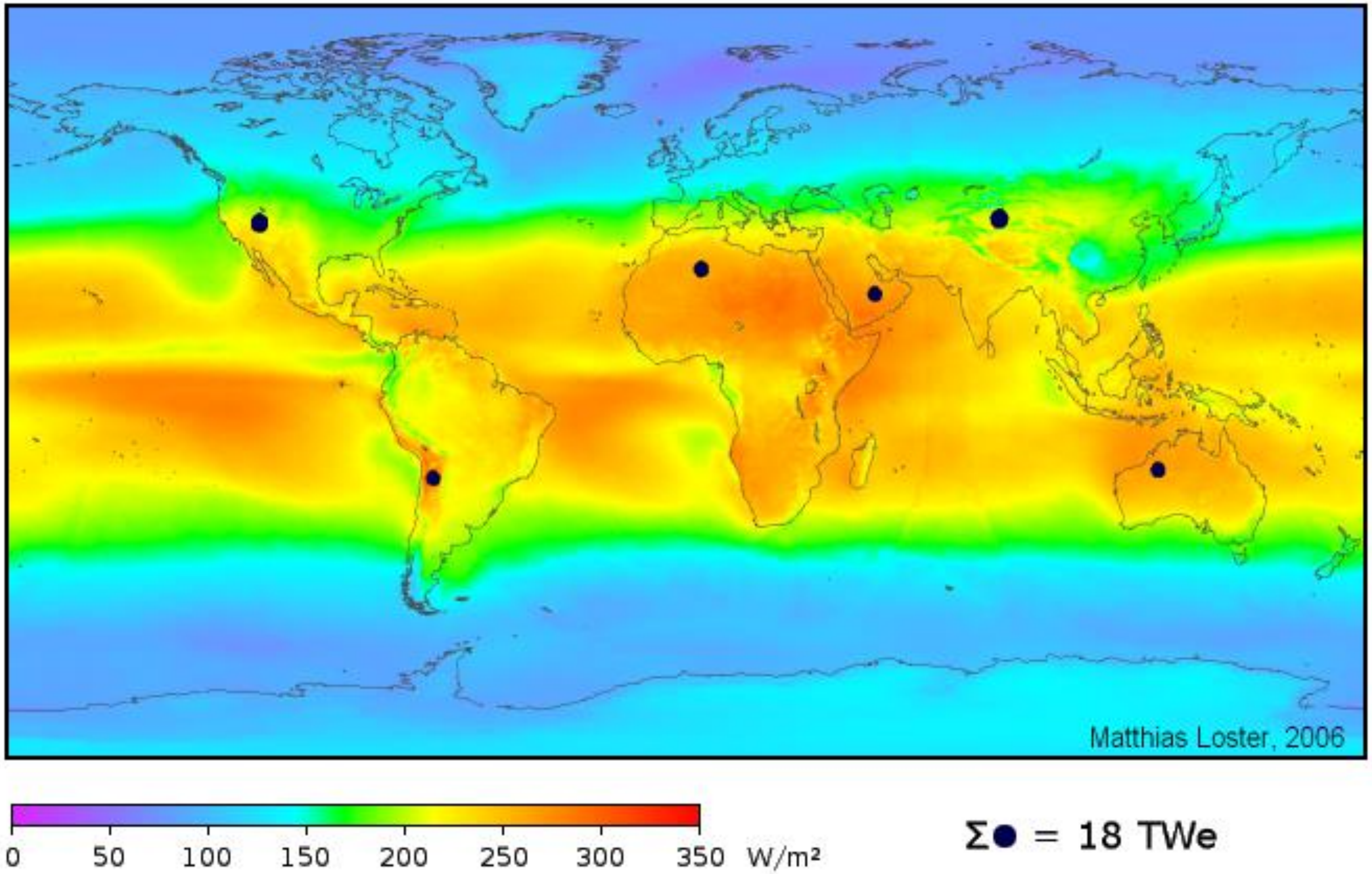
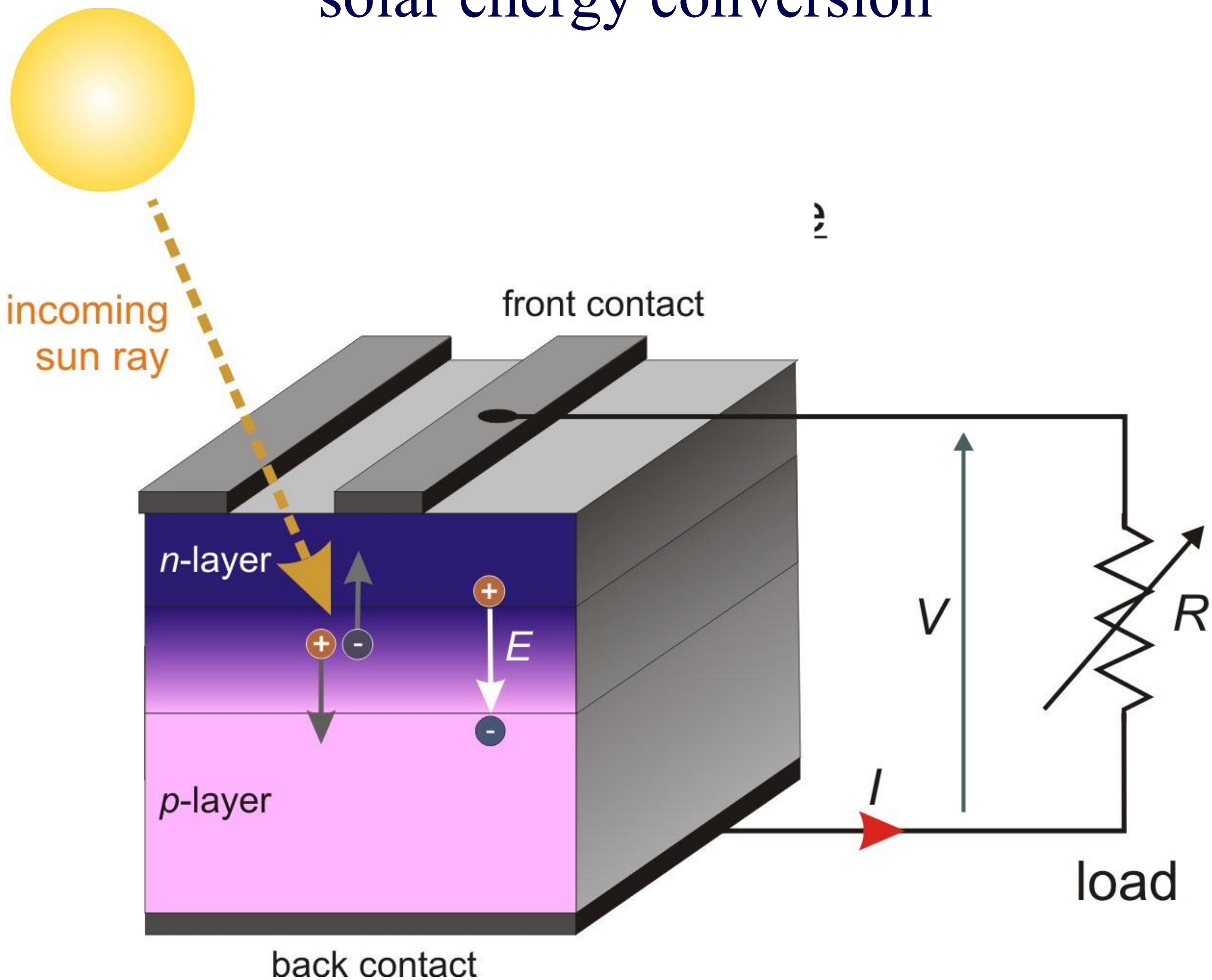
PV-Power for the Planet: Area requirements
Costs: 20 trillion Euros (incl. grid extension)



Scheme of photovoltaic solar energy conversion



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Essential for the photovoltaic effect:
Forming an electrical field in the transition region

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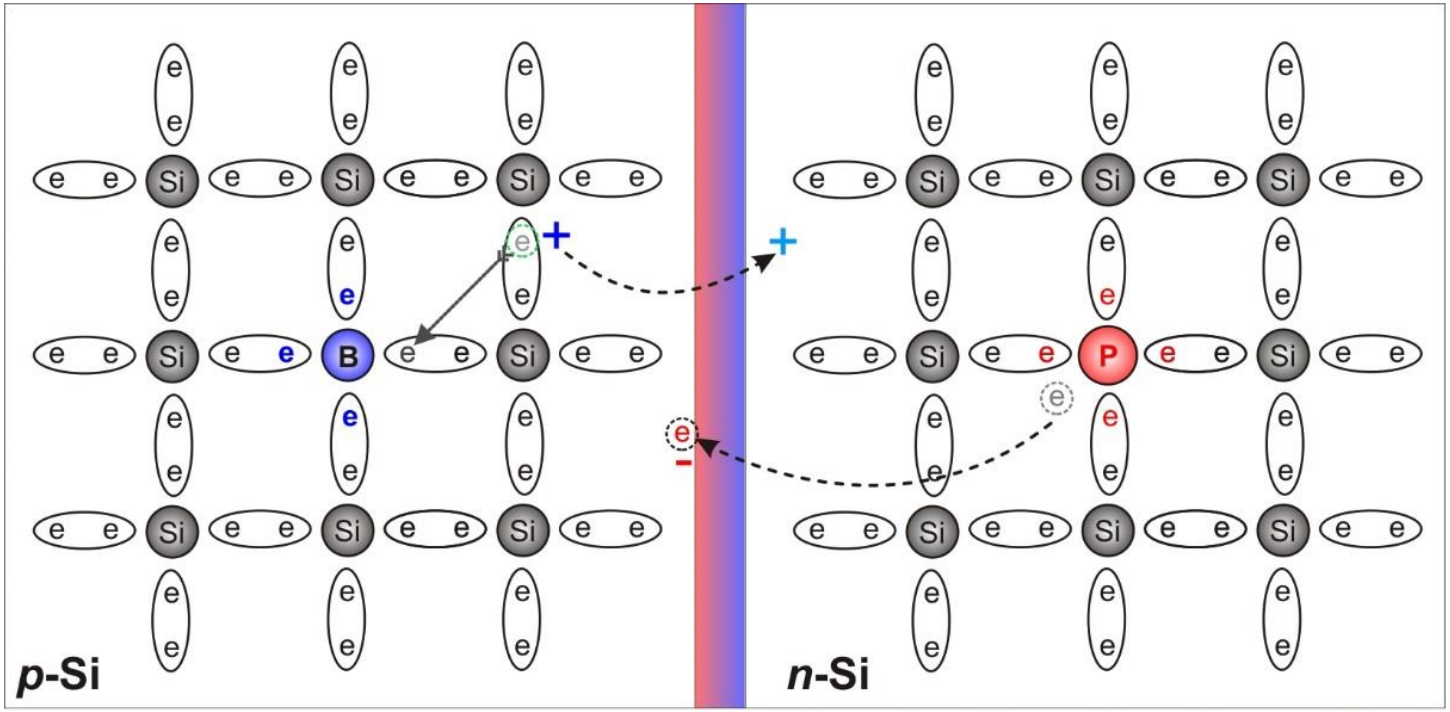

Doping with boron (3 outer electrons) causes free positive charge carriers (electron vacancy +)

If *p*-Si and *n*-Si are together, diffusion of free charge carriers into the other part occurs. Thus, the electrical neutrality is repealed: This creates an electric field in the transition region.

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Characteristics of a solar cell: *I-V* curve, power output, MPP

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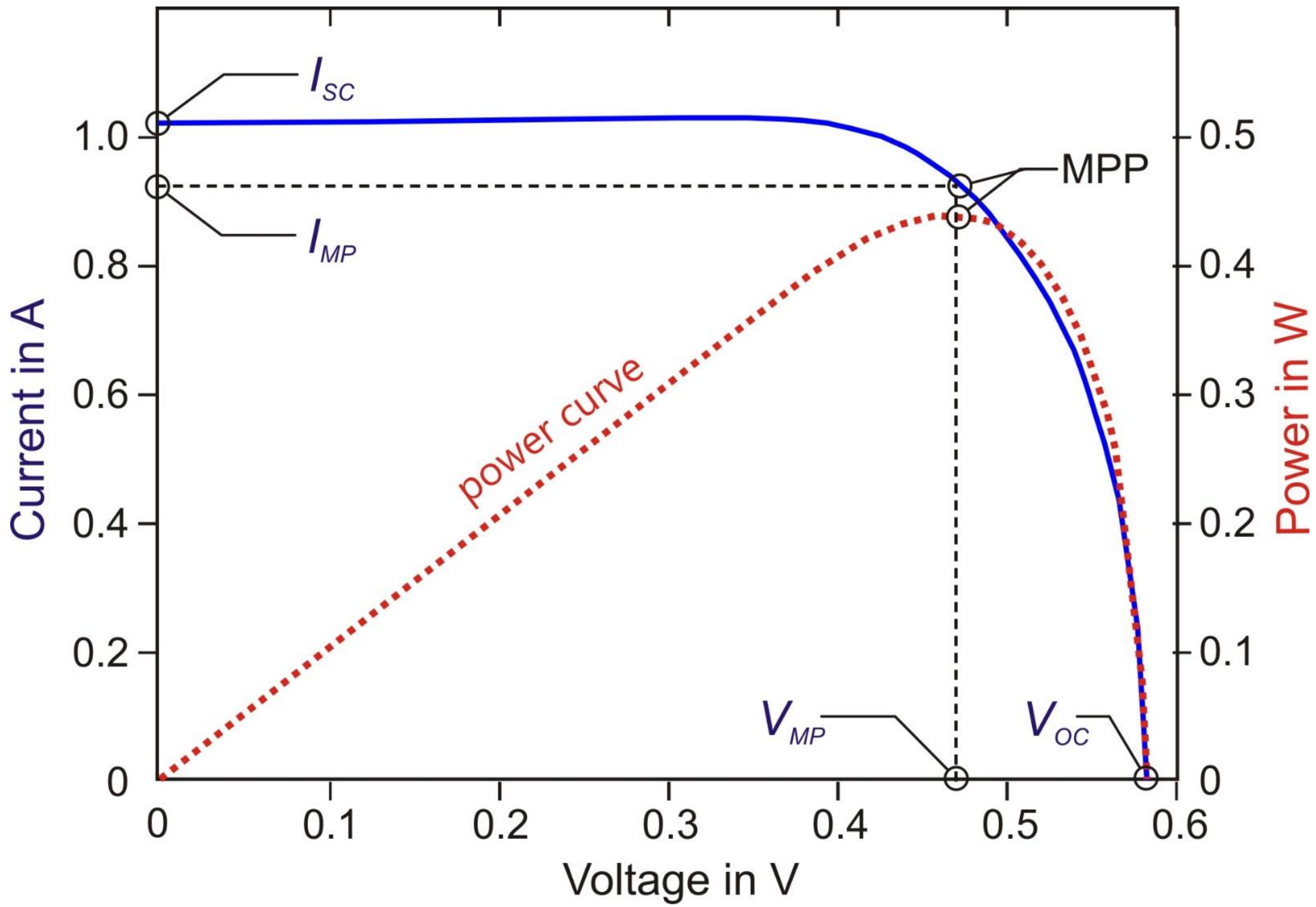

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I-V characteristics for different irradiance levels

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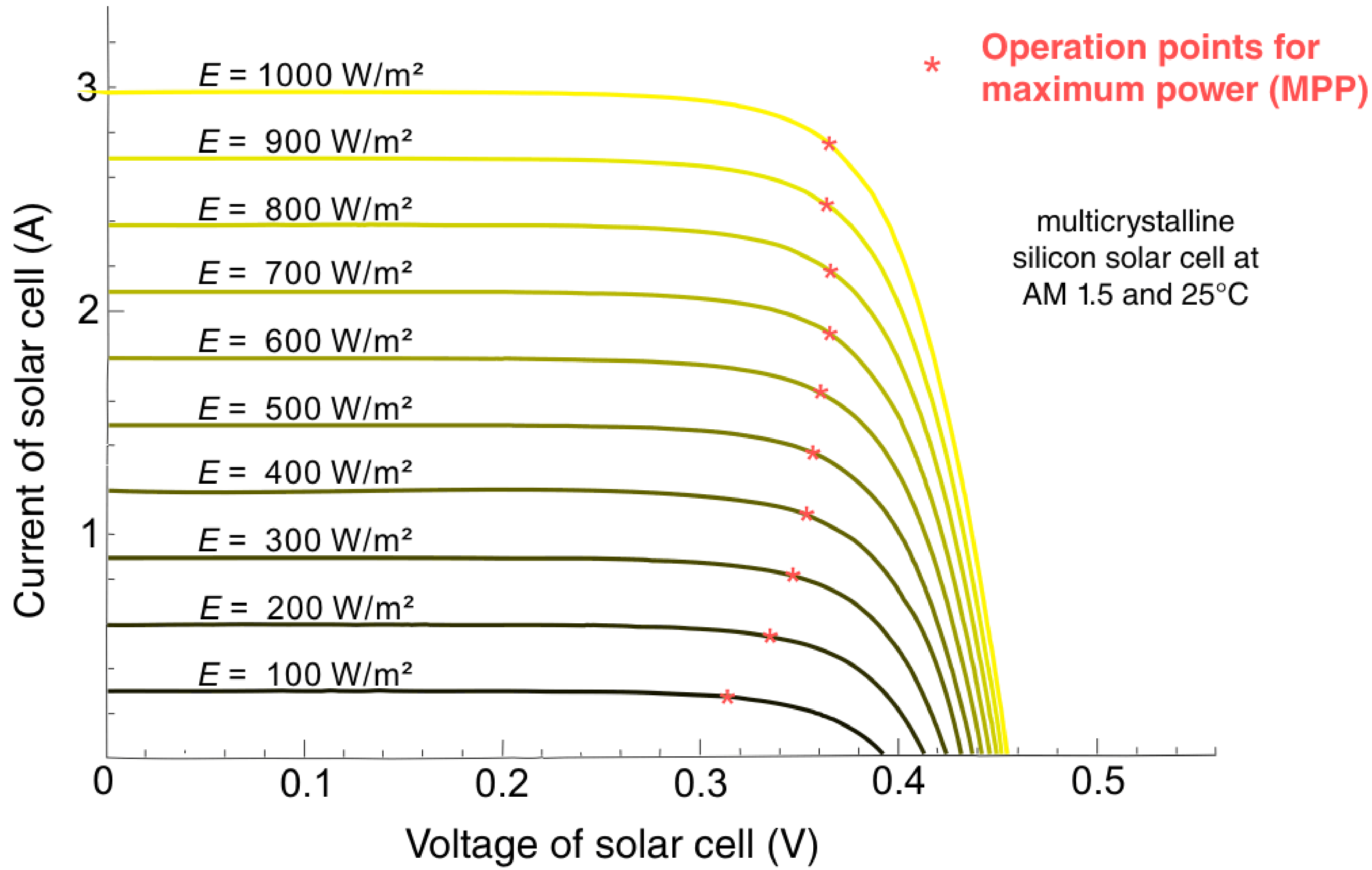

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I-V characteristics for different temperatures of cell

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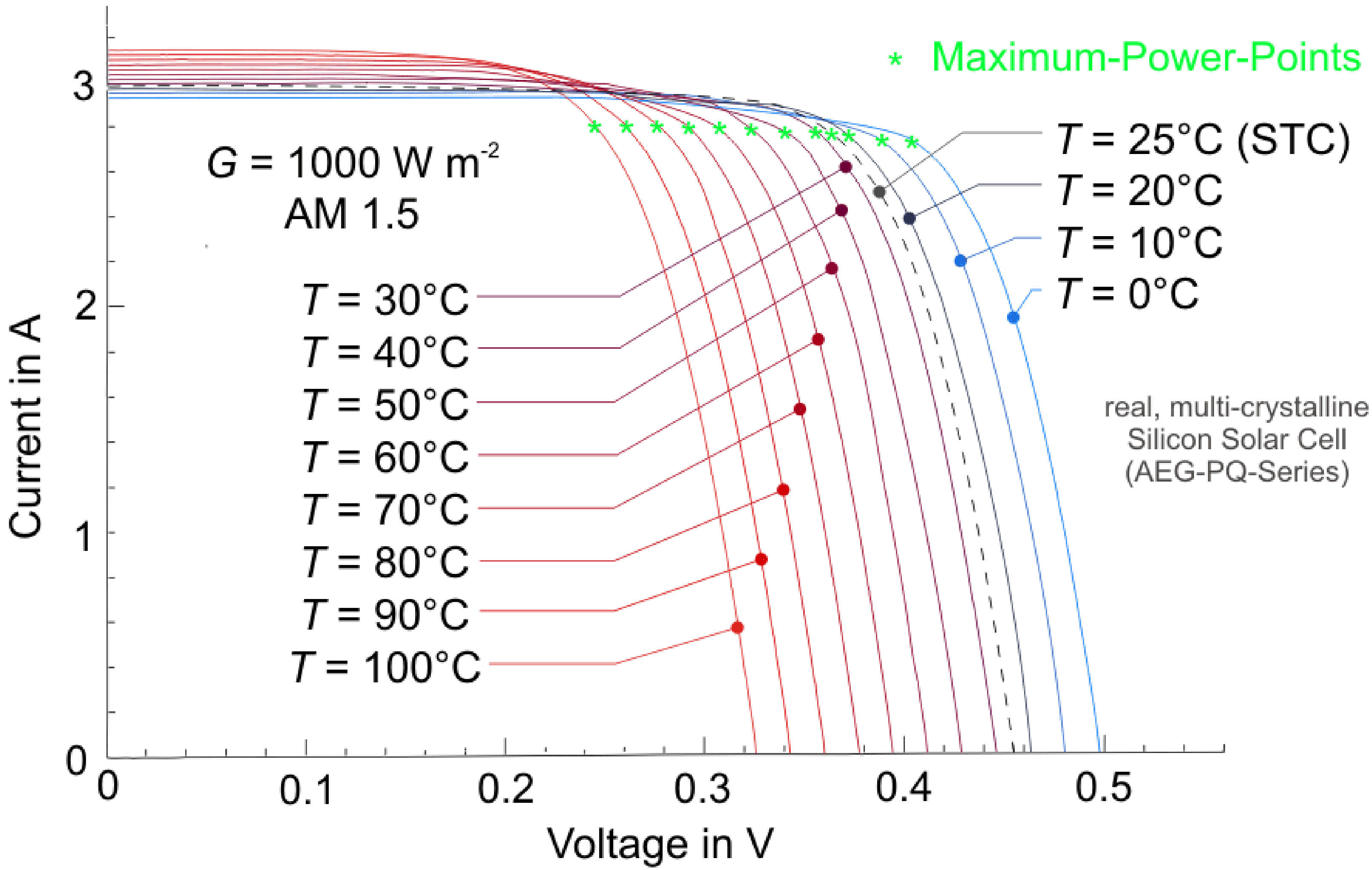

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Temperature coefficients of power, current, voltage

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Temperature coefficients for different PV technologies

	module eff.	**Tkoeff Pmax**	coeff. Current	coeff. Voltage	coff FF	NOCT
a-Si (triple)	5.3%	**-0.20%/K**	0.11%/K	-0.32%/K	0.02%/K	45.1
a-Si (tandem)	5.2%	**-0.20%/K**	0.07%/K	-0.30%/K	0.03%/K	49.0
CdTe	7.7%	**-0.23%/K**	0.05%/K	-0.30%/K	0.02%/K	45.1
a-Si (single)	5.5%	**-0.24%/K**	0.09%/K	-0.33%/K	0.00%/K	47.7
DSC	0.8%	**-0.30%/K**	0.50%/K	-0.30%/K	-0.50%/K	40.0
HIT	15.1%	**-0.31%/K**	0.03%/K	-0.25%/K	-0.08%/K	49.0
mono Si	11.6%	**-0.41%/K**	0.05%/K	-0.39%/K	-0.08%/K	45.8
CIS	9.1%	**-0.44%/K**	0.04%/K	-0.34%/K	-0.13%/K	47.0
multi Si	11.8%	**-0.44%/K**	0.05%/K	-0.39%/K	-0.10%/K	45.0
multi EFG Si	11.6%	**-0.47%/K**	0.10%/K	-0.41%/K	-0.16%/K	46.3
Ribbon Si	10.0%	**-0.47%/K**	0.06%/K	-0.49%/K	-0.03%/K	44.0
mono LGBC	13.3%	**-0.49%/K**	0.05%/K	-0.45%/K	-0.09%/K	47.0
Apex	7.6%	**-0.52%/K**	0.08%/K	-0.49%/K	-0.12%/K	45.7

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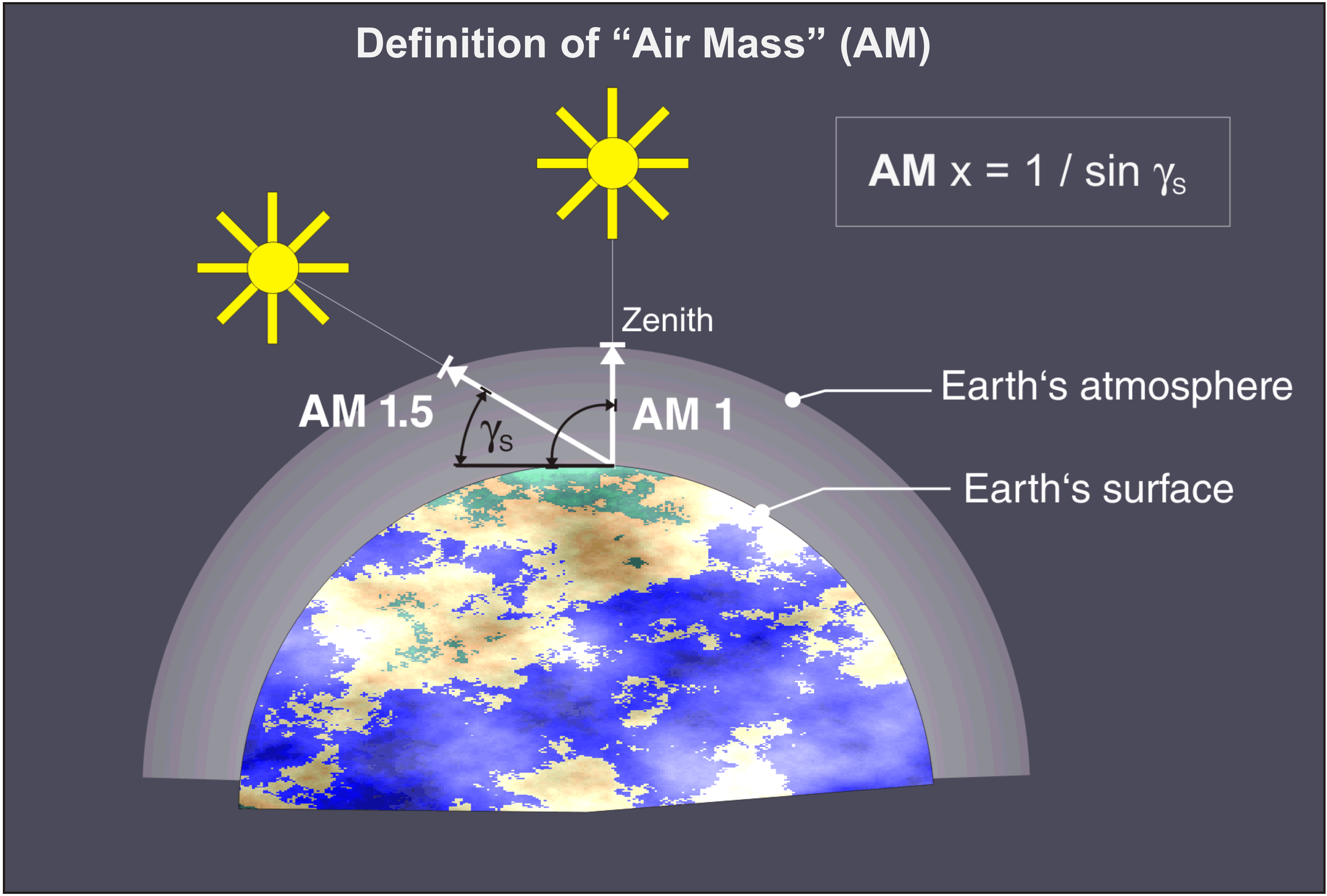

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Spectra during different parts of the day and the spectral efficiency of a solar cell

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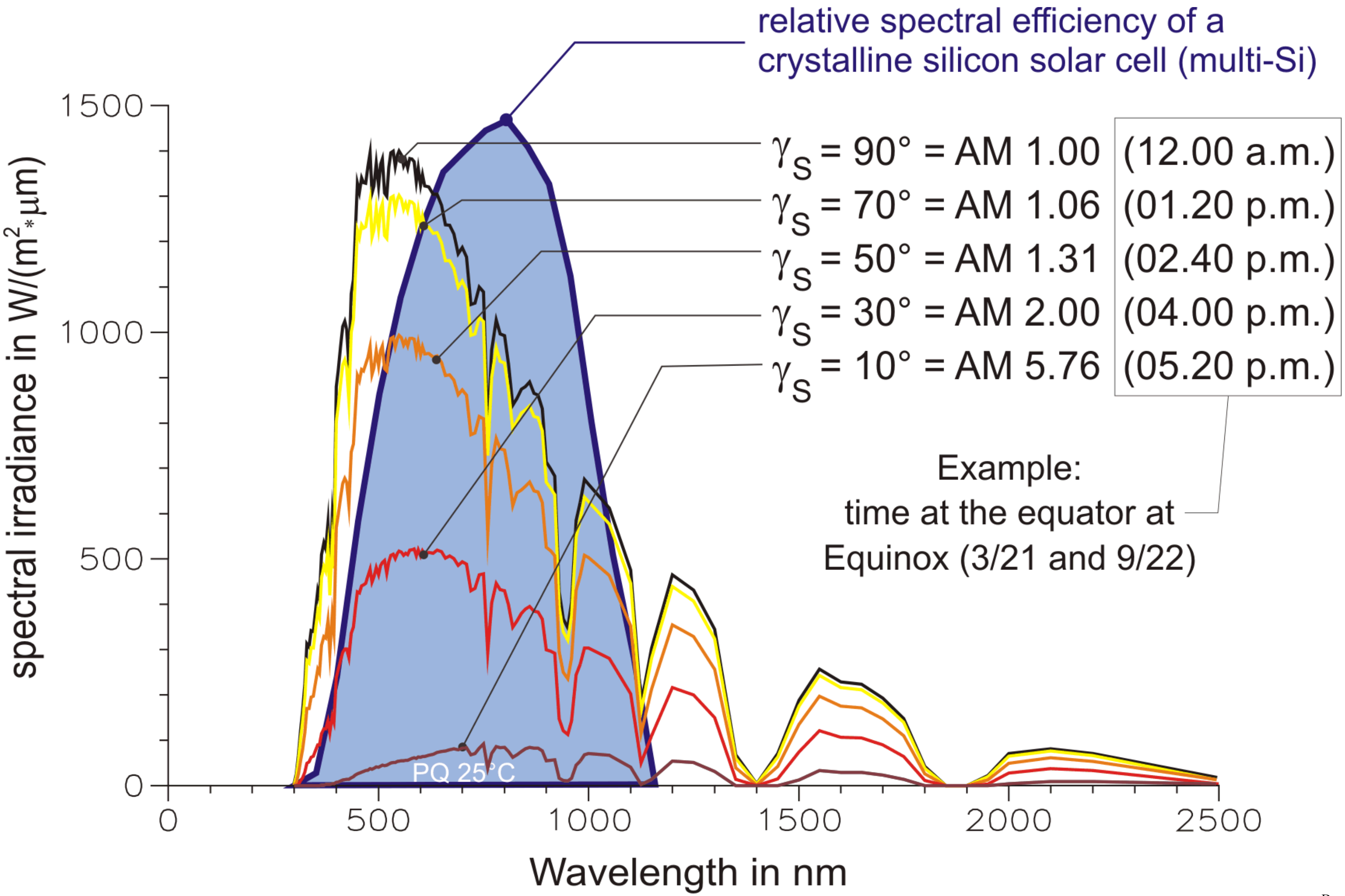

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Spectra during the day and the spectral efficiency of different solar cell technologies

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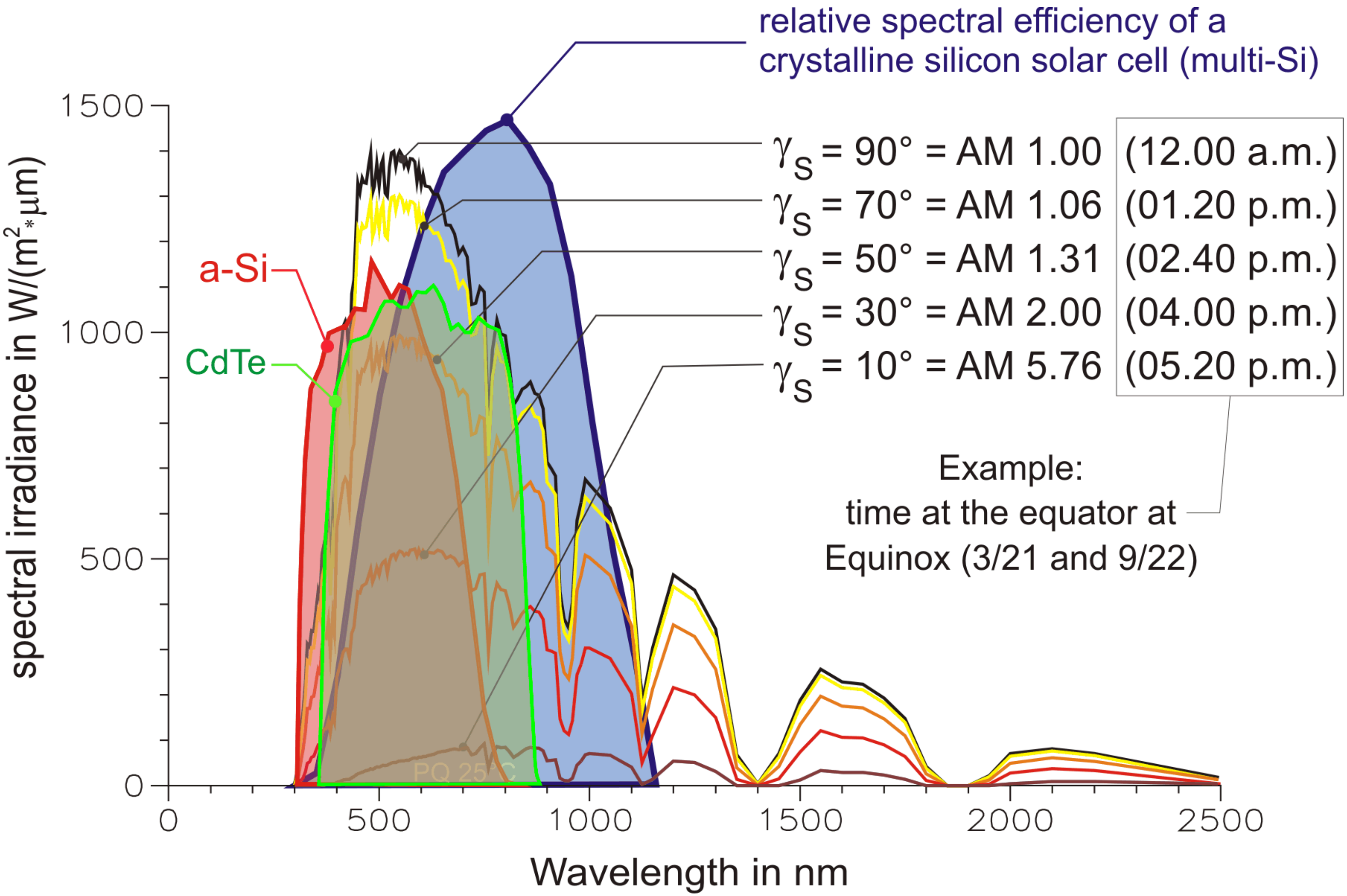

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From solar cell to PV generator

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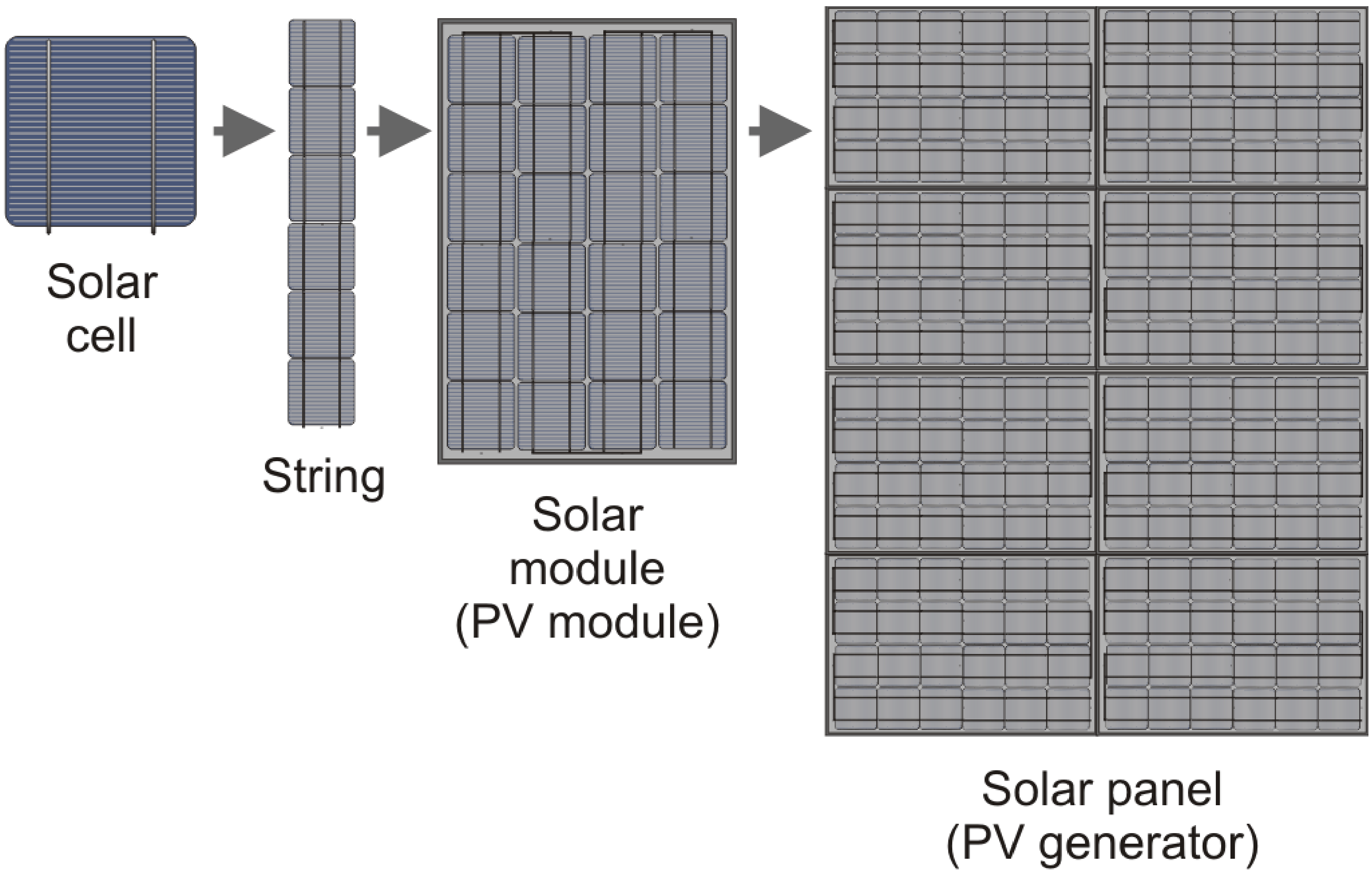

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PV module for crystalline cells with frame

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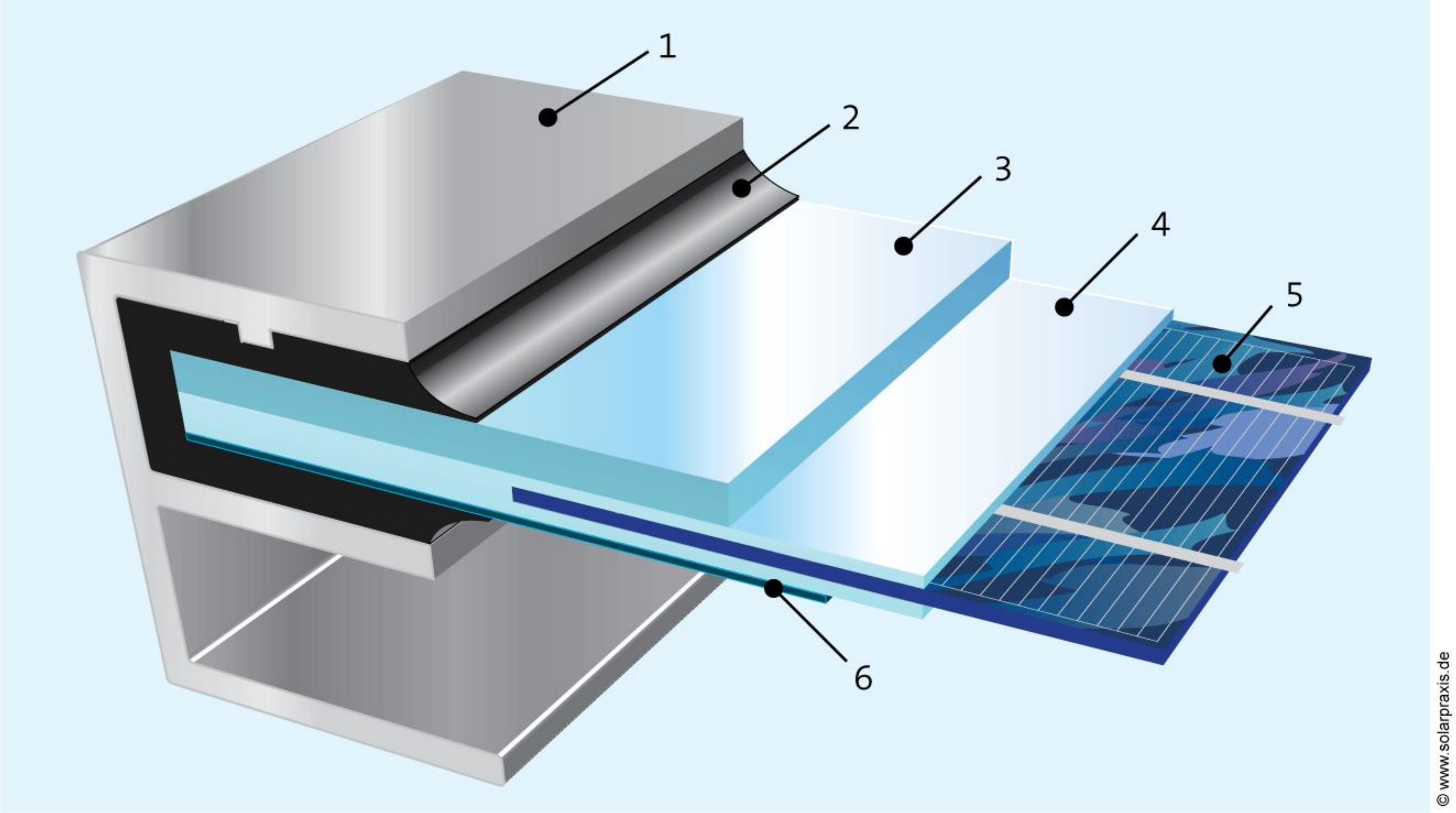

1 Aluminum frame, 2 Seal, gasket, 3 Glass, 4 EVA embedding, 5 crystalline solar cell, 6 Tedlar-Polyester-Foil

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Interconnection of modules, distribution-box, inverters via MC4 sockets and plugs

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STC: Standard Test Conditions

indicated by index “p” at Wattage: W_p

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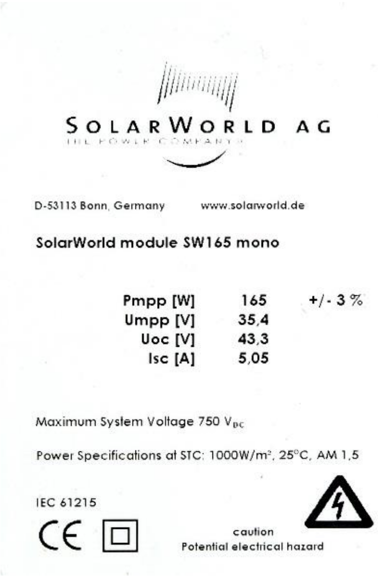
Fixed conditions to measure and compare the performance (e.g. P_{MPP}, V_{OC}, I_{SC}, η) of a PV module:



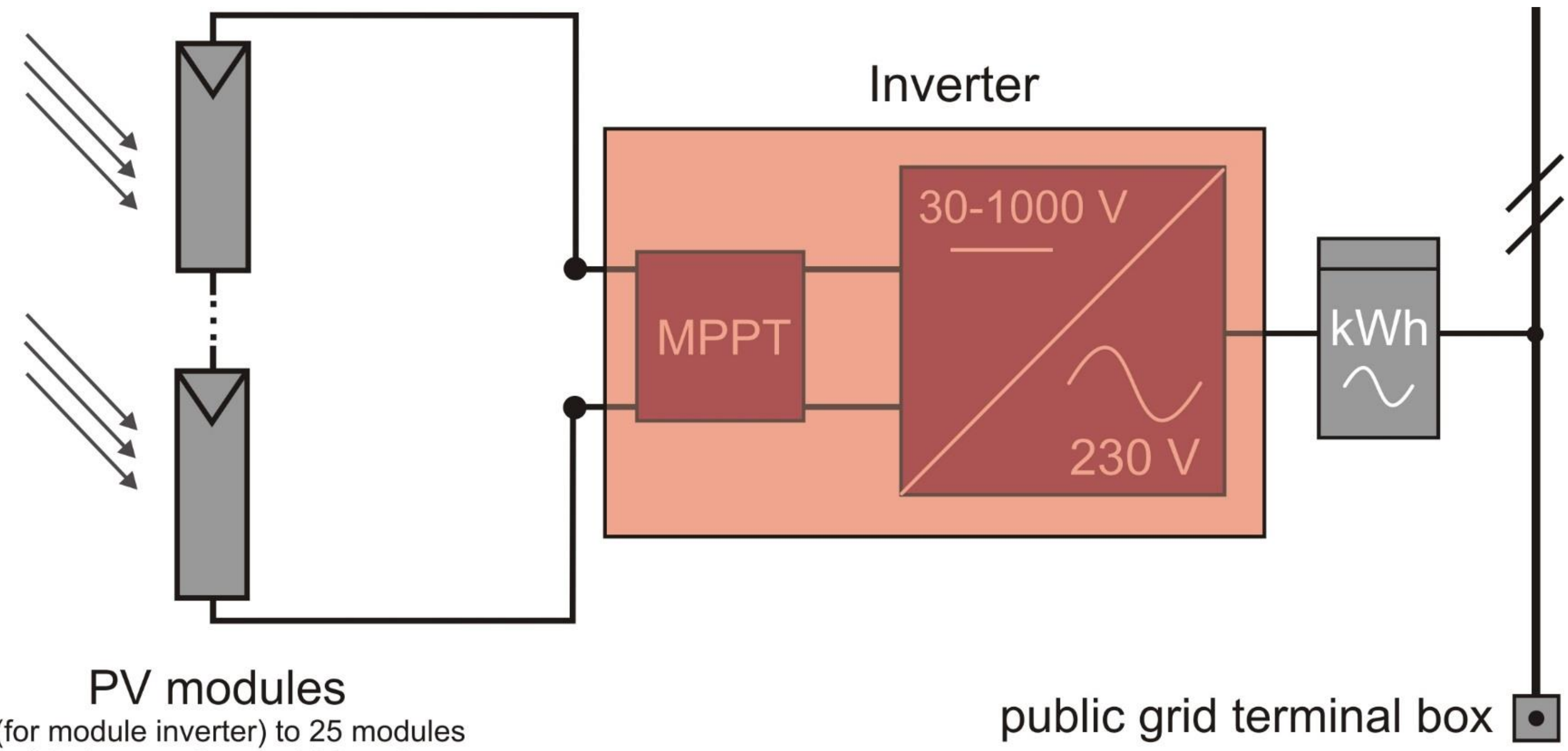
Cell Temperature:	$T_c = 25^\circ$ C
Global Irradiance level:	$E = 1000$ W/m²
Spectrum according to	AM 1.5
Incidence angle of irradiance	$\theta = 0^\circ$

Usually, STC is measured in the laboratory or in a factory via a solar simulator („Flasher“)

Scheme of Inverter with MPPT

Integration of Maximum-Power-Point-Tracker

Inverter for grid injection (grid-feeding):
Dependent on grid, synchronizes to grid voltage and frequency



PV modules
1 (for module inverter) to 25 modules
(Limit: max. System Voltage)

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PV grid-injection system: 1.5 million PV-houses in Germany

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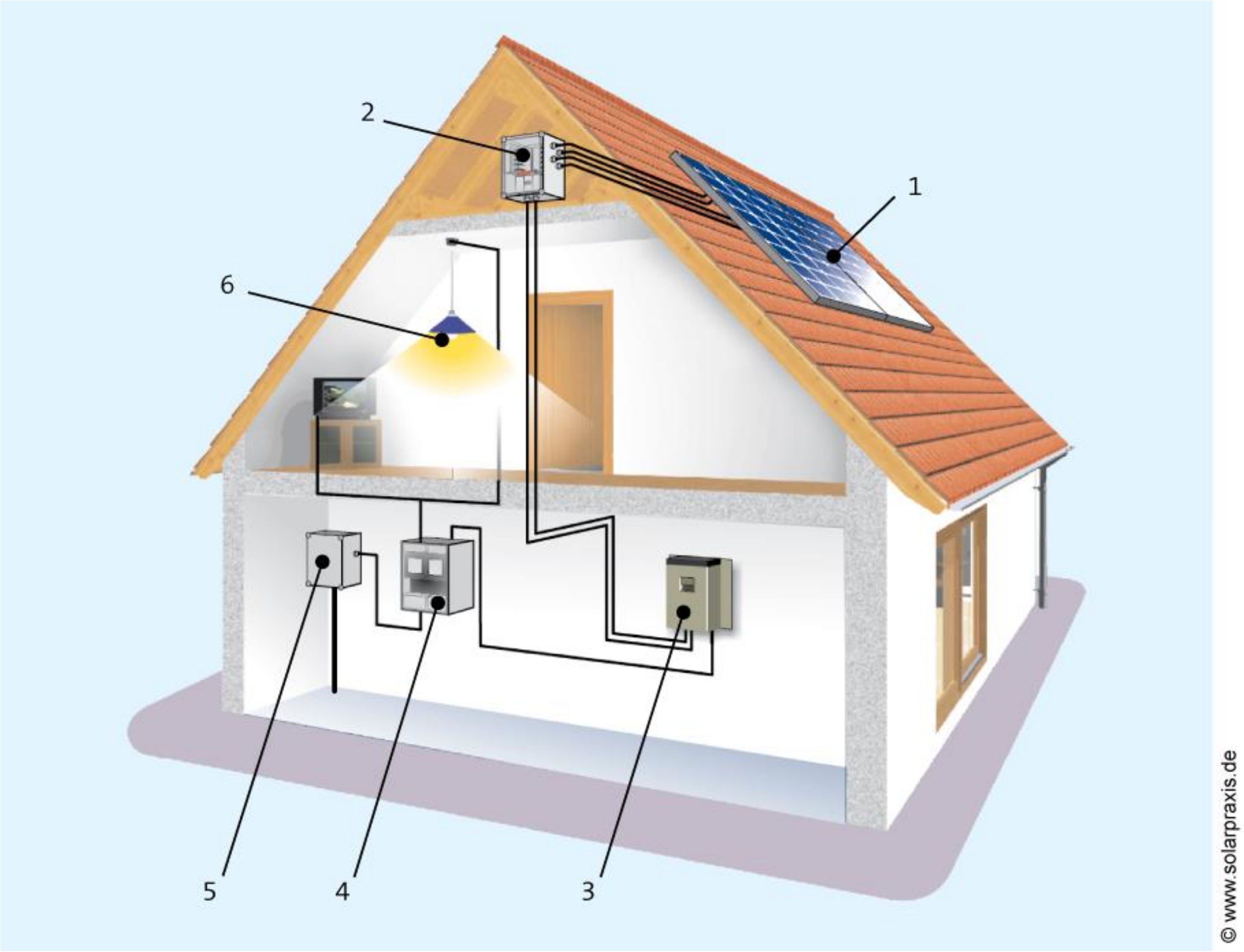

1 PV generator, 2 DC Junction box, 3 Inverter, 4 kWh-meter for consumption and PV injection, 5 grid connection, 6 local loads

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Grid-connected houses in Freiburg Generating more electricity than consumed

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PV system on Munich airport: Generation & Use during daytime

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11 MW PV power plant in Cerpa, Portugal

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67 MW PV power plant in Germany

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PV-learning-curve caused by effective feed-in legislation and investments in mass production (for crystalline Si-wafer based PV)

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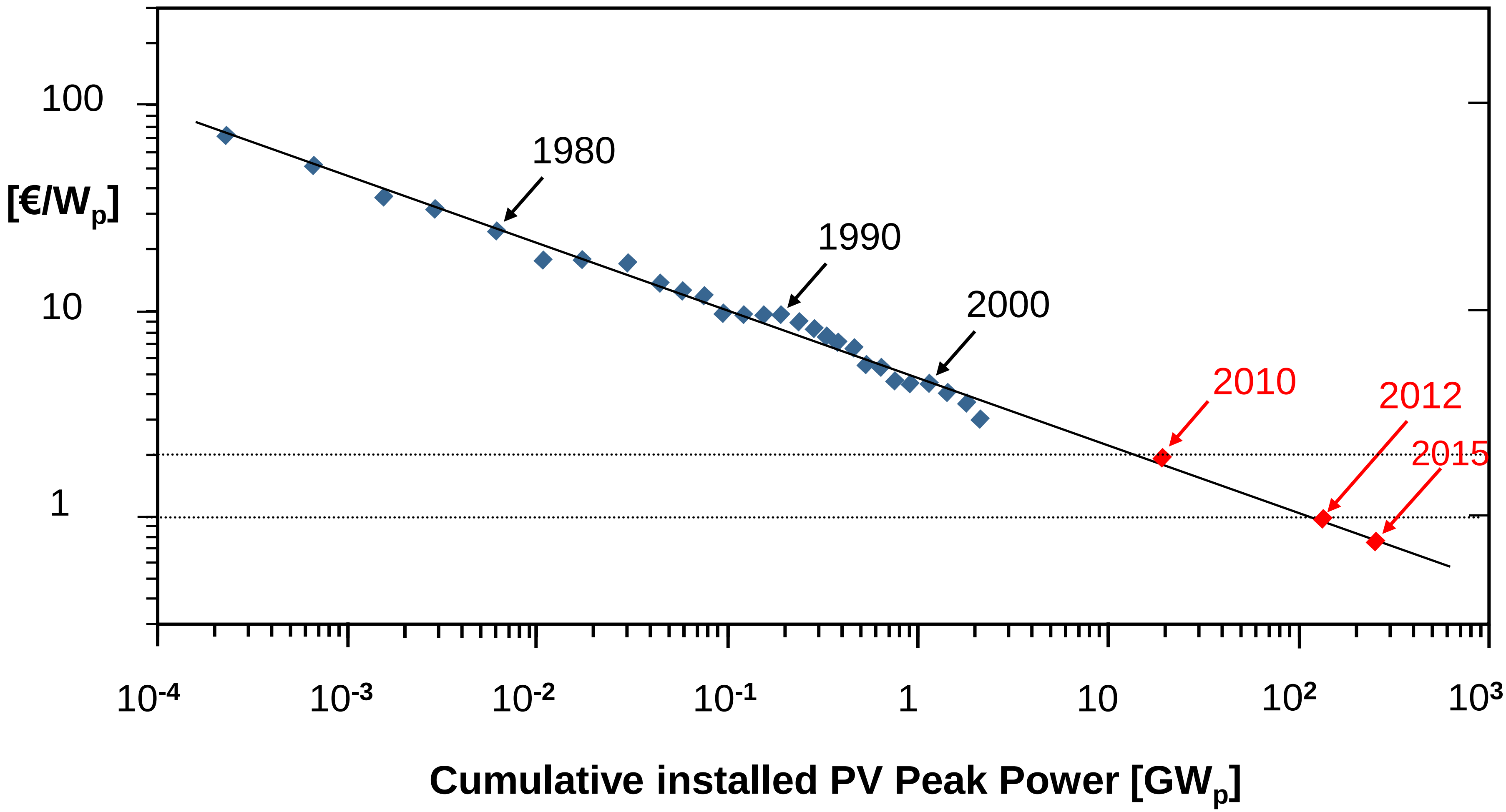

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Development of PV electricity costs in Germany (900 PV full-load hours per year) and in Guatemala (1800 PV full-load hours per year)

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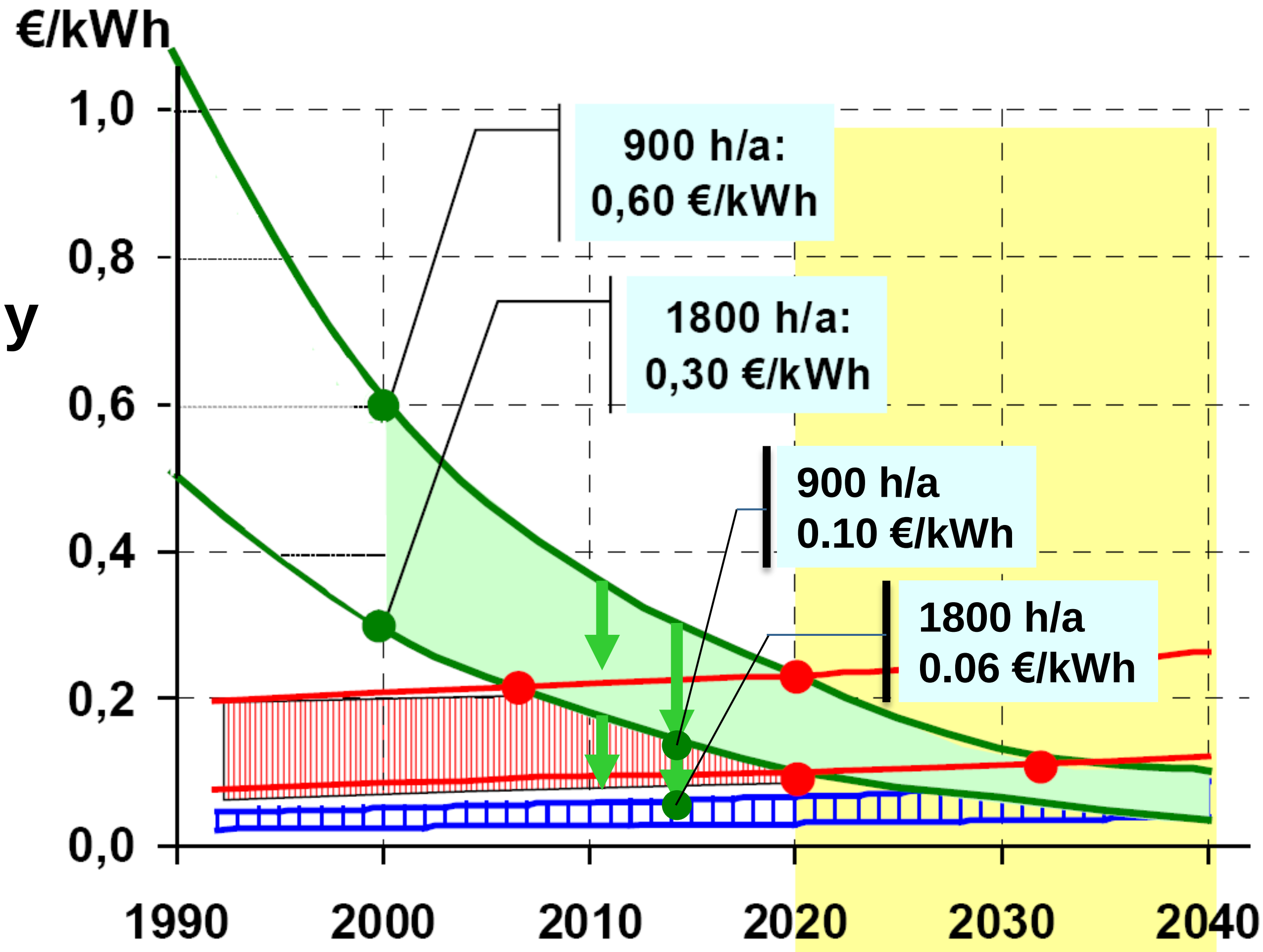
Costs for electricity supply (grid & PV)



PV

Peak load

Base load

References: Hoffmann 2000, Krauter 2010

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PV cumulative installed capacity 2000-2014 (in MW)

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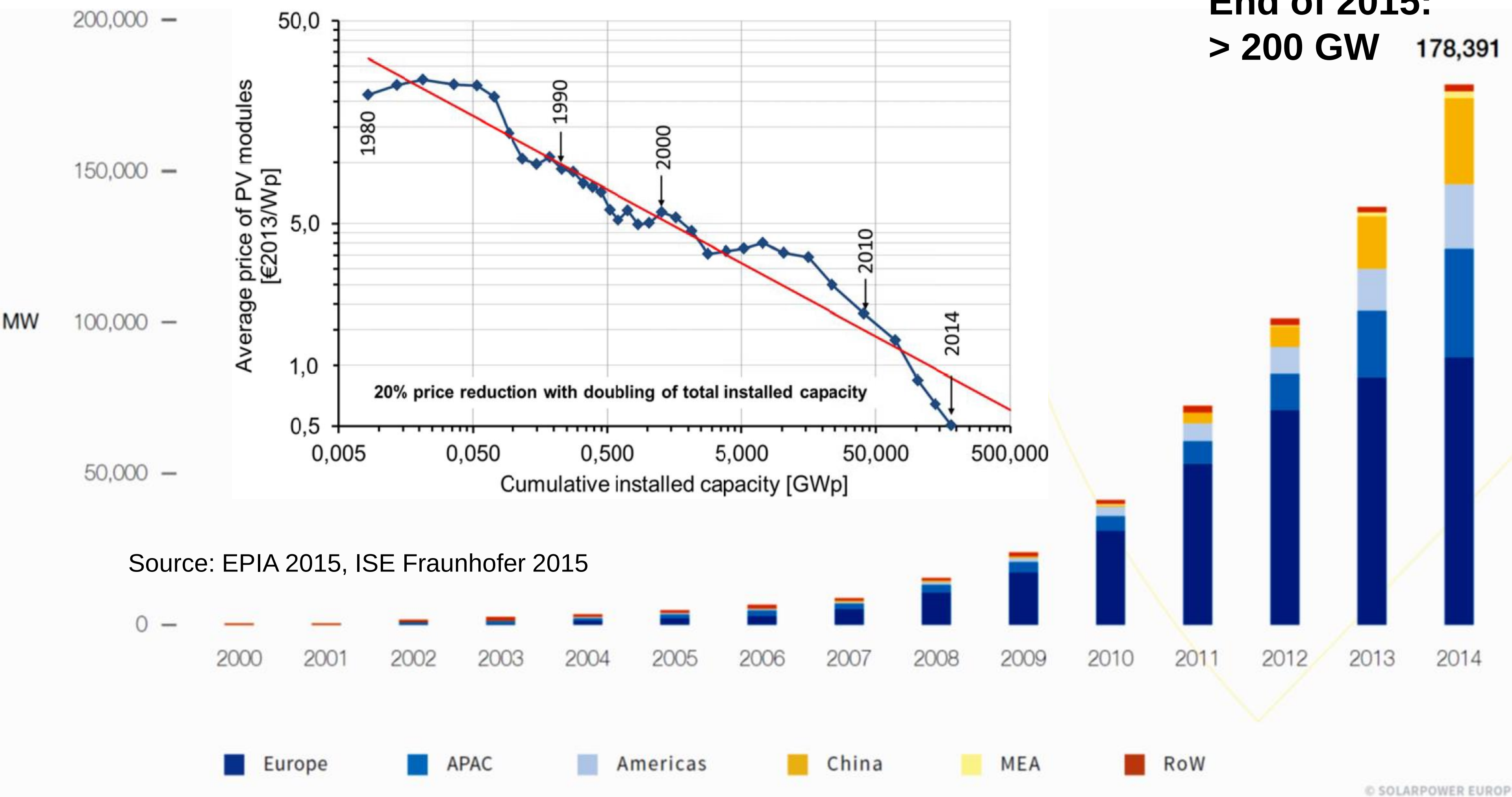
End of 2015:
> 200 GW



Source: EPIA 2015, ISE Fraunhofer 2015

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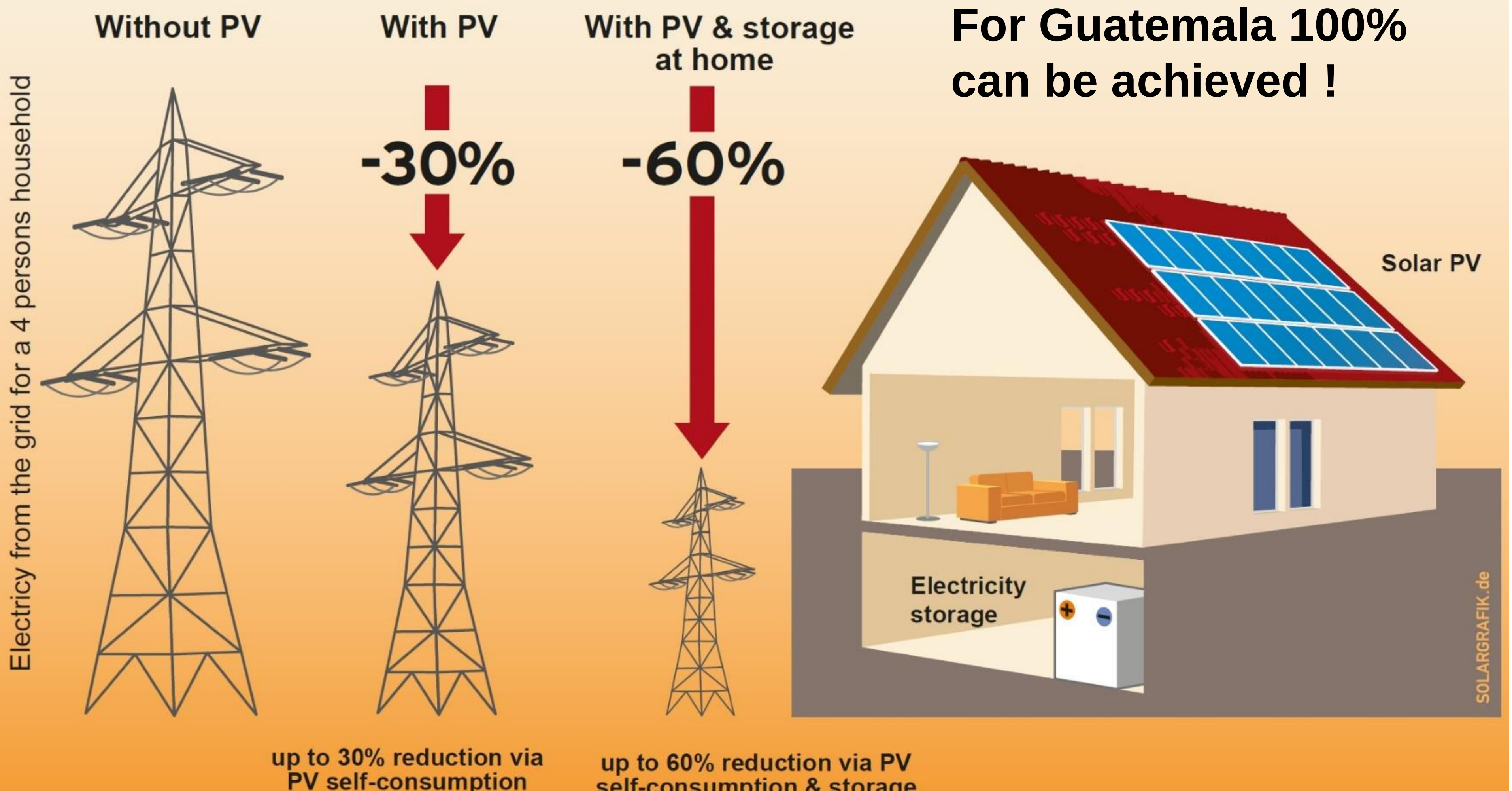
New trend: PV & home storage: Up to 60% less electricity from the grid

German case -
For Guatemala 100%
can be achieved !



Base: Household with 4 persons: 4500 kWh/a, PV generator of 5 kW, effective storage capacity: 4 kWh

www.solarwirtschaft.de

Frauenhofer ISE, Quaschning HTW Berlin, BSW-Solar

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First applications of decentralized PV

Space, science fiction, remote power supply

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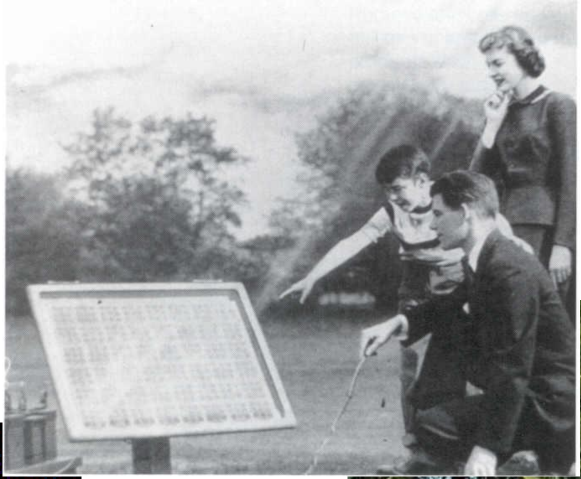
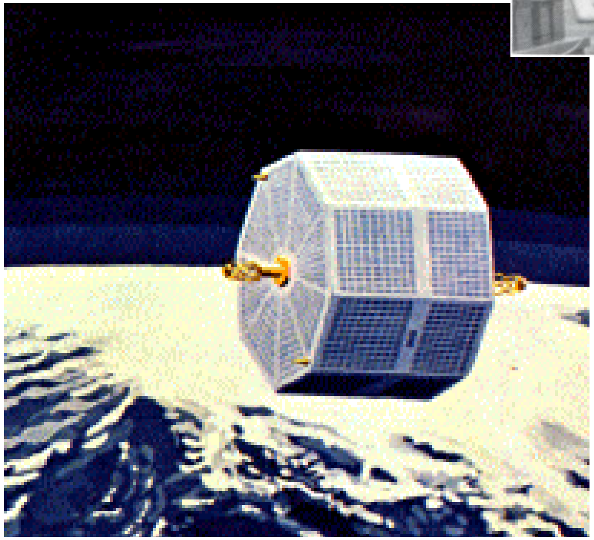
Important:
Far away from electrical grid





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Market for decentralized PV systems

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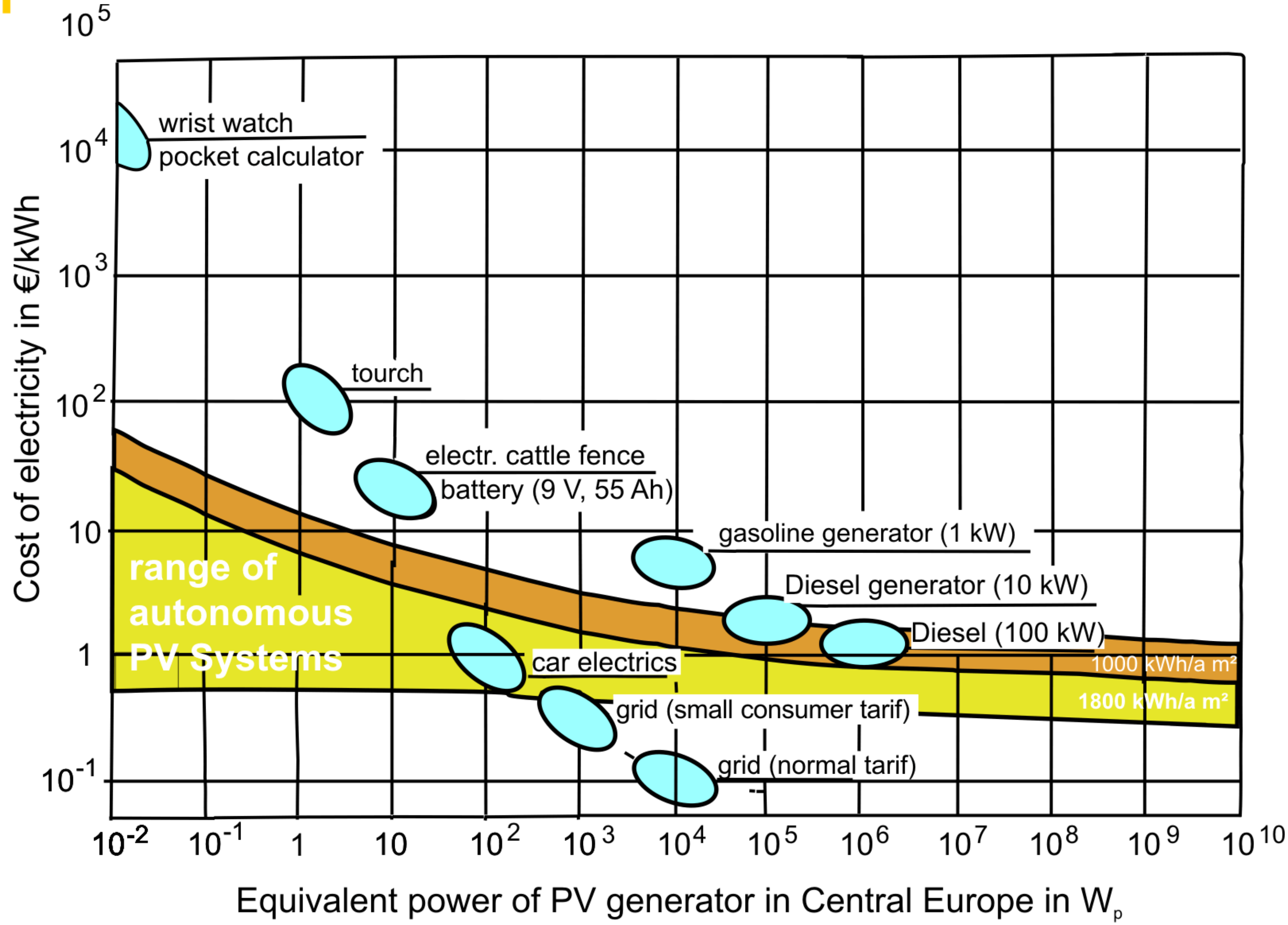

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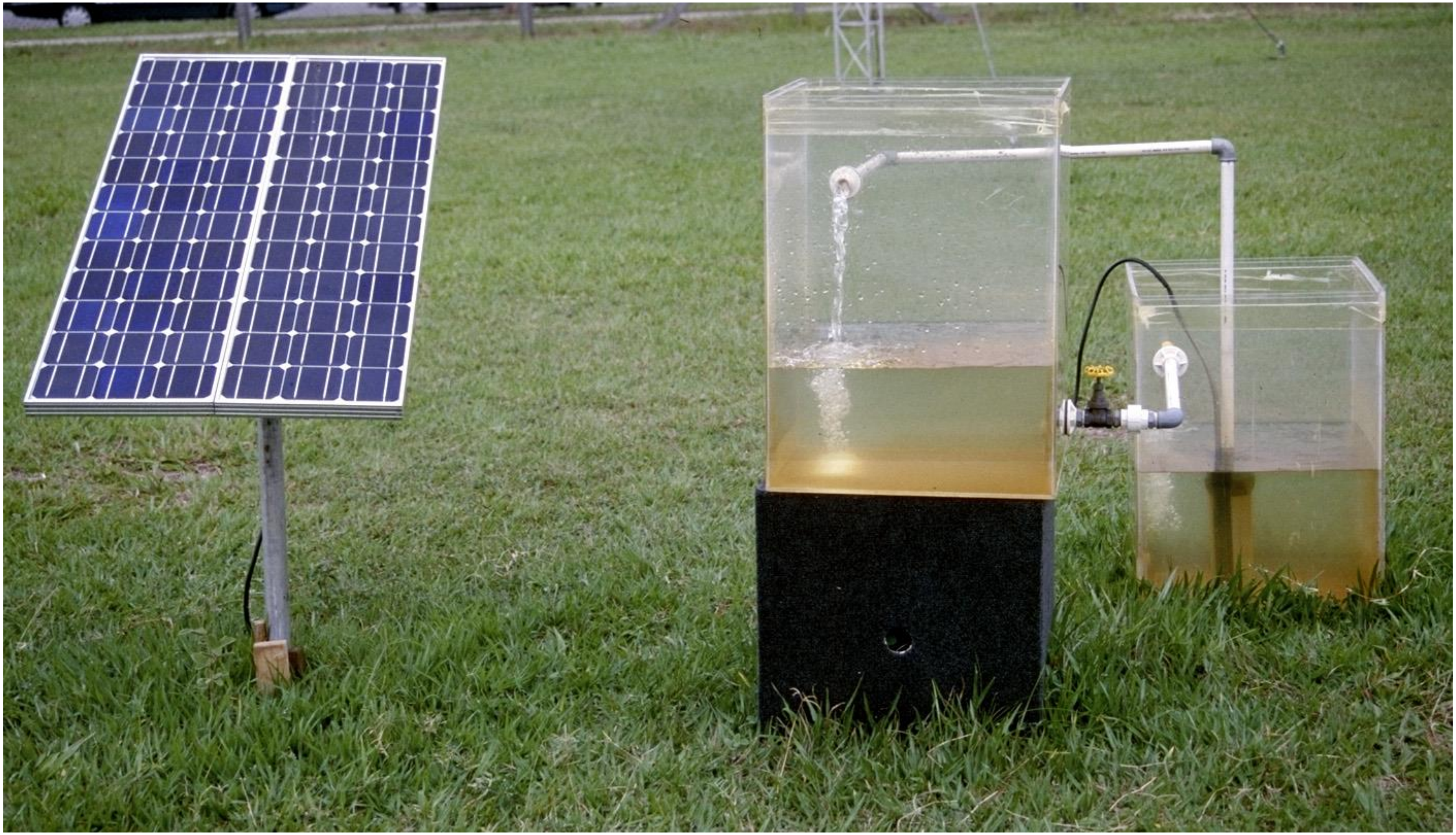
Solar pump, directly connected to a PV generator (via a DC-DC converter)



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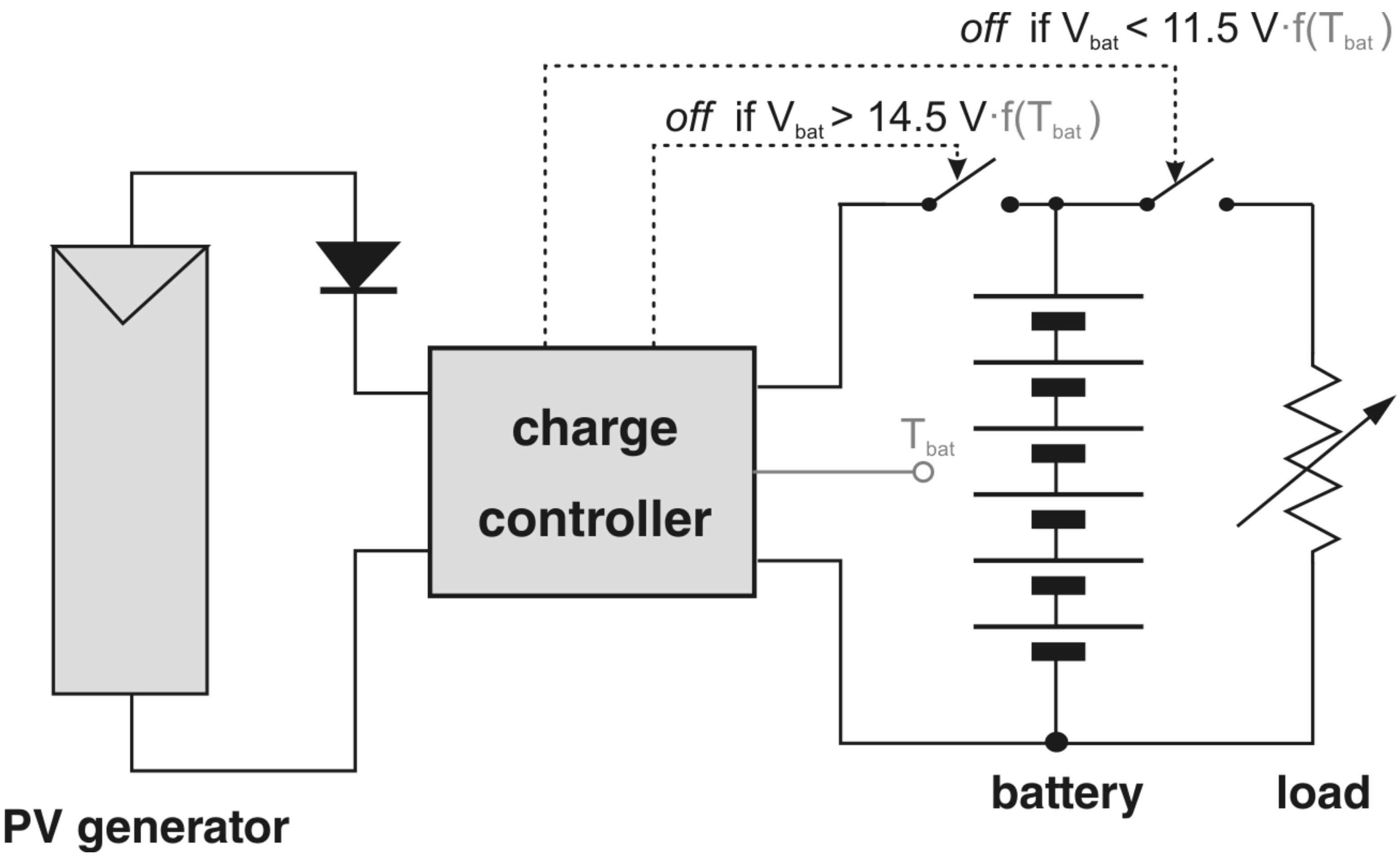
Scheme of simple "Solar Home System" (SHS) for DC loads with battery storage



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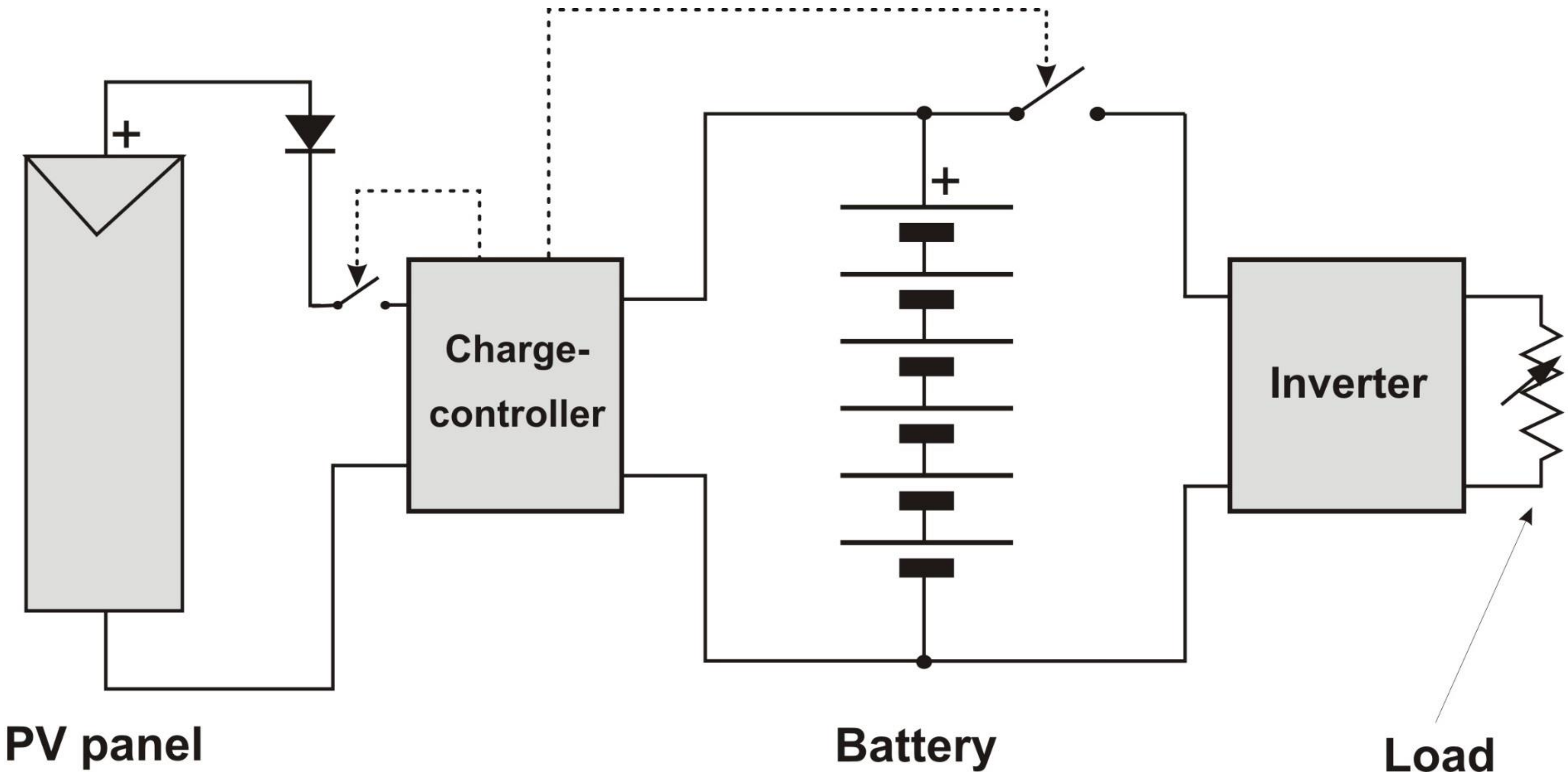
Scheme of simple "Solar Home System" (SHS) for AC loads with battery storage



Typical size for sunny locations: For a daily consumption of **400 Wh/d** a PV panel of **140 W_p** is sufficient. For a maximum discharge of 50% and 2 days of autonomy, the battery capacity is **150 Ah** at 12 V

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Examples: Charge controllers & Inverters for off-grid systems

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How to size a small PV off-gid system

- Determination of load: Power of loads, duration of use: ΣW_{load}
- Determination of battery size: max. depth of discharge (DoD: typical for lead-acid batteries: 50%), days of autonomy (DoA, e.g. 4 days in Germany, 2 days in the tropics):

$$W_{battery} = W_{load} \cdot DoA / DoD$$

- Energy to be generated by PV (use energy efficiency!):

$$W_{PV} = W_{load} / (\eta_{charge\ controller} \cdot \eta_{Bat} \cdot \eta_{Inverter})$$

- Daily irradiance at a typical day of the worst month of operation (from measurements, tables, maps, or simulation): $W_{irrad\ day}$
- Area of PV generator: $A_{PV} = W_{PV} / (W_{irrad\ day} \cdot \eta_{PV})$

Annual irradiance in Central America: Value relevant for grid-feeding

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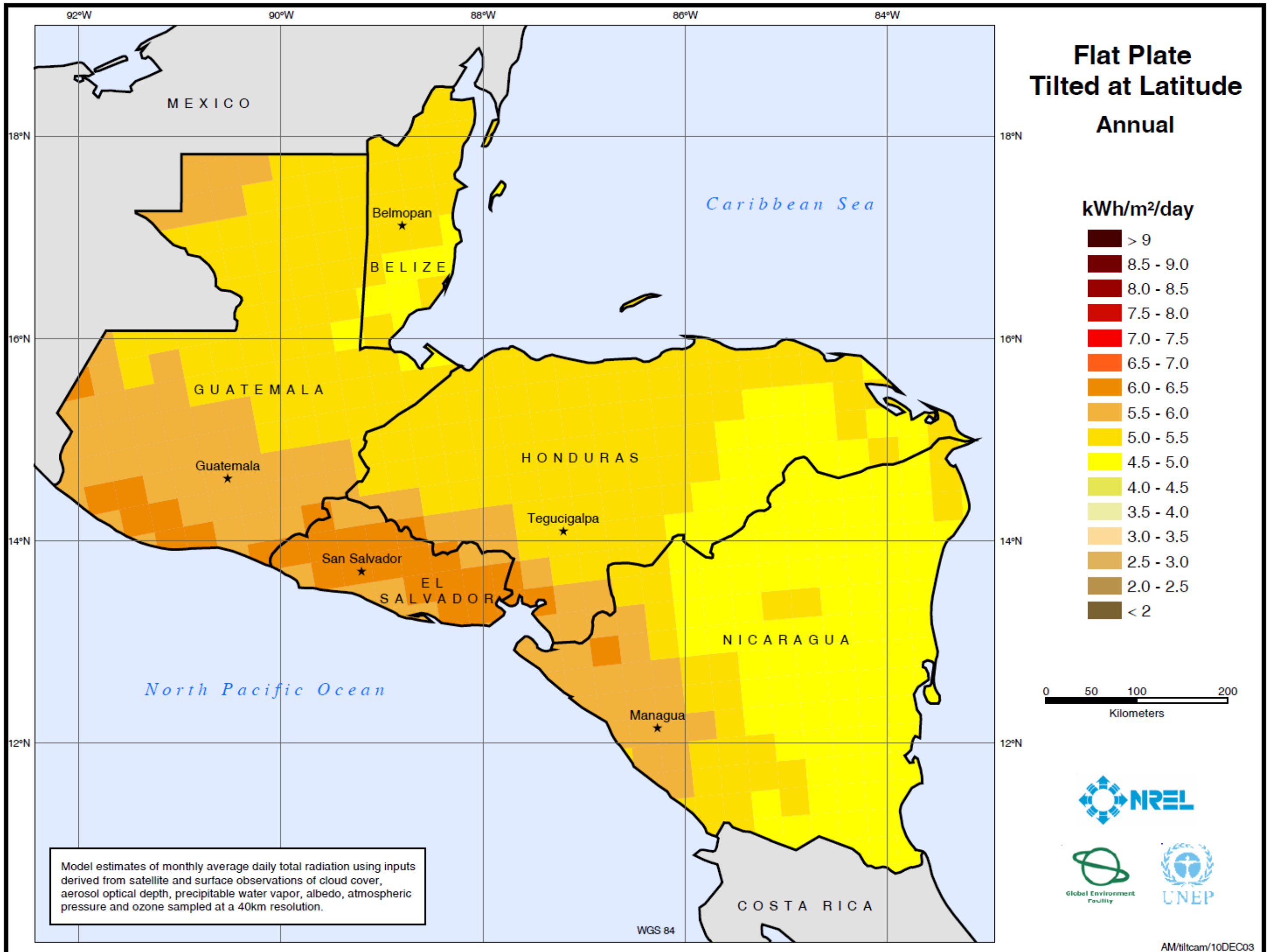

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A day in month with worst irradiance: Relevant for independent power supply

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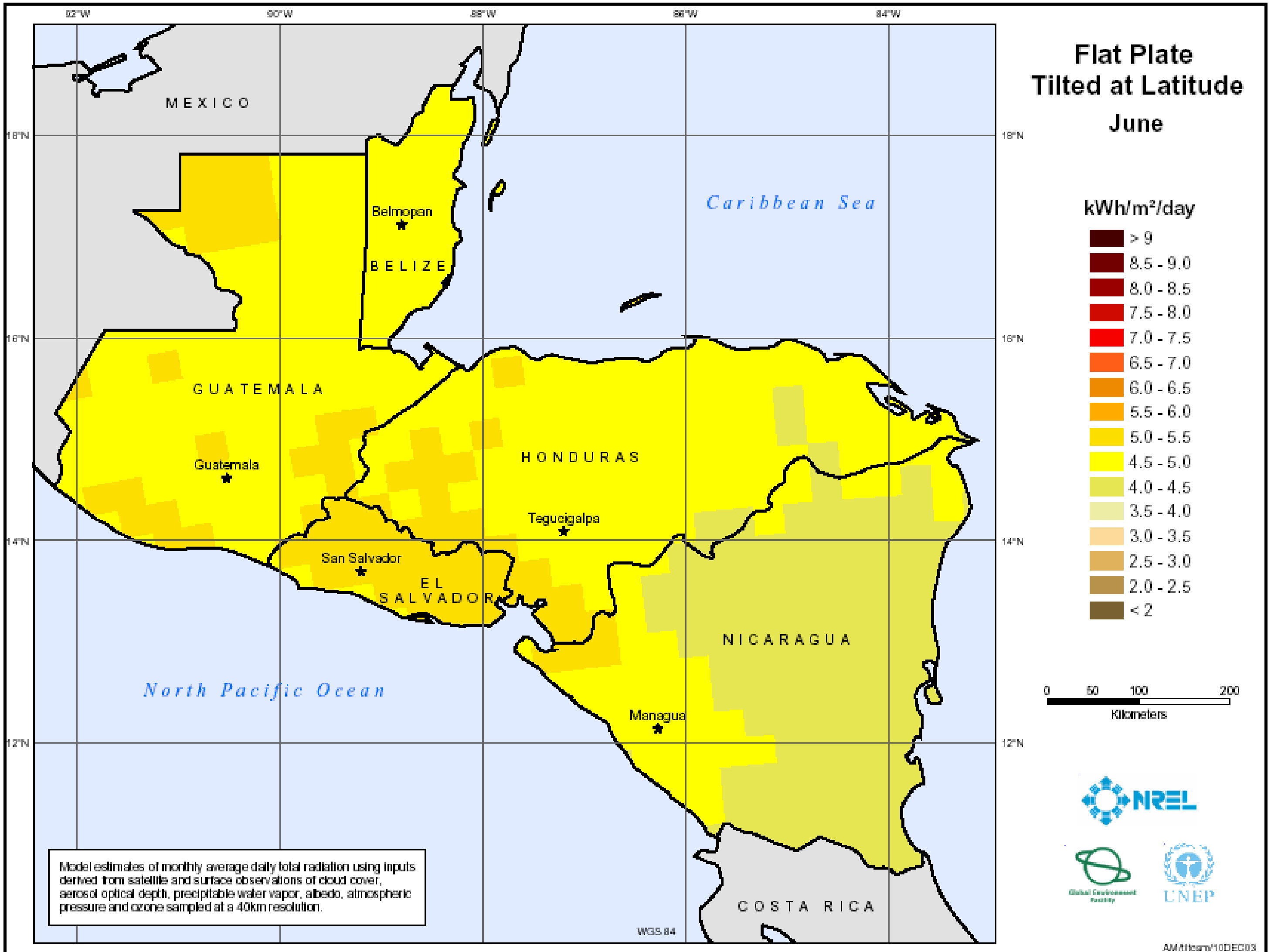

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Cost share of an autonomous PV system for 20 years (20 kW_p, 60 kWh supply per day)

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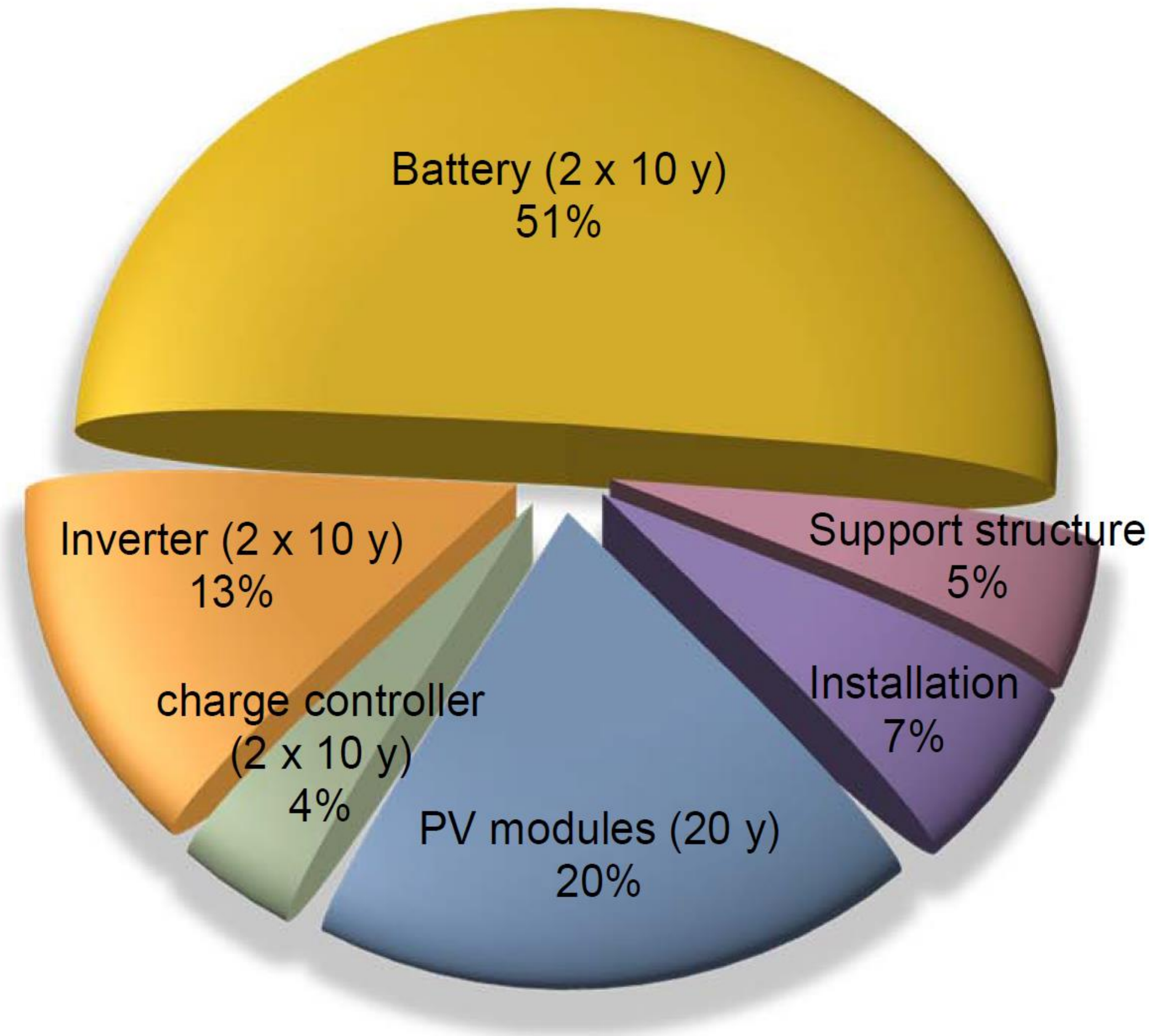

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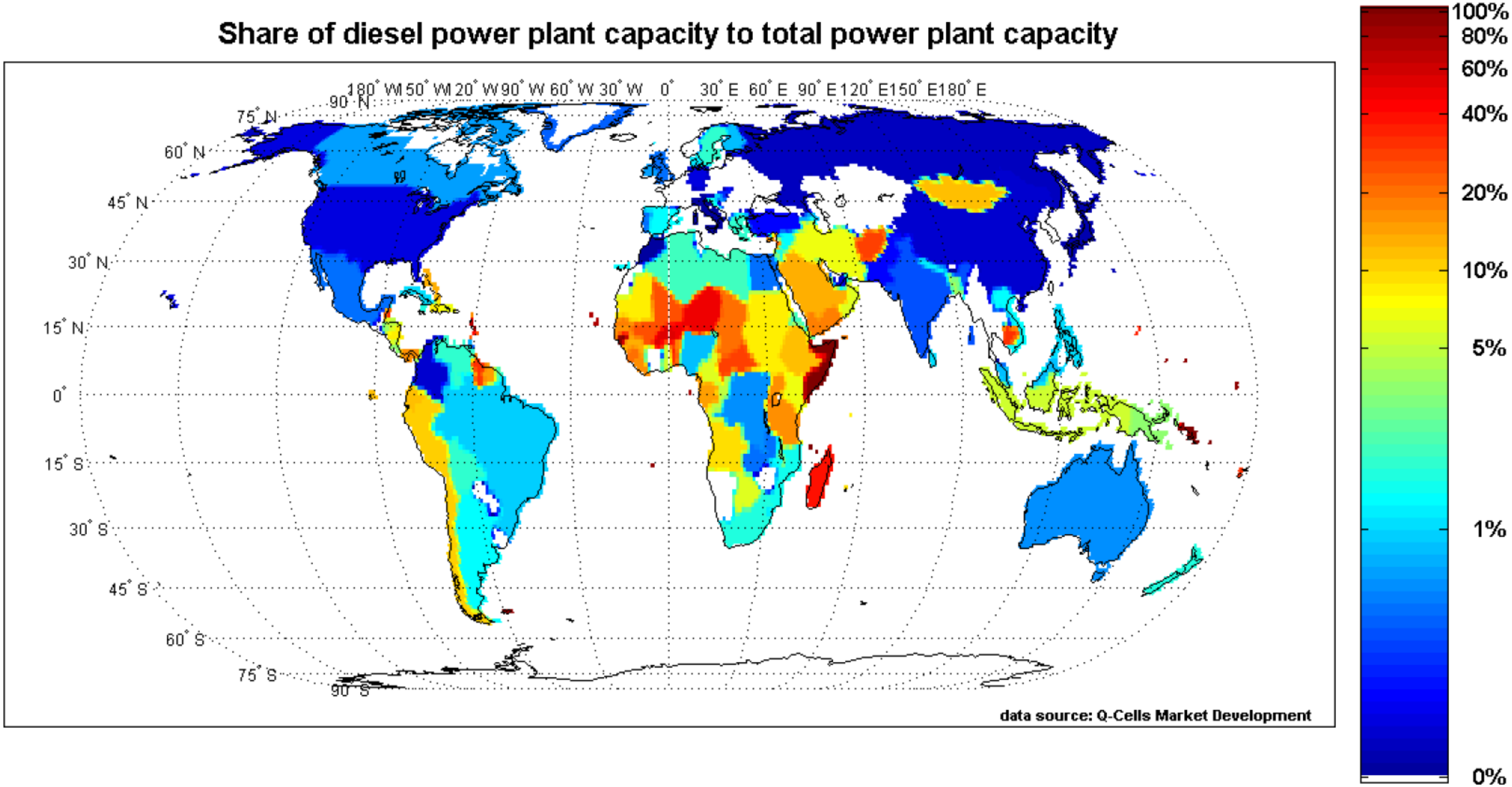
Share of Diesel generation used for electrical power supply



Source: C. Breyer, RLI, 5th ARE Workshop Academia meets Industry, 27th EUPVSEC, Frankfurt 2012

Diesel vs. PV generation costs

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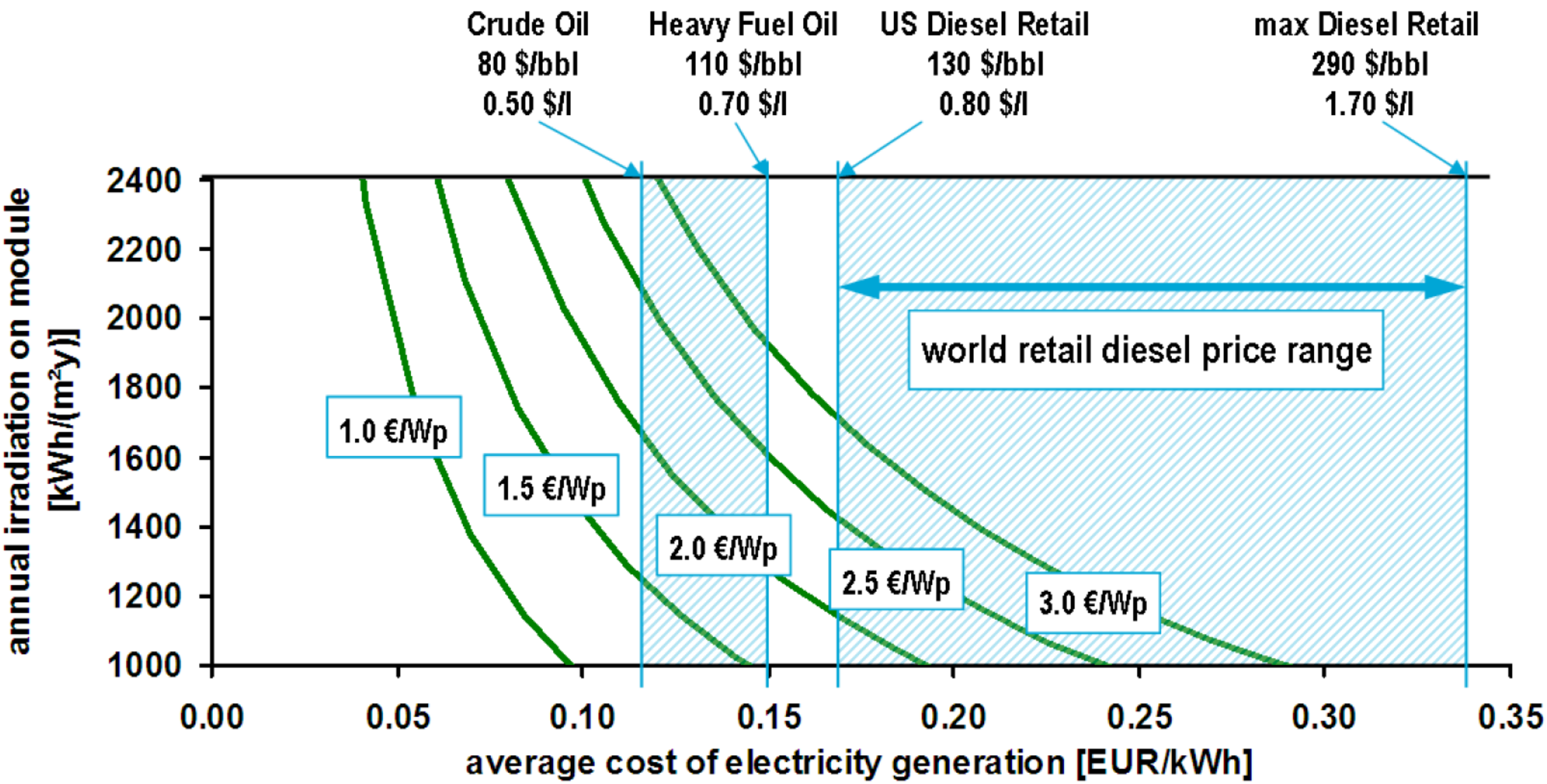

Key insights:

- current PV system prices of < 2,000 €/kWp enable PV LCOE of 10 – 15 €ct/kWh
- cost of diesel generated power is significantly higher, if no subsidies are paid for diesel

Source: C. Breyer, RLI, 5th ARE Workshop Academia meets Industry, 27th EUPVSEC, Frankfurt 2012

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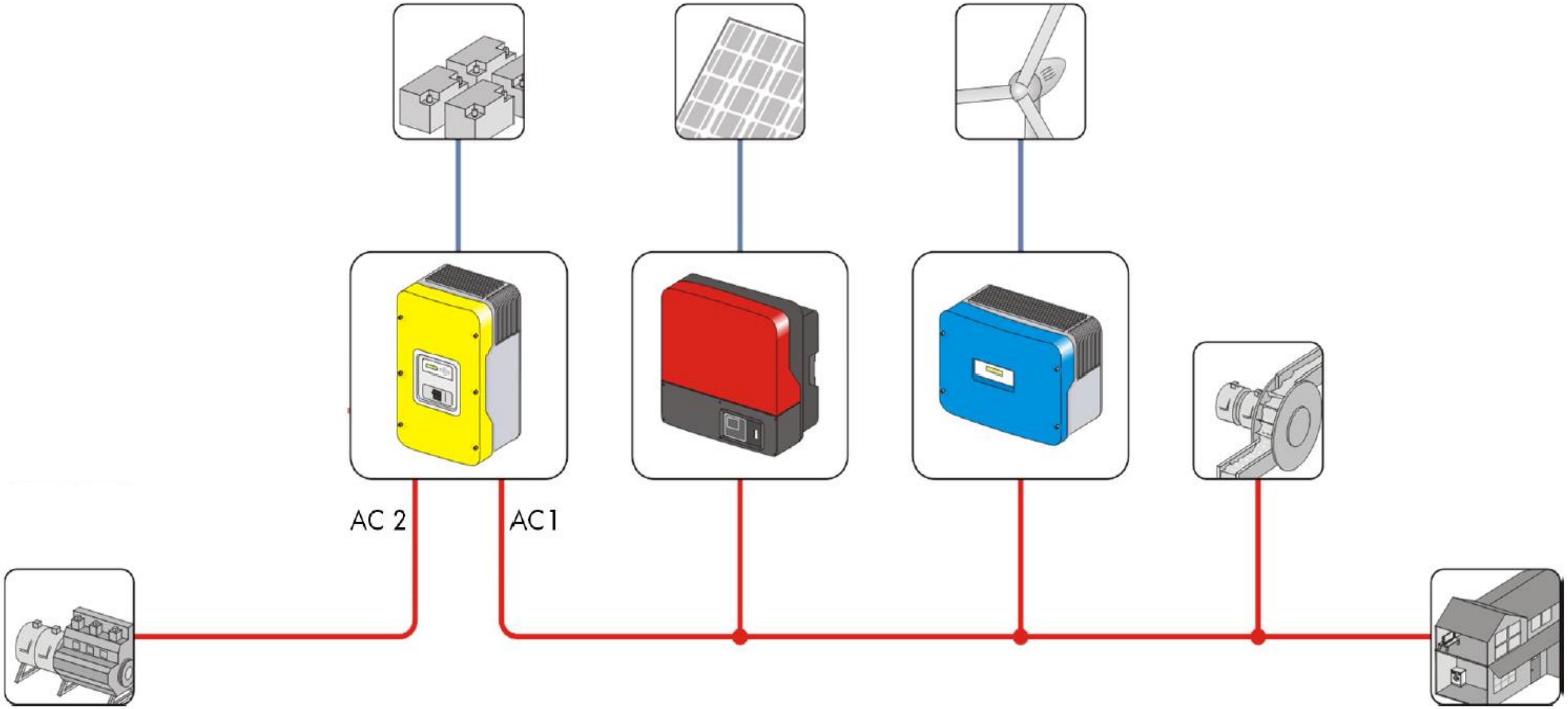
Important points for implementation

- Project identification: Load, Irradiance, Land, Security
- Financing: PPA, Carbon Trading, taxes, tax reductions, subsidies, interest rates, inflation, risks
- Equipment: components suitable for high operating temperature, high sand & salt contents of air, UV-stability, warranty (local dealer)
- Infrastructure: importation, transport, mounting equipment, tools, accessibility of location of installation, installation team, training of local supervisor, maintenance (financing & training), problem management, future development

Combination of different energy sources for cost-efficient decentralized power supply: Hybrid system



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Questions?

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