Off-grid Power for Wireless Networks

Training materials for wireless trainers

The Abdus Salam
International Centre
for Theoretical Physics

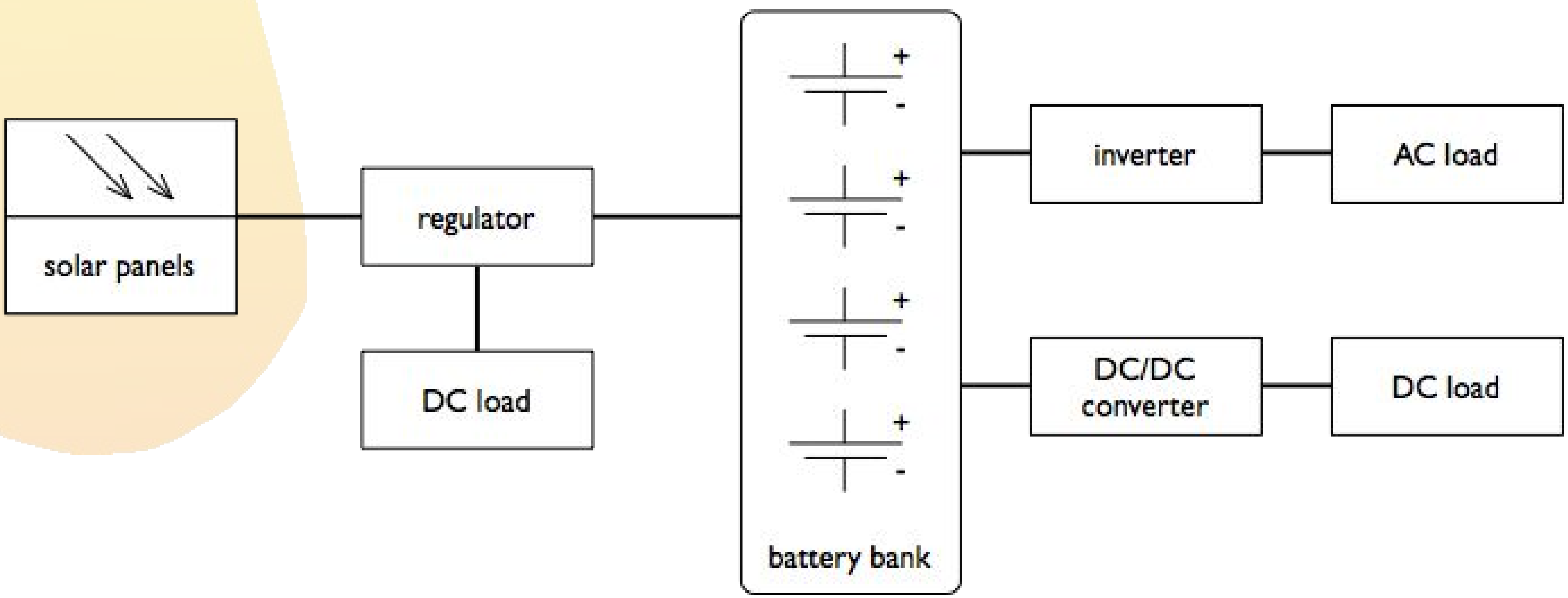
United Nations
Educational, Scientific and
Cultural Organization

Goals

- Provide a general view of the parts that comprise a **solar photovoltaic** system for telecommunication
- Understand the variables that affect the performance of a such a system
- Examine briefly the use of wind electrical generators

Photovoltaic system

A basic photovoltaic system consists of five main components: the **sun**, the ***solar panel***, the ***regulator***, the ***batteries***, and the ***load***. Many systems also include a ***voltage converter*** to allow use of loads with different voltage requirements.



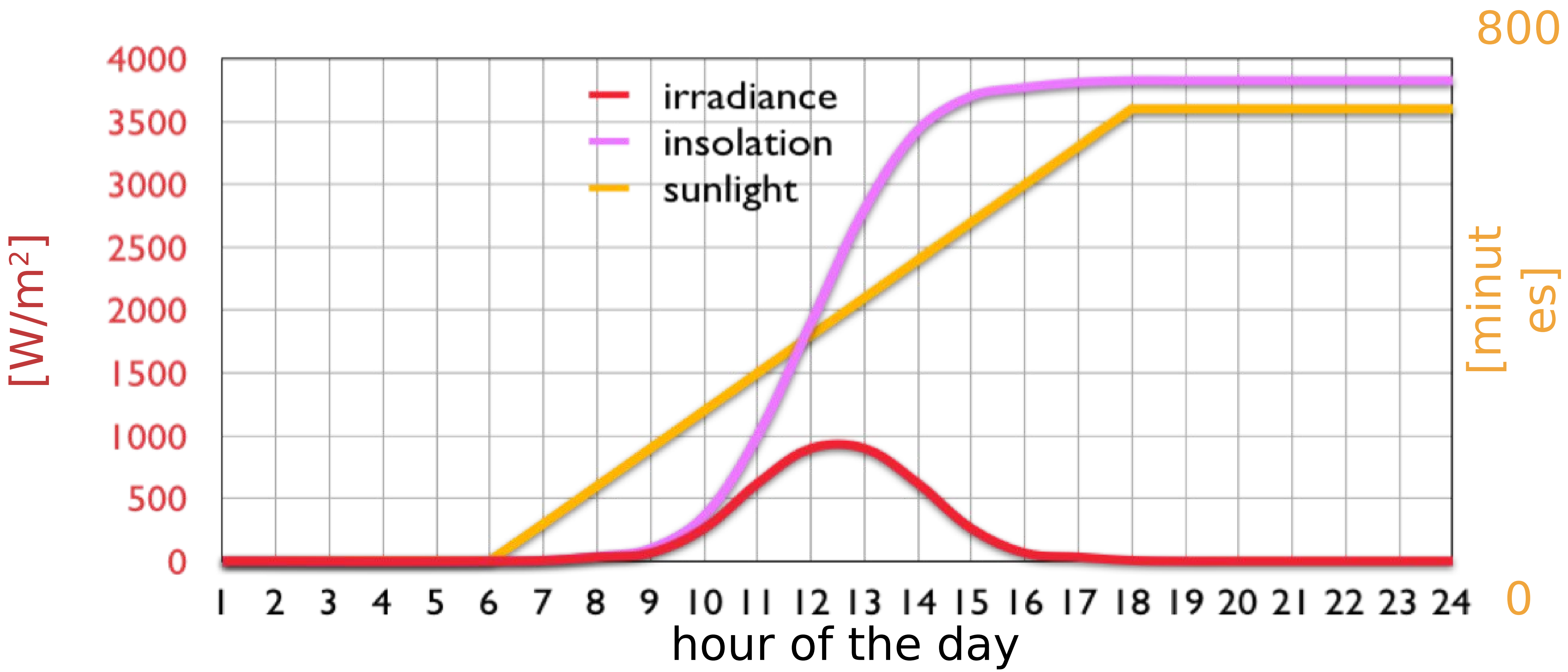
Solar power

A photovoltaic system is based on the ability of certain materials to convert the electromagnetic energy of the sun into electrical energy. The total amount of solar energy that lights a given area per unit of time is known as ***irradiance*** and it is measured in ***watts per square meter*** (***W/m^2***).

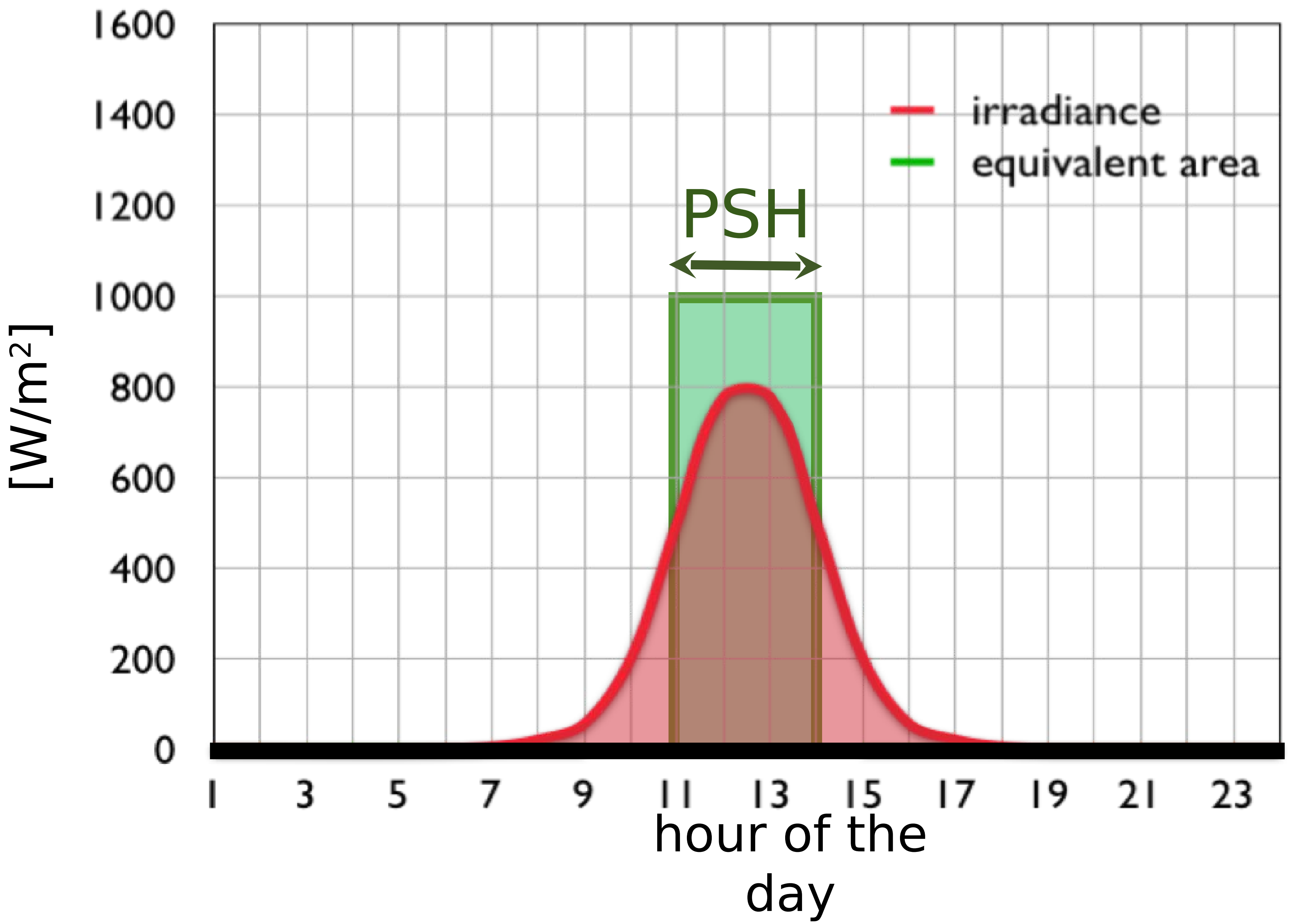
This energy is normally averaged over a period of time, so it is common to talk about total irradiance per hour, day or month.

Irradiance, irradiation/insolation, light

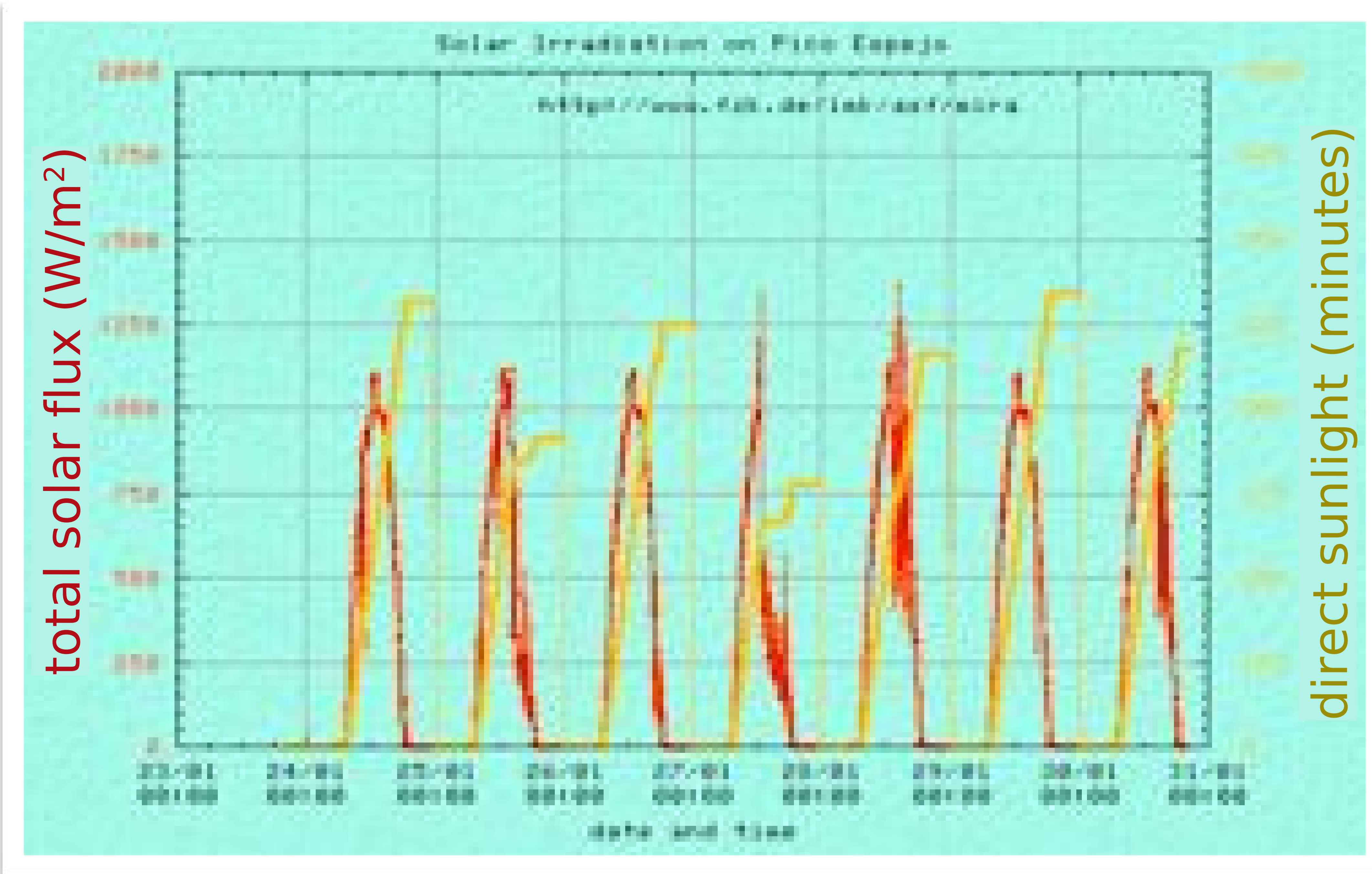
This graph shows **solar irradiance** (in W/m^2), **insolation** (cumulative irradiance) and **sunlight** (in minutes):



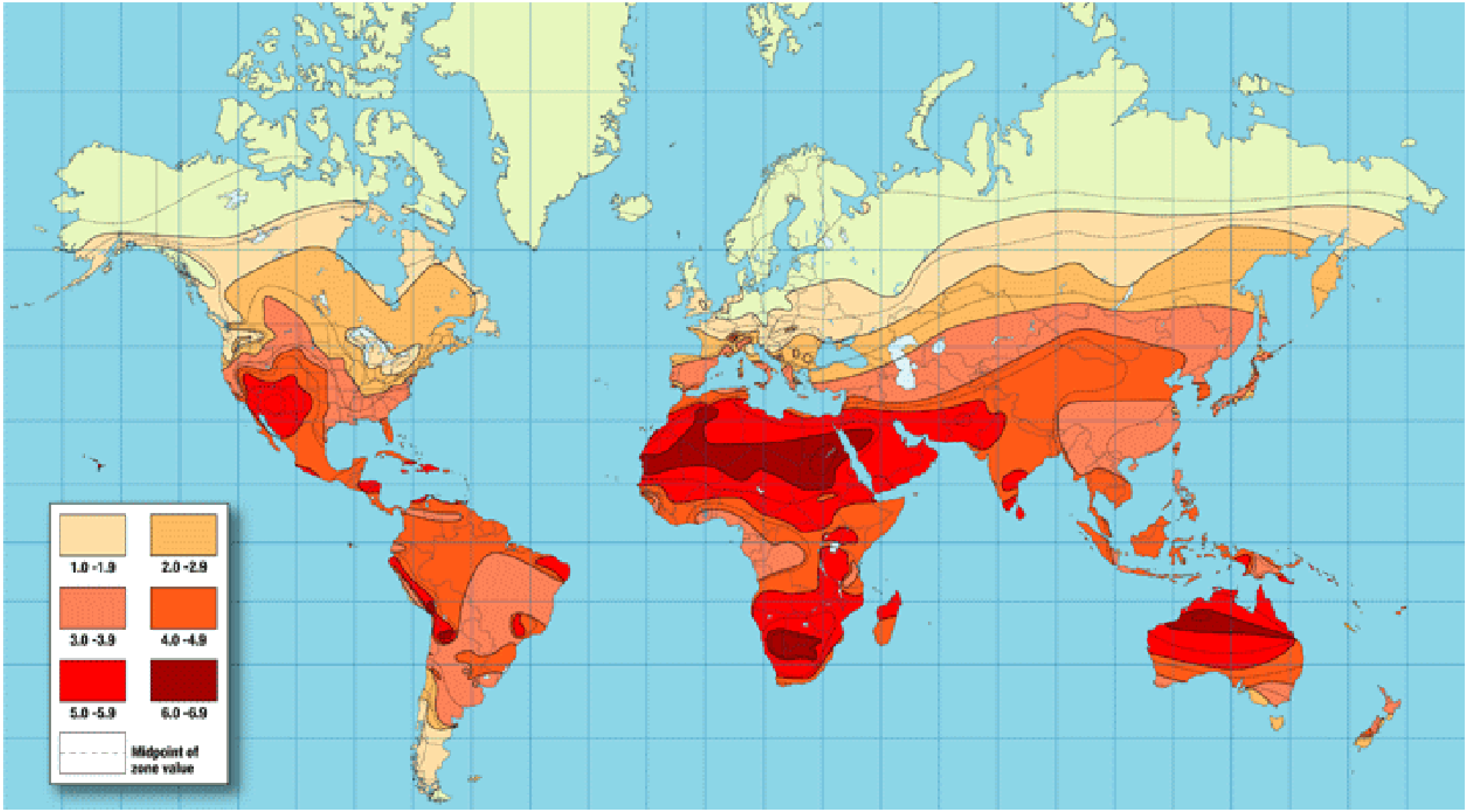
Peak Sun Hours



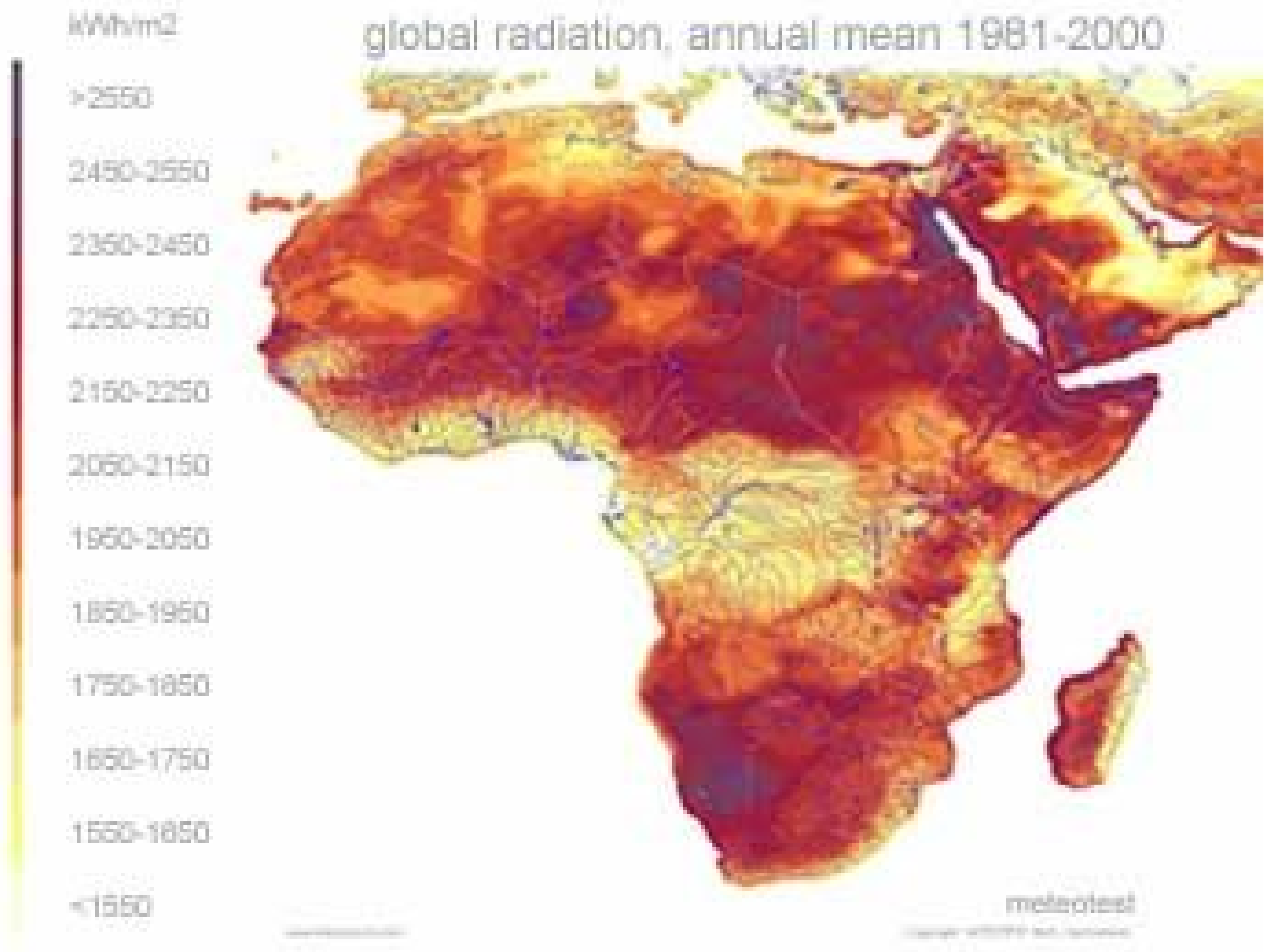
Real data: irradiance and sunlight



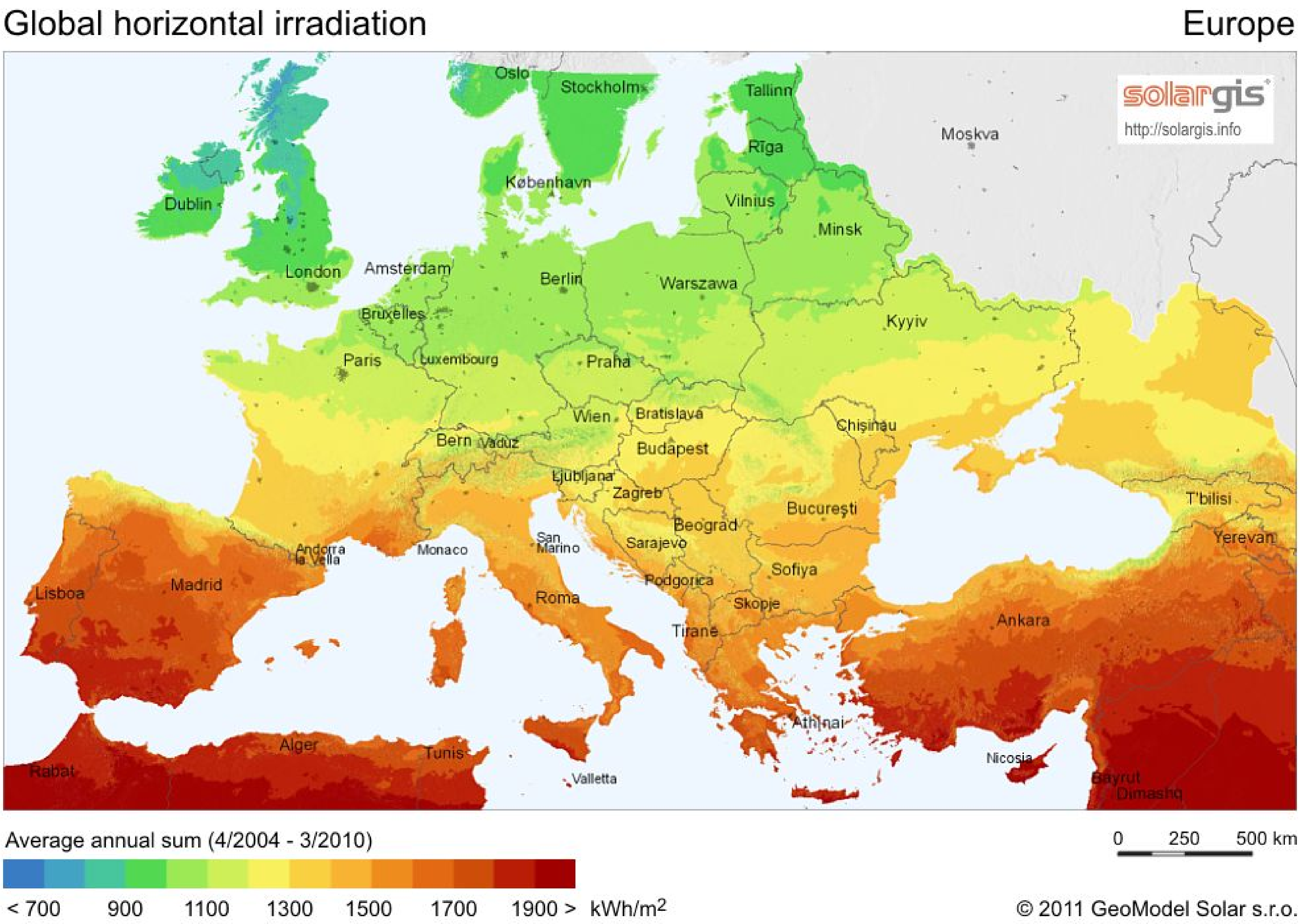
Real data: world map / insolation



Real data: e.g. Africa



Real data: e.g. Europe



Peak sun hours

Various organizations have produced maps that include average values of daily global irradiation for different regions. These values are known as ***peak sun hours*** or ***PSH***s.

You can use the PSH value for your region to simplify your calculations. One unit of “peak sun” corresponds to a radiation of 1000 watts per square meter.

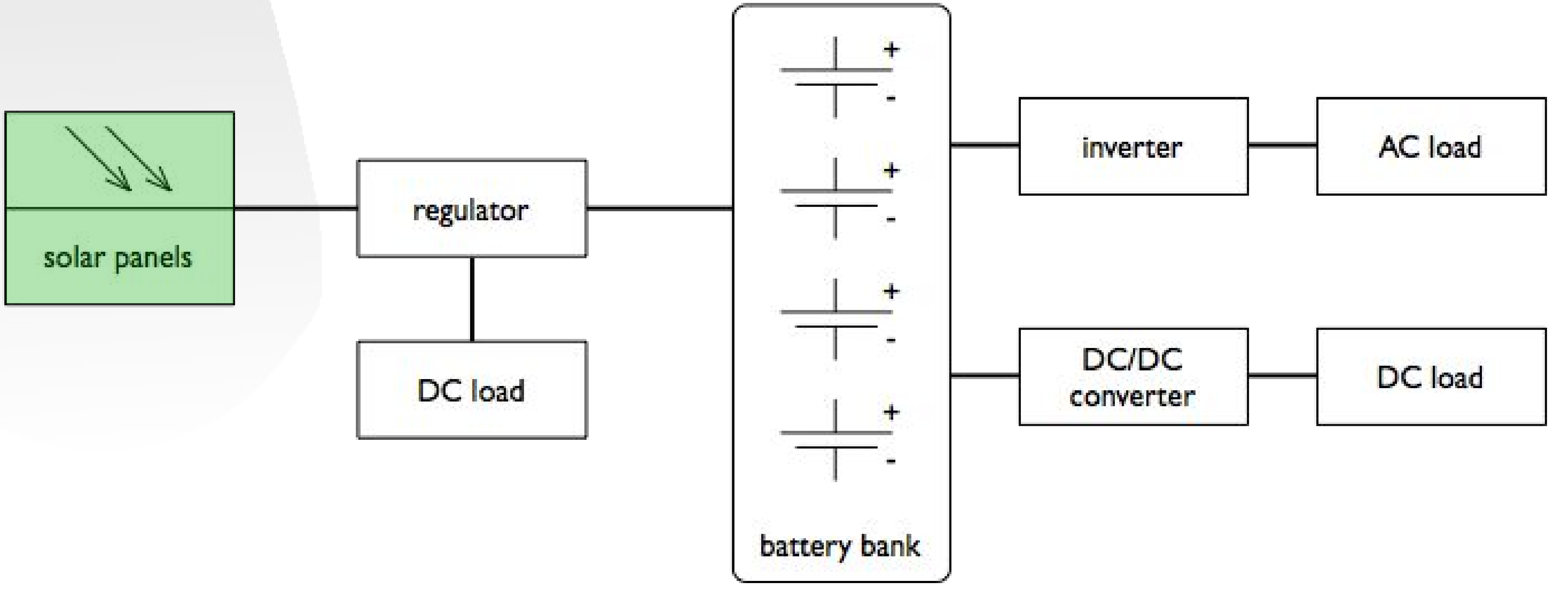
http://www.solar4power.com/solar-power-global-maps.html

http://www.synergyenviron.com/resources/solar_insolation_tool.asp

http://eosweb.larc.nasa.gov

Solar panels

The most obvious component of a photovoltaic system are the ***solar panels***.



Solar panels

A solar panel is made of many solar **cells**

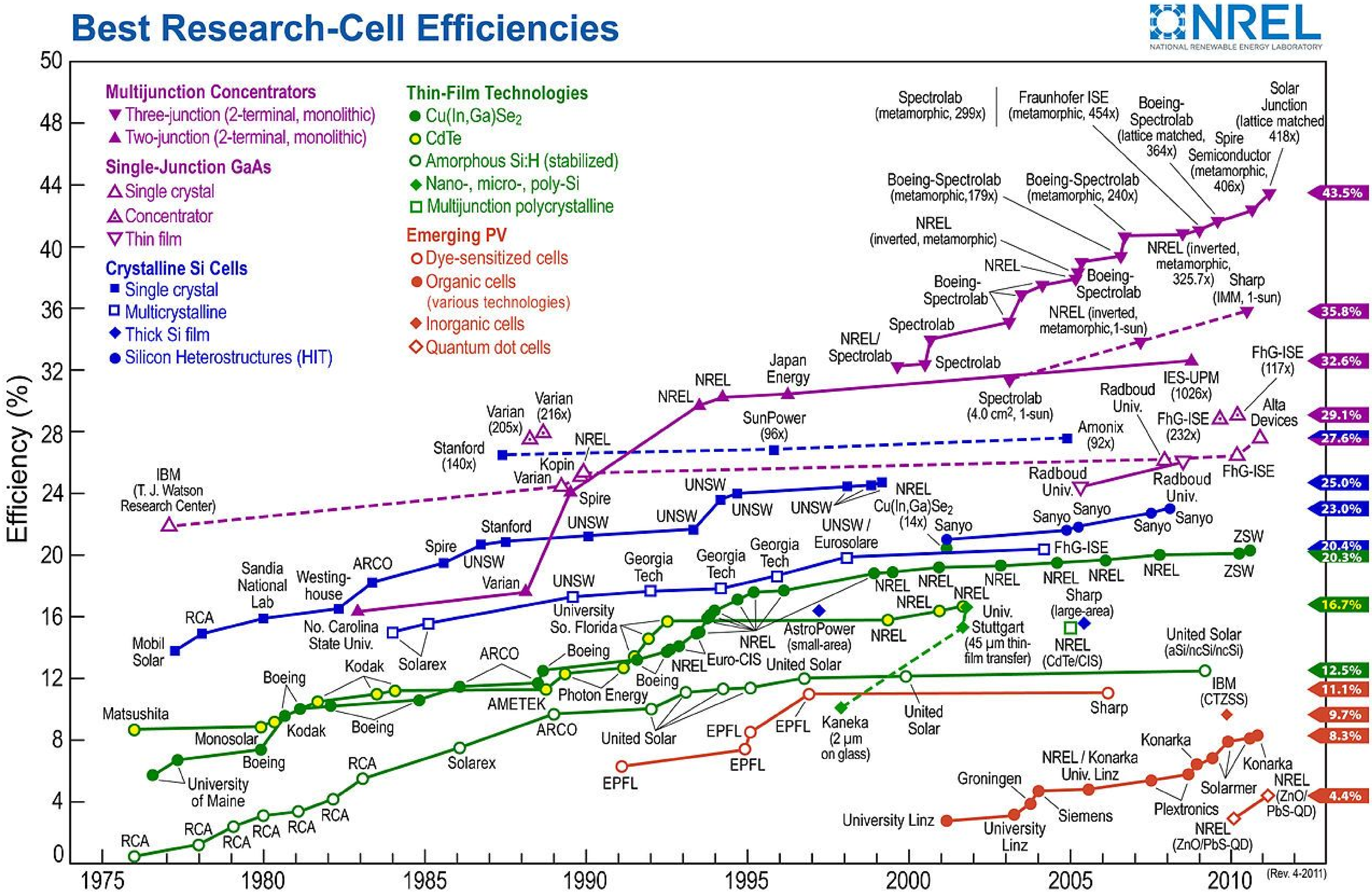
There are many types of solar panel:

- **Monocrystalline**: expensive, best efficiency
- **Polycrystalline**: cheaper, less efficient
- **Amorphous**: the cheapest, lowest efficiency, short lifespan
- **Thin-film**: very expensive, flexible, low efficiency, special uses
- **CIGS**: Copper Indium Gallium Selenide
- **Experimental new types**, e.g.

Efficiency

Manufacturer Name	Module Model Number	PTC	Area (sqft)	PTC/ Sqft	Description
SunPower Corporation	SPR-230-WHT-U	209.5	13.395	**15.64**	230W Monocrystalline Module, White Backsheet
SunPower Corporation	SPR-225-BLK-U	201.9	13.395	**15.073**	225W Monocrystalline Module, Black Backsheet
Sanyo Electric Co. Ltd.	HIP-215NKHA1	199.6	13.486	**14.801**	215W HIT Power N Hybrid Amorphous/Monocrystalline
SunPower Corporation	SPR-220-WHT-U	198.2	13.395	**14.797**	220W Monocrystalline Module, White Backsheet
SunPower Corporation	SPR-220-BLK-U	197.3	13.395	**14.729**	220W Monocrystalline Module, Black Backsheet
Sanyo Electric Co. Ltd.	HIP-210NKHA1	194.9	13.486	**14.452**	210W HIT Power N Hybrid Amorphous/Monocrystalline
SunPower Corporation	SPR-215-WHT-U	193.5	13.395	**14.446**	215W Monocrystalline Module, White Backsheet
Sanyo Electric Co. Ltd.	HIP-205BA19	190.7	13.486	**14.141**	HIT Power 205W - Hybrid Amorphous/Monocrystalline
SunPower Corporation	SPR-210-WHT-U	189	13.395	**14.11**	210W Monocrystalline Module, White Backsheet
Sanyo Electric Co. Ltd.	HIP-205NKHA1	190.2	13.486	**14.104**	205W HIT Power N Hybrid Amorphous/Monocrystalline
SunPower Corporation	SPR-210-BLK-U	188.1	13.395	**14.043**	210W Monocrystalline Module, Black Backsheet
SunPower Corporation	SPR-205-BLK-U	183.6	13.395	**13.707**	205W Monocrystalline Module, Black Backsheet
Schuco USA LP	SPV 210 SMAU-1	192.1	15.766	**12.184**	210W Monocrystalline Module, Black Frame
Siliken California Corp	SLK60P6L 235 Wp	210.7	17.476	**12.056**	235W Polycrystalline Module
Siliken California Corp	SLK60P6L 230 Wp	206.1	17.476	**11.793**	230W Polycrystalline Module
REC ScanModule AB	REC230AE-US (BLK)	200.7	17.025	**11.789**	230W Polycrystalline Module, High Performance
Solon Ag Fuer Solartechnik	P220/6+/01 235Wp	208	17.653	**11.783**	235W Polycrystalline Module
Suntech Power Co.	STP280-24/Vb-1	246	20.908	**11.766**	280W Polycrystalline Module, MC Connectors
ET Solar Industry, Ltd	ET-P672270	241.8	20.908	**11.565**	270W Polycrystalline Module
aleo solar AG	S18.230	204.5	17.689	**11.561**	230W Polycrystalline Module
REC ScanModule AB	SCM225	196.5	17.025	**11.542**	225W Polycrystalline Module
Siliken California Corp	SLK60P6L 225 Wp	201.5	17.476	**11.53**	225W Polycrystalline Module
Solon Ag Fuer Solartechnik	P220/6+/01 230Wp	203.4	17.653	**11.522**	230W Polycrystalline Module
ET Solar Industry, Ltd	ET-P672265	237.1	20.908	**11.34**	265W Polycrystalline Module
Suntech Power Co.	STP270-24/Vb-1	236.9	20.908	**11.331**	270W Polycrystalline Module, MC Connectors
aleo solar AG	S18.225	199.9	17.689	**11.301**	225W Polycrystalline Module
Sharp Corporation	ND-U230C1	198	17.541	**11.288**	230W Polycrystalline Module, Locking Connector
Solartech Power Inc.	SPM230P	197.9	17.541	**11.282**	230W Polycrystalline Module
REC ScanModule AB	SCM220	192	17.025	**11.278**	220W Polycrystalline Module
Siliken California Corp	SLK60P6L 220 Wp	197	17.476	**11.272**	220W Polycrystalline Module

Efficiency

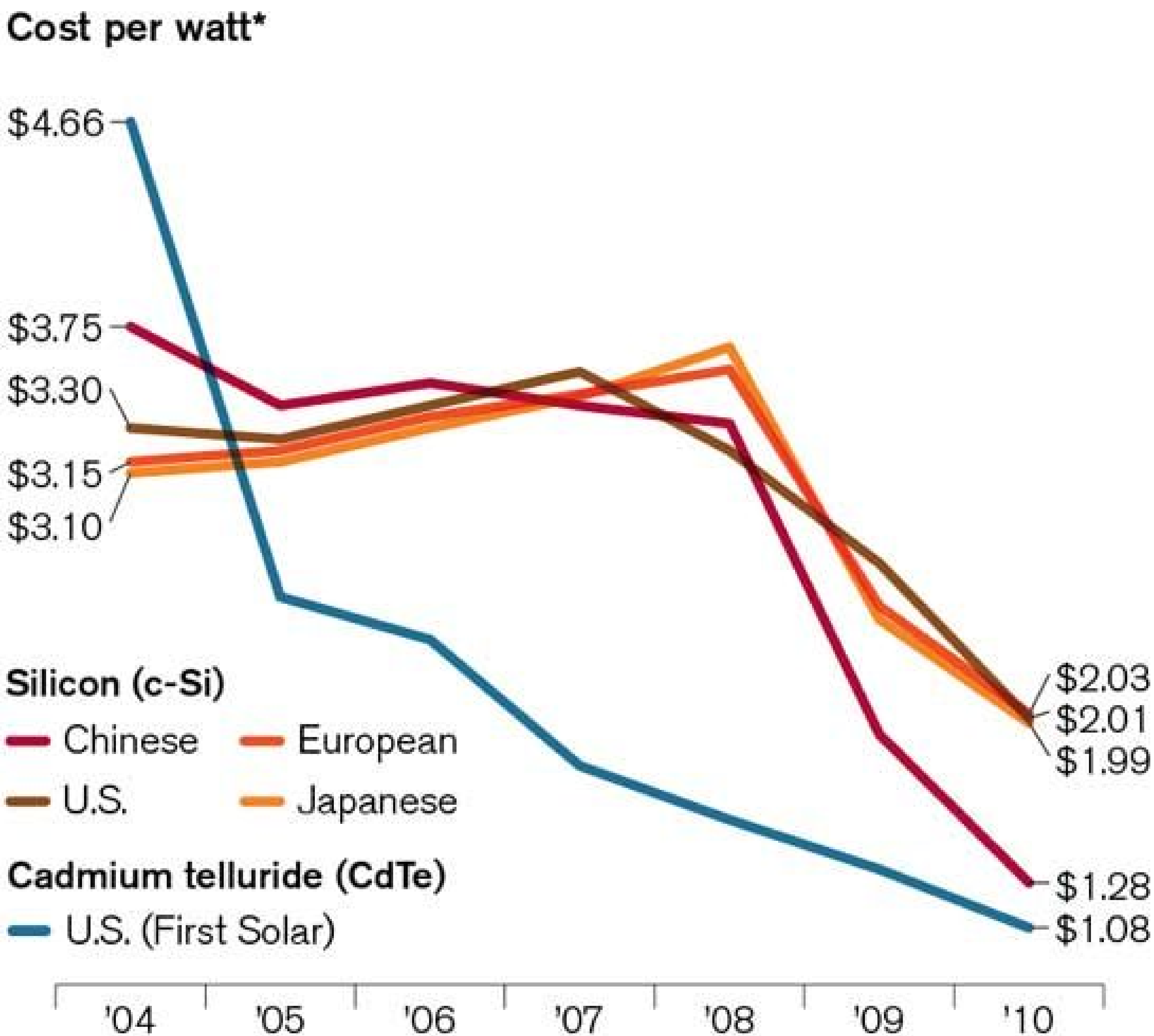


Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
50
48
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
(Rev. 4-2011)
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Silicon Heterostructures (HIT)
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
Inorganic cells
Quantum dot cells
43.5%
35.8%
32.6%
29.1%
27.6%
25.0%
23.0%
20.4%
20.3%
16.7%
12.5%
11.1%
9.7%
8.3%
4.4%
Spectrolab (metamorphic, 299x)
Fraunhofer ISE (metamorphic, 454x)
Boeing-Spectrolab (lattice matched, 364x)
Solar Junction (lattice matched 418x)
Spire Semiconductor (metamorphic, 406x)
Boeing-Spectrolab (metamorphic,179x)
Boeing-Spectrolab (metamorphic, 240x)
NREL (inverted, metamorphic)
NREL (inverted, metamorphic, 325.7x)
Sharp (IMM, 1-sun)
NREL (inverted, metamorphic,1-sun)
Spectrolab (4.0 cm2, 1-sun)
IES-UPM (1026x)
FhG-ISE (117x)
FhG-ISE (232x)
Alta Devices
Amonix (92x)
SunPower (96x)
Japan Energy
Stanford (140x)
Varian (205x)
Varian (216x)
IBM (T. J. Watson Research Center)
Radboud Univ.
Kopin
Spire
UNSW
Sanyo
ZSW
United Solar (aSi/ncSi/ncSi)
IBM (CTZSS)
Sharp
Konarka
Solarmer
NREL (ZnO/PbS-QD)
Plextronics
Siemens
Groningen
University Linz
NREL / Konarka Univ. Linz
Kaneka (2 μm on glass)
Univ. Stuttgart (45 μm thin-film transfer)
NREL (CdTe/CIS)
Sharp (large-area)
AstroPower (small-area)
Euro-CIS
Georgia Tech
University So. Florida
No. Carolina State Univ.
Solarex
Kodak
Boeing
ARCO
AMETEK
Photon Energy
Westing-house
Sandia National Lab
Mobil Solar
RCA
Matsushita
Monosolar
University of Maine
EPFL

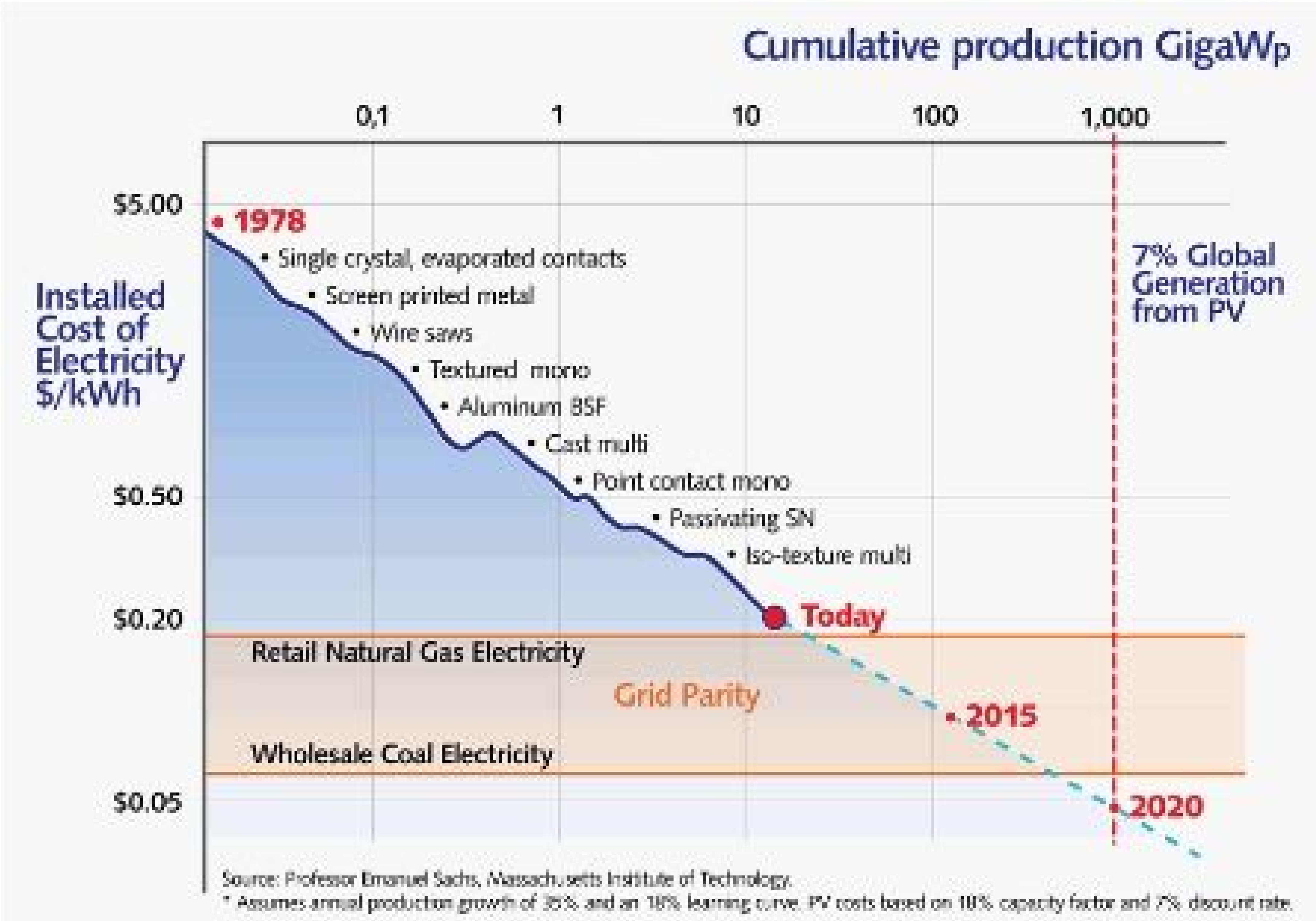
Price / Market

- Early 2012, the price of pv panels (in sizes of approx. 100W) is about $1 / W
- Total system cost for kW systems is estimated at about $3 / W

Price / Market: PV panels



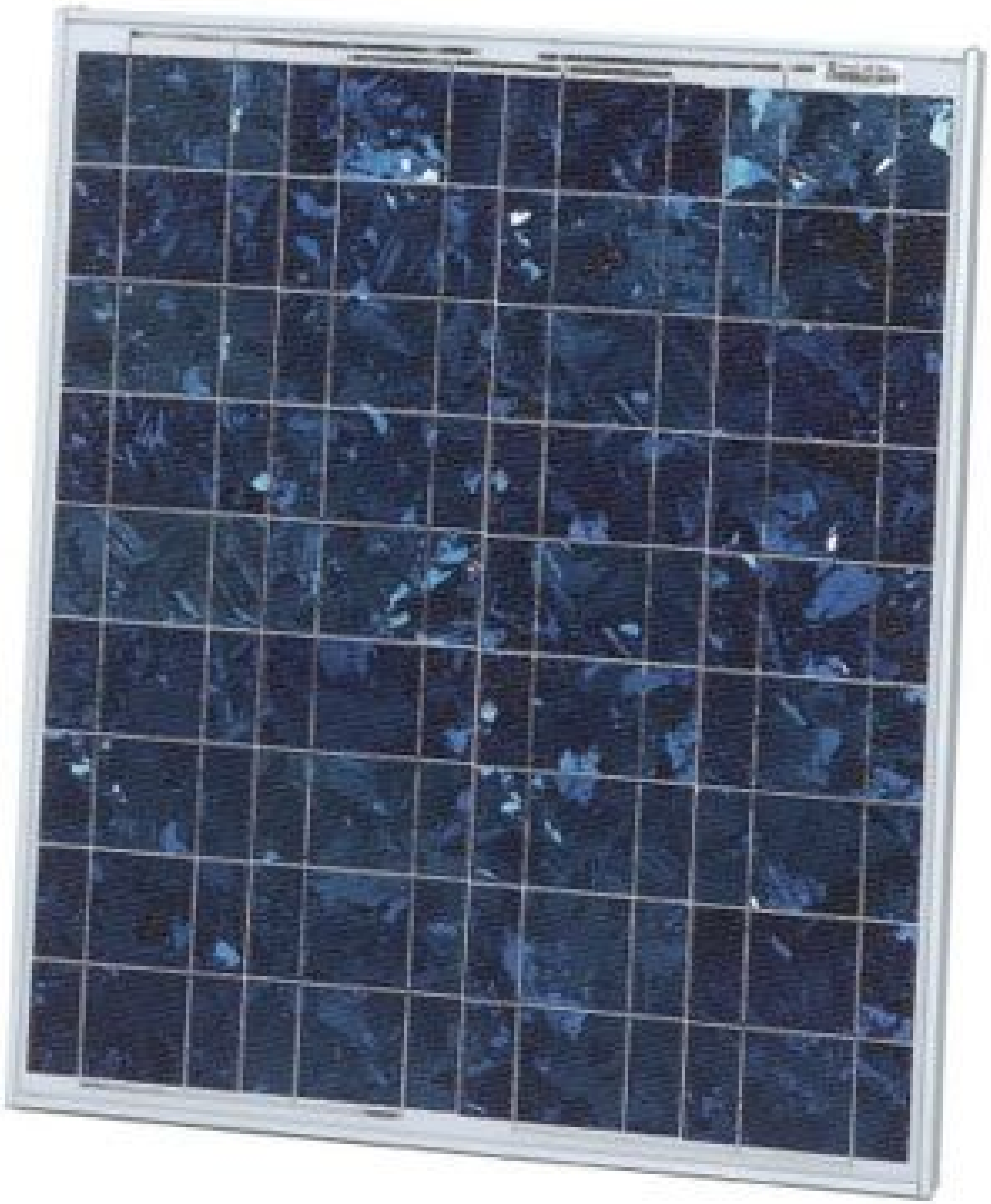
Price / Market: energy production



Sizes of PV energy

Monochrystalline cells

Polychrystalline cells



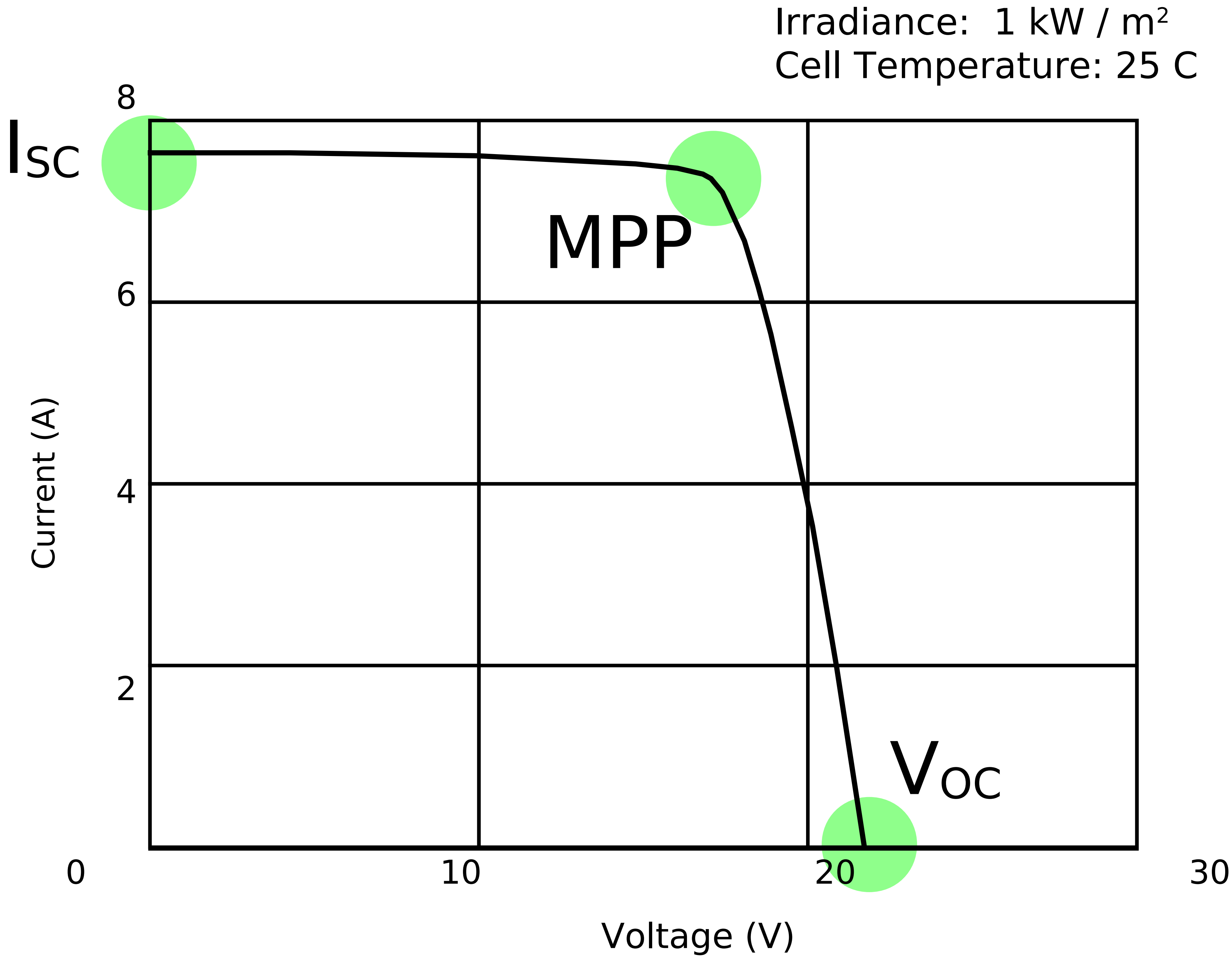
Thin film & CIGS cells

Basic laws of electricity

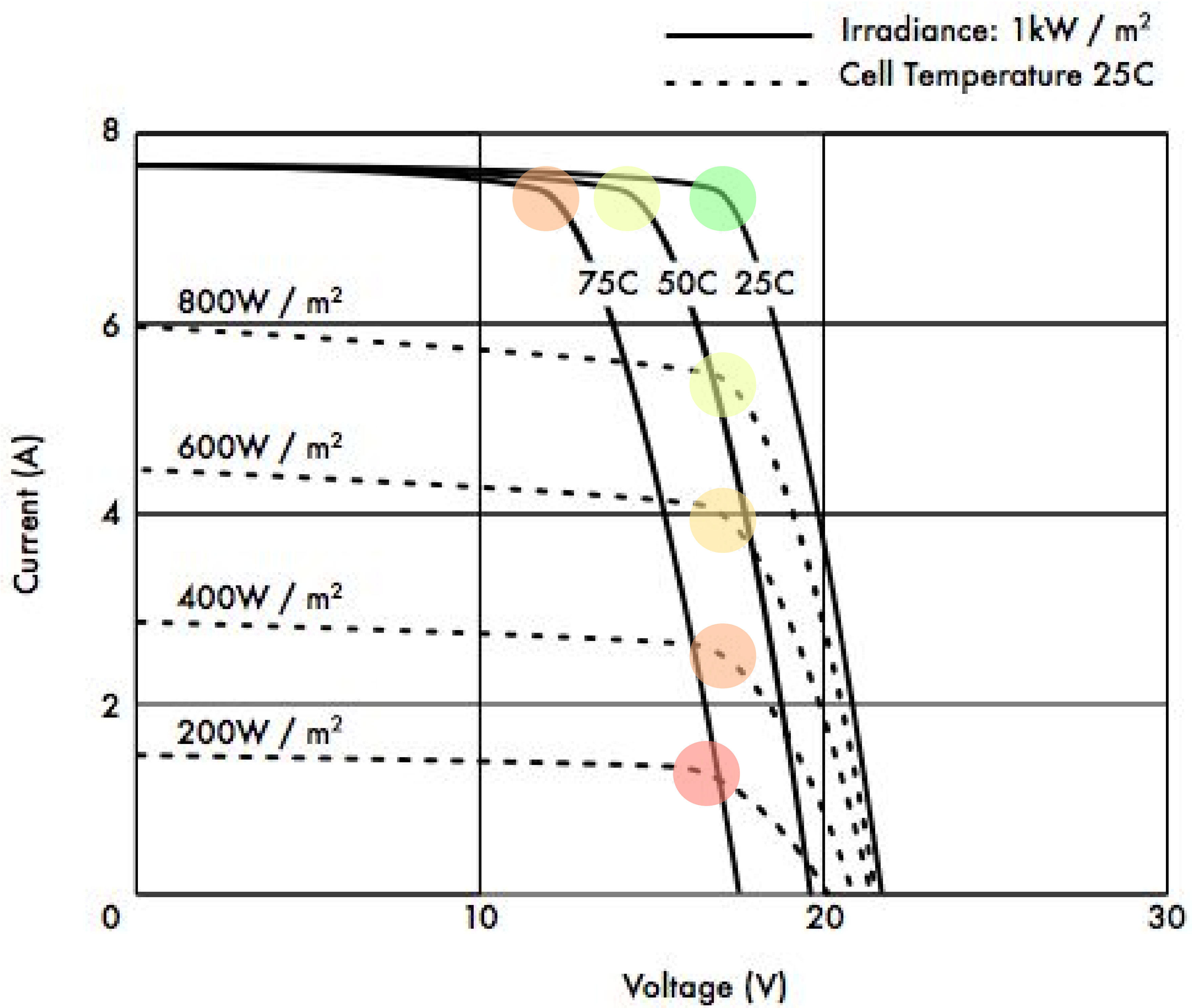
- Voltage U [V Volt]
- Current I [A Ampere]
- Power P [W Watt]
- Resistance R [Ω Ohm]

$$\mathbf{P = U \times I}$$
$$\mathbf{U = R \times I}$$
$$\mathbf{P = R \times I^2}$$

Solar panel IV curve



Solar panel IV curve for different amounts of irradiance and temperature

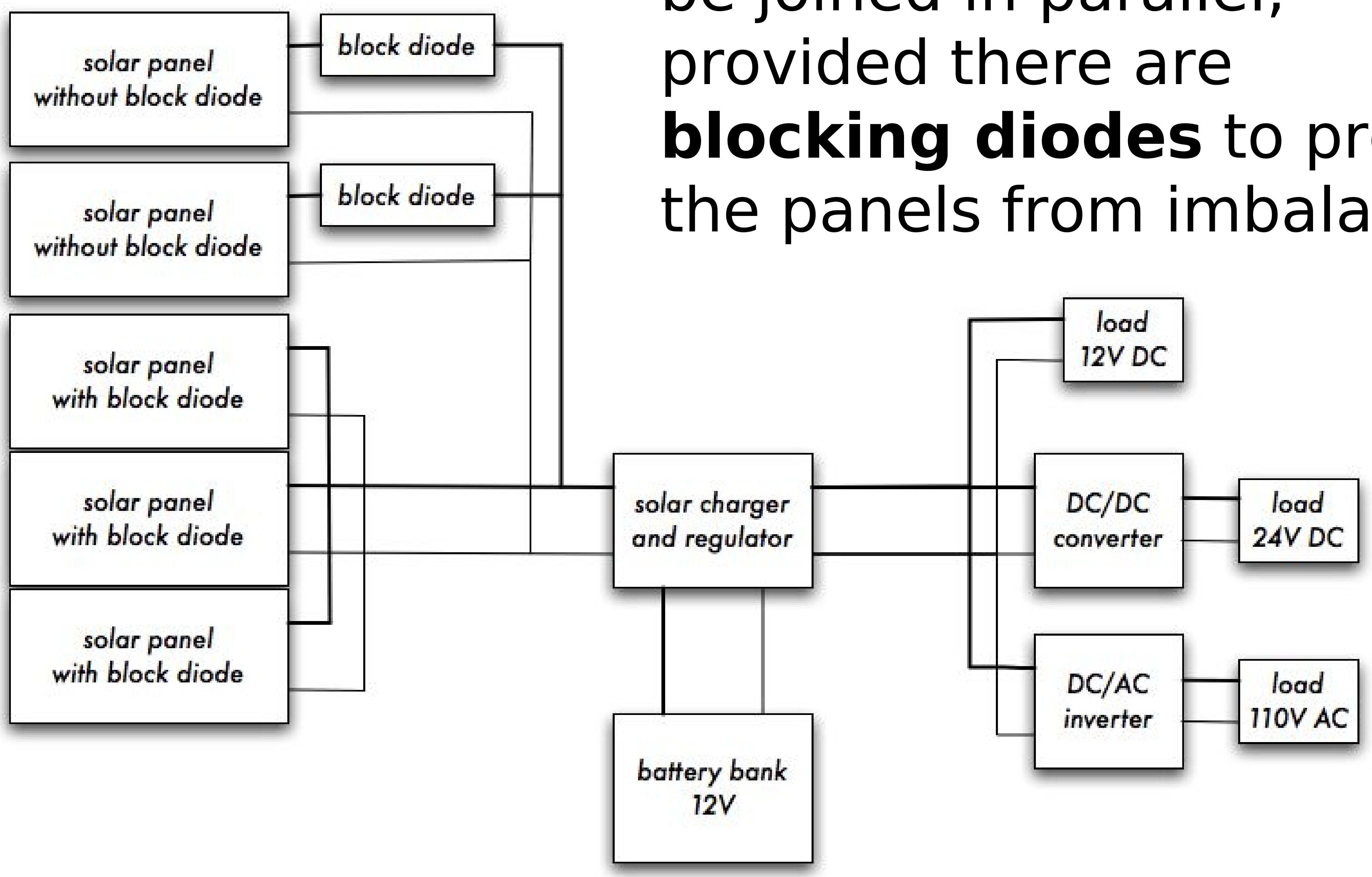


Optimizing panel performances

Optimal angle = Latitude + 5°

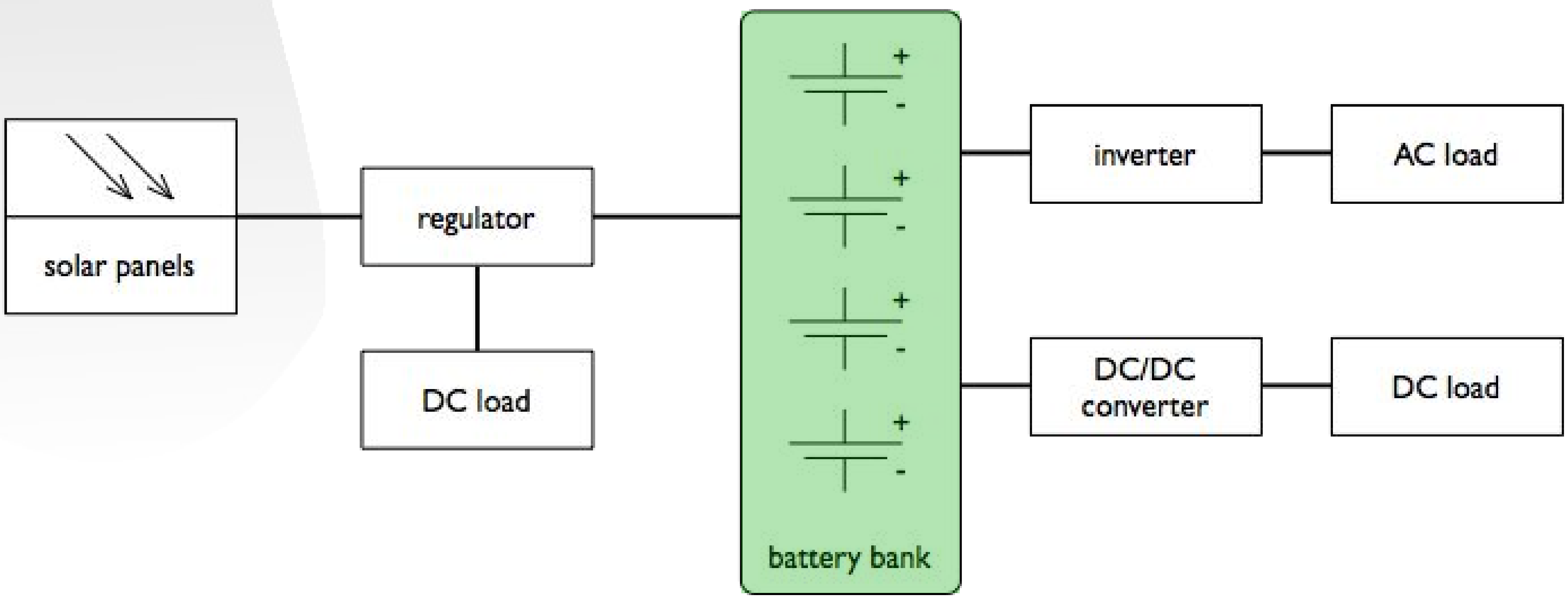
Photovoltaic system

If more power is required, multiple solar panels may be joined in parallel, provided there are **blocking diodes** to protect the panels from imbalances.



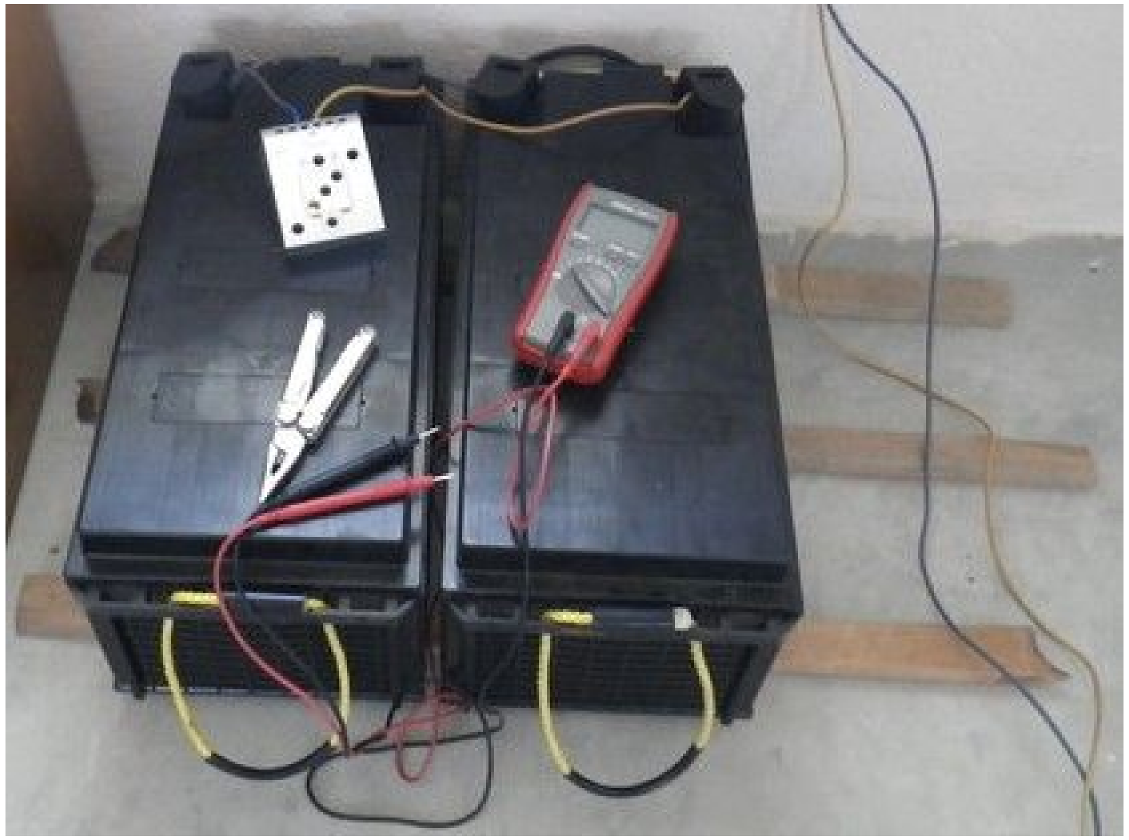
Batteries

Batteries are at the heart of the photovoltaic system, and determine the operating voltage.



Batteries

The ***battery*** stores the energy produced by the panels that is not immediately consumed by the load. This stored energy can then be used during periods of low solar irradiation (at night, or when it is cloudy).



Batteries

The most common type of batteries used in solar applications are maintenance-free lead-acid batteries, also called **recombinant** or **VRLA** (valve regulated lead acid) batteries. They belong to the class of deep cycle or stationary batteries, often used for backup power in telephone exchanges.
A **Gel cell battery** is one form of a VLRA battery.

They determine the ***operating voltage*** of your installation, for best efficiency all other devices should be designed to work at the same voltage of the batteries.

Operating voltage

Most autonomous solar systems work at 12 or 24 volts. Preferably, a wireless device that runs on DC should be used, operating at the 12 volts that most lead acid batteries provide.

A router or access point that accepts 8-20 volts DC is perfect. Most cheap access points have a switched mode voltage regulator inside and will work through a wide voltage range without modification or becoming hot (even if the device was shipped with a 5 or 12 Volt power supply).

Designing a battery bank

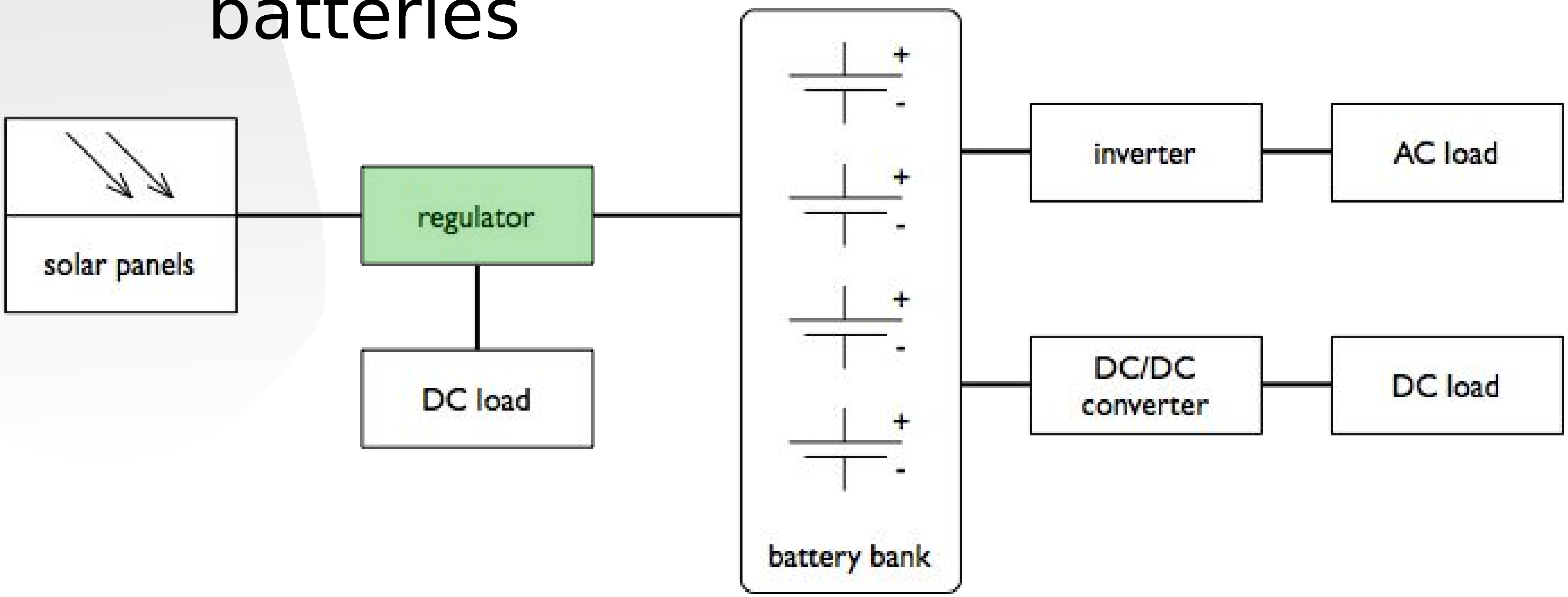
- The size of your battery bank will depend upon: the storage capacity required the maximum discharge rate the storage temperature of the batteries (lead-acid only). The storage capacity of a battery (amount of electrical energy it can hold) is usually expressed in amp-hours (Ah).

- A battery bank in a PV system should have sufficient capacity to supply needed power during the longest expected period of cloudy weather.

Regulator

The ***regulator*** is the interface between the solar panels and the battery, and can often provide power for moderate DC loads.

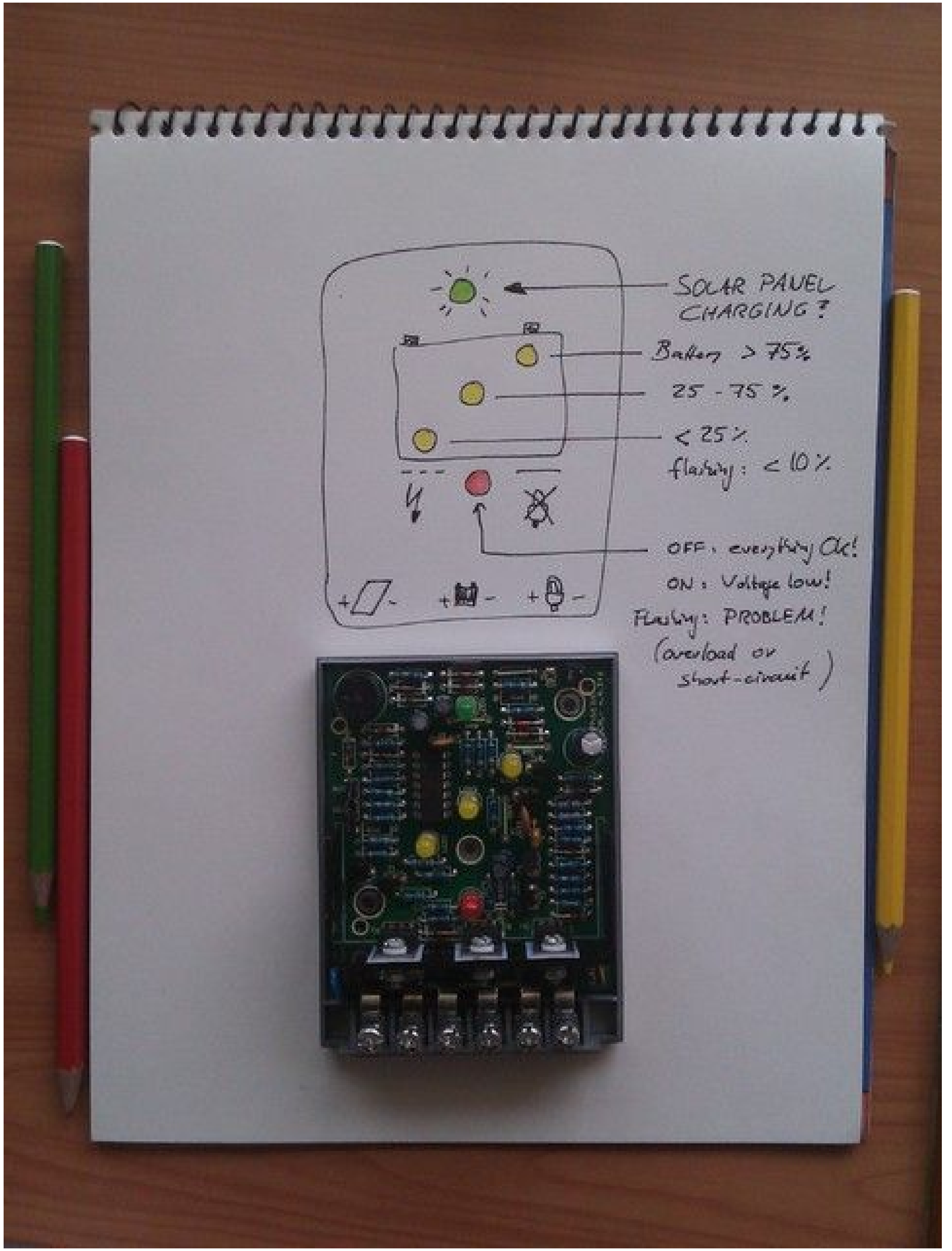
It protects the system against **overcharge** or **overdischarge** of batteries



Regulator

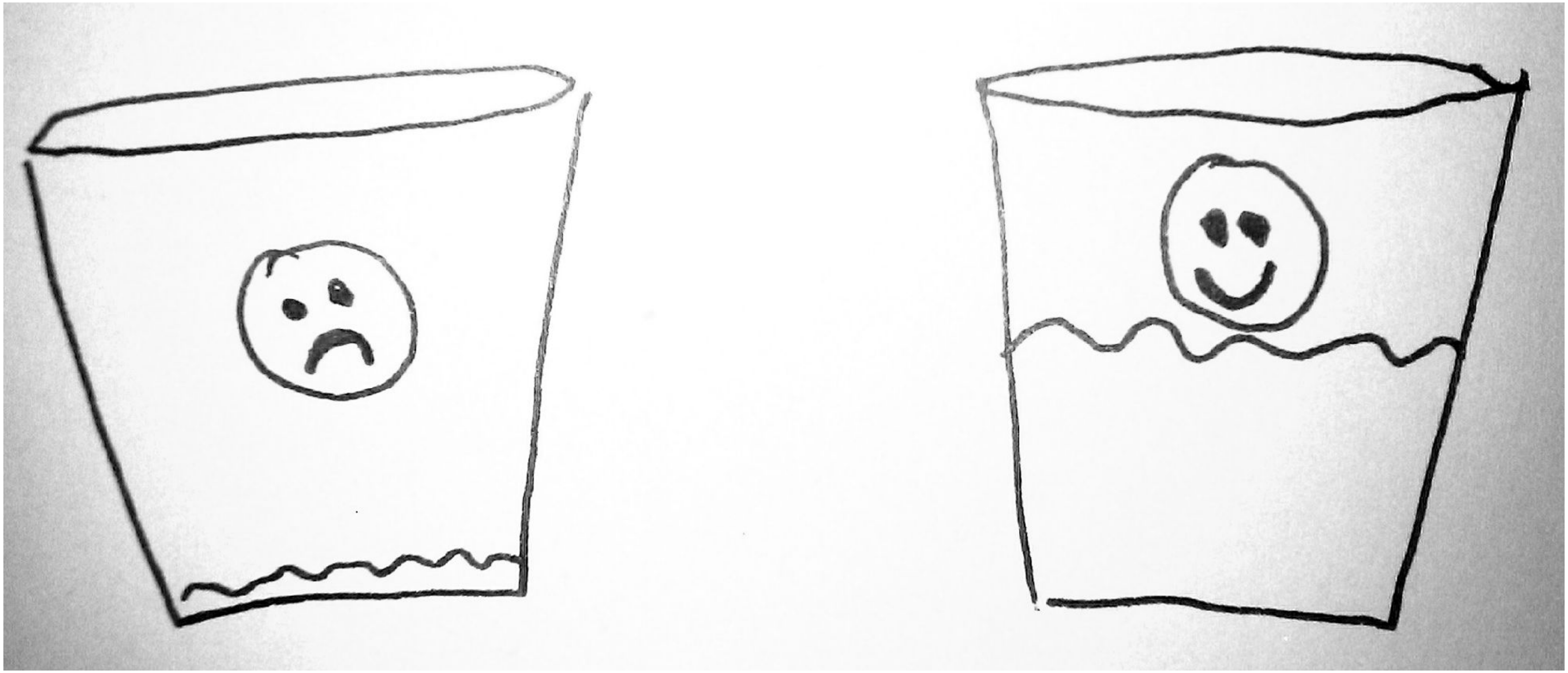
PROSTAR
PROSTAR-30
SOLAR CHARGE CONTROLLER
VERSION: PS-30
MORNINGSTAR corporation
CHARGING
TEMP. SENSOR
BATTERY STATUS
BLINK: LOW
ON: LVD
BATTERY TYPE
1 - GEL
2 - SEALED
3 - FLOODED
SOLAR
BATTERY
LOAD
SENSE

Regulator



SOLAR PANEL CHARGING?
Battery > 75%
25 - 75 %
< 25 %
flashing: < 10 %
OFF: everything OK!
ON: Voltage low!
Flashing: PROBLEM!
(overload or short-circuit)

Avoiding overdischarge



Maximizing battery life

Lead acid batteries degrade quickly if they are discharged completely.

A car battery will **lose 50% of its design capacity within 50 -100 cycles if it is fully discharged** during each cycle.

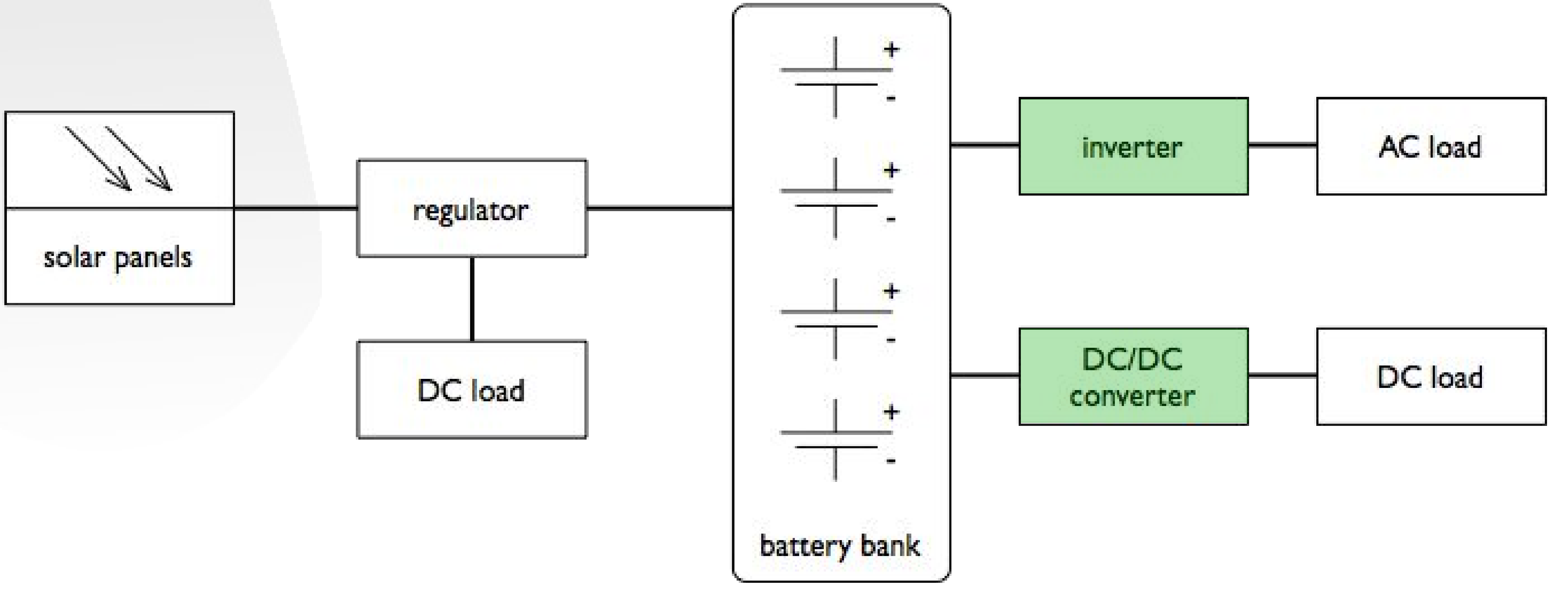
Never discharge a 12 Volt lead acid battery below 11.6 volts!

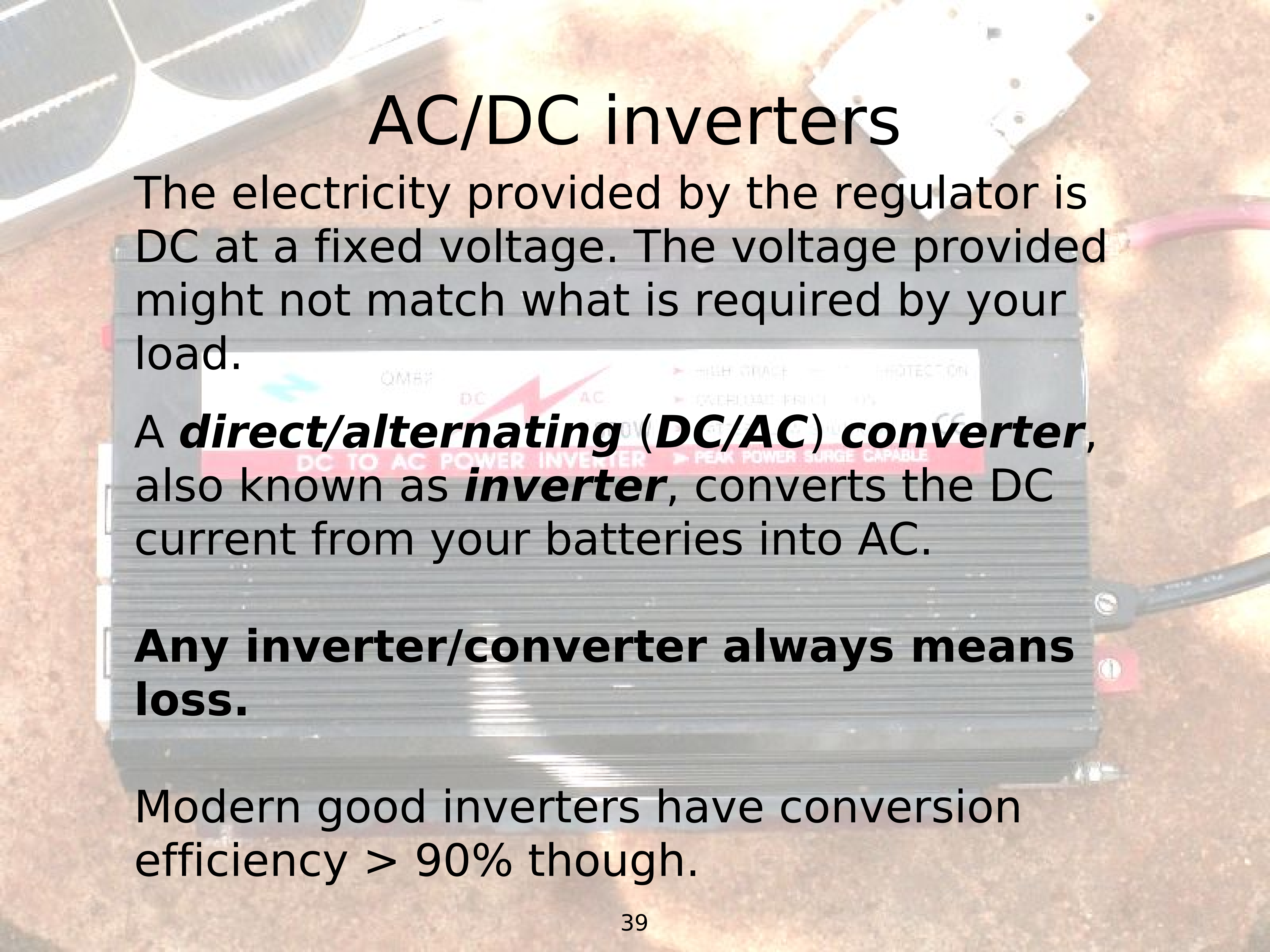
In cyclic use it is not advisable to discharge a truck battery below 70%. Keeping the charge to 80% or more will significantly increase the battery's useful lifespan.

Optimized deep cycle batteries will tolerate discharge down to 50%.

Voltage converters

An ***inverter*** turns DC into AC, usually at 110V or 220V. A ***DC/DC converter*** changes the input DC voltage into a desired value.





AC/DC inverters

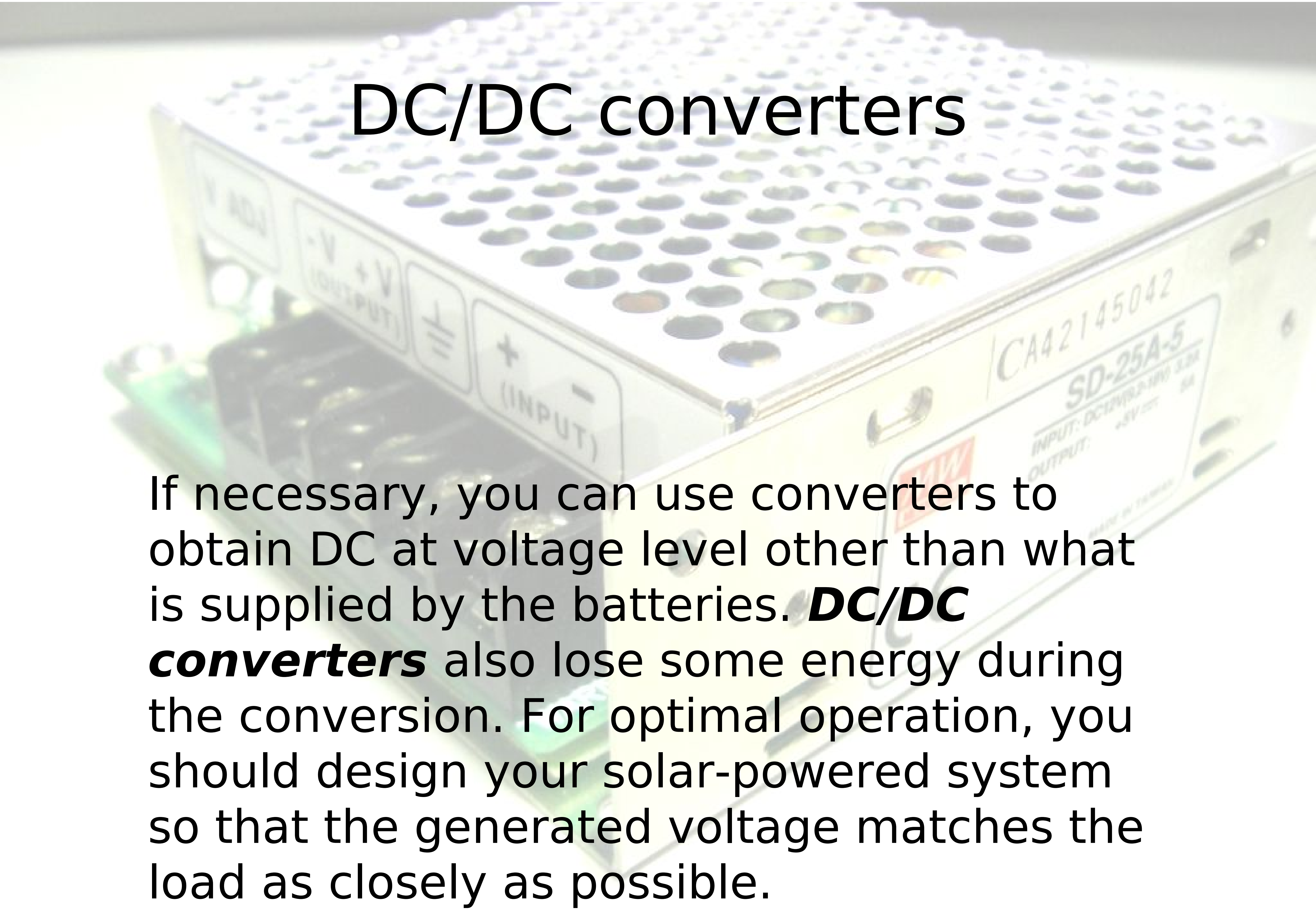
The electricity provided by the regulator is DC at a fixed voltage. The voltage provided might not match what is required by your load.

A ***direct/alternating*** (***DC/AC***) ***converter***, also known as ***inverter***, converts the DC current from your batteries into AC.

Any inverter/converter always means loss.

Modern good inverters have conversion efficiency > 90% though.

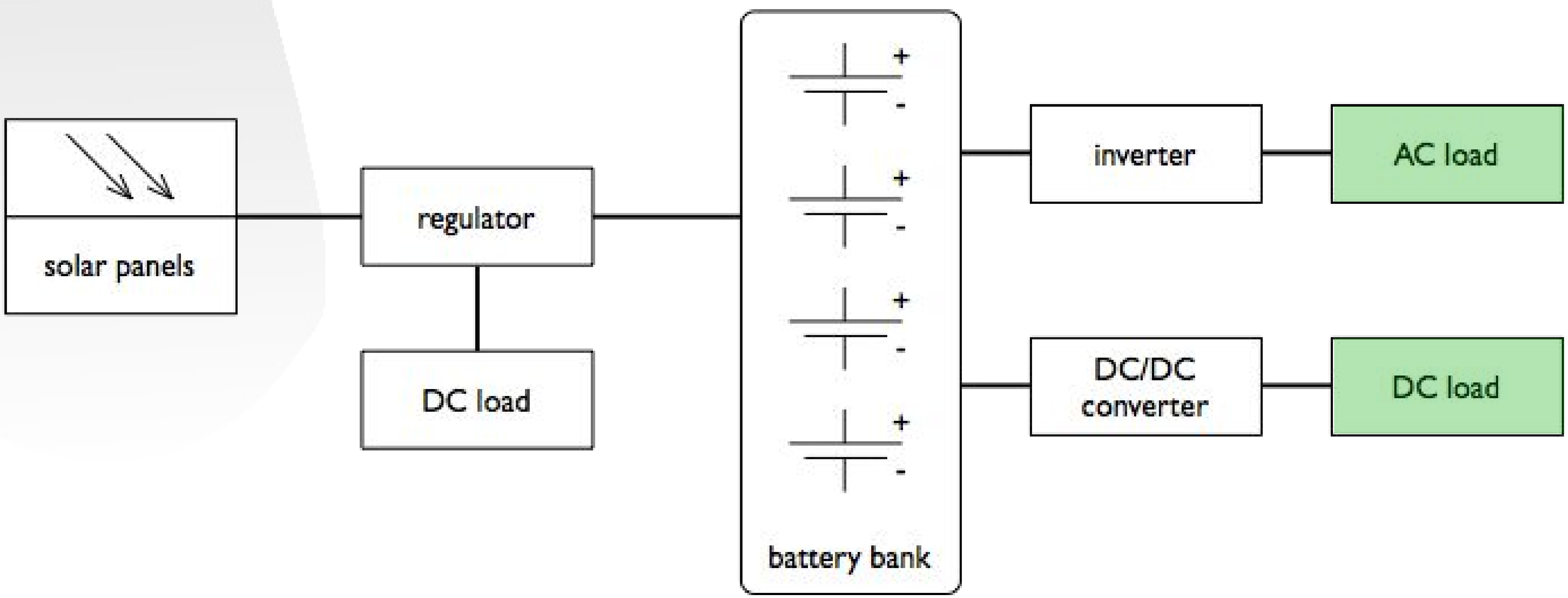
DC/DC converters



If necessary, you can use converters to obtain DC at voltage level other than what is supplied by the batteries. ***DC/DC converters*** also lose some energy during the conversion. For optimal operation, you should design your solar-powered system so that the generated voltage matches the load as closely as possible.

The load

The ***load*** is the work that is actually done by the solar energy system.



The Load

The ***load*** is the equipment that consumes the power generated by your energy system.

The load is expressed in watts, which are

$$\text{watts} = \text{volts} \times \text{amperes}$$

If the voltage is already defined, the load can be sometimes given in amperes.

Power consumption

The easiest way to measure how much power your load requires is to use a laboratory power supply that features a voltage and ampere meter. You can tune the voltage at the laboratory power supply and see how much current the device draws at different voltages.

If a laboratory power supply is not available, measurement can be performed by using the supply shipped with the device. Interrupt one cable that goes to the DC input of your device and insert an ***ampere-meter*** .

Power consumption

The amount of power consumed can be calculated with this formula:

$$P = U \times I$$

P is the power in Watts, ***U*** is voltage in Volts, and ***I*** is the current in Amperes.For example:

$$6 \text{ Watts} = 12 \text{ Volts} \times 0.5 \text{ Ampere}$$

If this device is operating for an hour it will consume 6 Watt-hours (Wh), or 0.5 Ampere-hours (Ah) at 12V. Thus the device will draw 144 Wh or 12 Ah per day.

Dimensioning a PV system

- Always involves some guessing
- Based on insolation data, measurements and lots of **experience**
- **Different approaches**

Approaches for dimensioning a PV system

- ***Worst month*** approach: get insolation data for worst month and compare to load/consumption
- **“Battery sufficient for longest dark period”** approach: Longest period without charge gives you capacity. Then design PV part such that you can recharge in reasonable time.

Wind power

A ***wind generator*** is an alternative option for an autonomous system.

The average wind speed over the year should be at least 3 to 4 meters per second.

Hint: locate the generator as high as possible

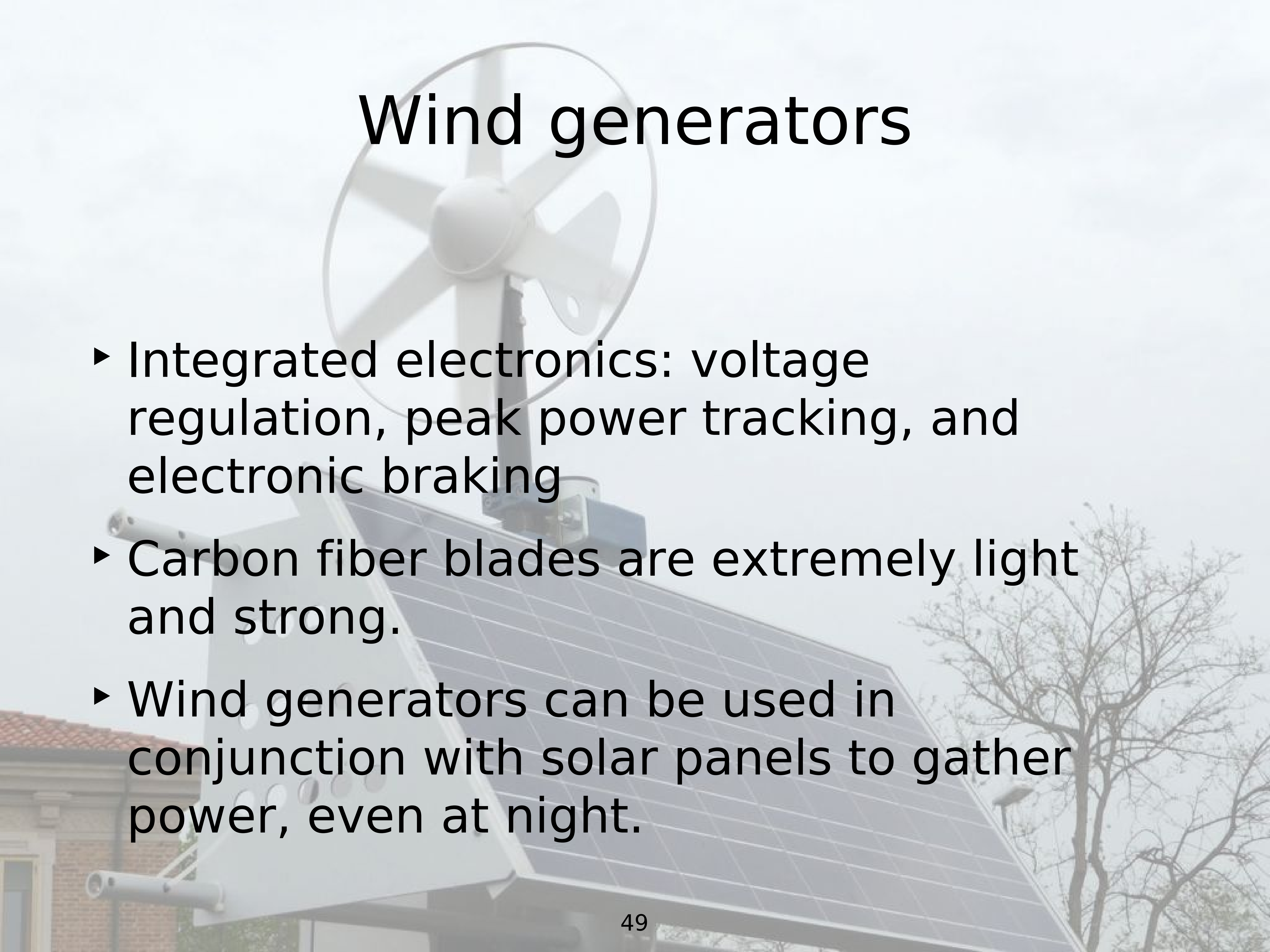
Wind power

The maximum available wind power is given by:

$$P = 0.5 * 1.225 * v^3 \ [W/m^2]$$

where v is in m/s, and assuming air density of 1.225 kg/m^3.
This corresponds to dry air at standard atmospheric pressure at sea level and 15 Celsius.

The efficiency of wind generators range between 20 and 40%



Wind generators

- Integrated electronics: voltage regulation, peak power tracking, and electronic braking
- Carbon fiber blades are extremely light and strong.
- Wind generators can be used in conjunction with solar panels to gather power, even at night.

An inexpensive Wind generator can be built out of an automotive alternator connected to a suitable propeller.
A voltage regulator and battery is still required
Beware of safety guidelines for this kind of construction!

Conclusions

- Solar or wind power are viable means to provide energy where grid power is unavailable, unstable or to compete with it
- Batteries for energy storage and proper charge regulators are as important as the panels
- Photovoltaic systems are expensive, so it pays to minimize load and do a careful estimation of the real minimum requirements
- Experience beats theory in planning
- Avoid using power inverters where possible
- Wind and hydro offer cheaper alternatives

Thank you for your attention

For more details about the topics presented in this lecture, please see the book ***Wireless Networking in the Developing World***, available as free download in many languages at:

http://wndw.net/