Renewable Energy Sources

Wind power - basics

- Wind is generated by uneven distribution of solar irradiation heating of the Earth's surface.
- The heated surface heats adjacent air proportionally, which then begins to flow upwards.
- This circulation, combined with the Earth's rotation and the alternation of day/night, creates pressure differences in the atmosphere, which produce wind.

Wind power - basics

- In terms of electricity generation, wind speed is a critical quantity
- Wind speed depends on distance between the surface and a given speed vector, and on surface roughness:

$$\frac{v^*}{v_0^*} = \left(\frac{h}{h_0}\right)^n \quad (-)$$

Where v^* ($m.s^{-1}$) is average wind speed in the distance h (m) from surface, v_0^* is reference average wind speed in distance h_0 (m) from surface and n (-) is surface roughness (n = 0.14 (water, sand) - 0.5+ (cities)).

Wind energy and power

- Since kinetic energy is defined as

$$E = \frac{1}{2} m \cdot v^2 \text{ (J)}$$

- And since mass of air can be written as:

$$m = \rho \cdot V = \rho \cdot A \cdot s \text{ (kg)}$$

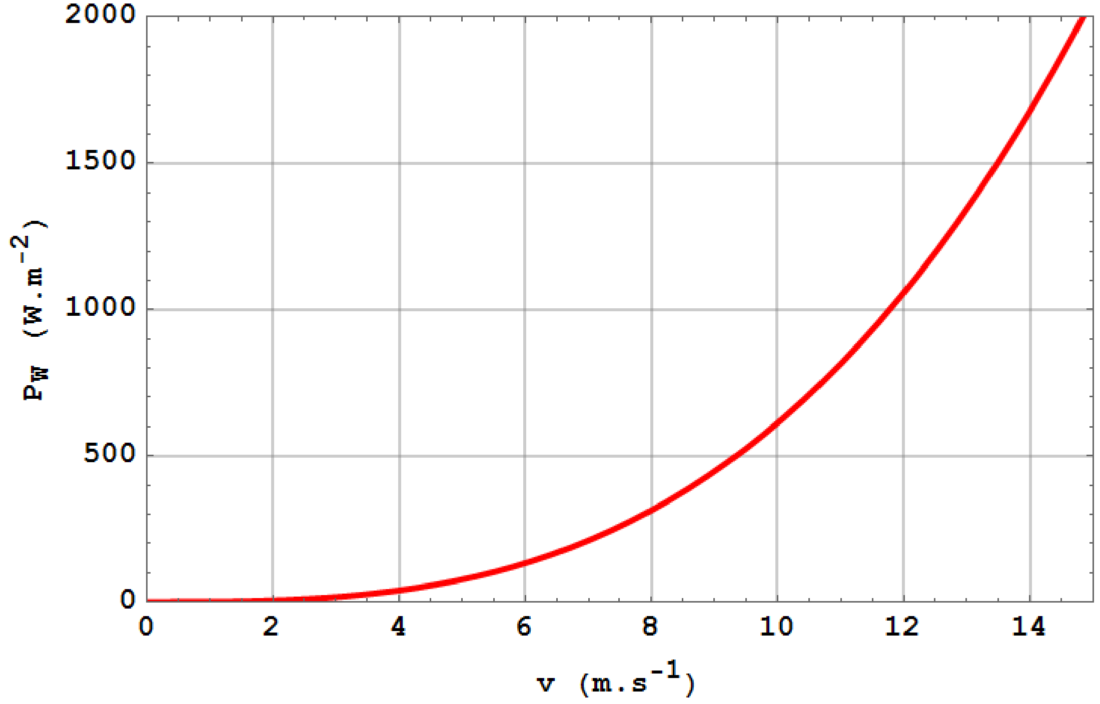
- The wind power flowing through a unit area *A* (1 m^2) is then given by the equation:

$$P_w = \frac{E}{A \cdot t} = \frac{1}{2} \cdot \rho \cdot \frac{A \cdot s}{A \cdot t} \cdot v^2 = \frac{1}{2} \cdot \rho \cdot 1 \cdot v \cdot v^2 = \frac{1}{2} \cdot \rho \cdot v^3 \quad (\mathrm{W \cdot m^{-2}})$$

Wind energy and power

- Should air temperature and density be constant over a time period, wind energy can be derived from wind power as:

$$E_W = \frac{\rho}{2} \cdot \int_{t_0}^{t} P_W \cdot dt \text{ (J)}$$

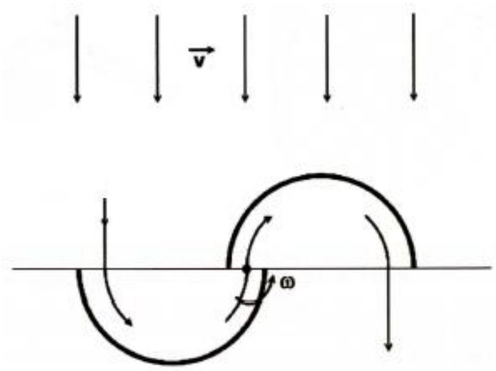


Wind engines

- Wind engines transfer kinetic energy of wind to mechanical energy. In wind power plants, the mechanical energy is subsequently transformed into electricity.
- Primarily, there are two types of wind engines:
  - Drag-based engine
  - Lift-based engine
- Additionally, according to the position of a rotation axis, there are two more types:
  - Horizontal axis
  - Vertical axis

Drag-based engines

- The oldest type of wind engines.
- Rotary motion based on aerodynamic resistance.
  - The downwind part of the motion must always exhibit higher aerodynamic resistance than the upwind part.
- Peripheral speed of the rotor is always lower or equal (no-load) to wind speed.
- Energy conversion efficiency: 15 - 23 %



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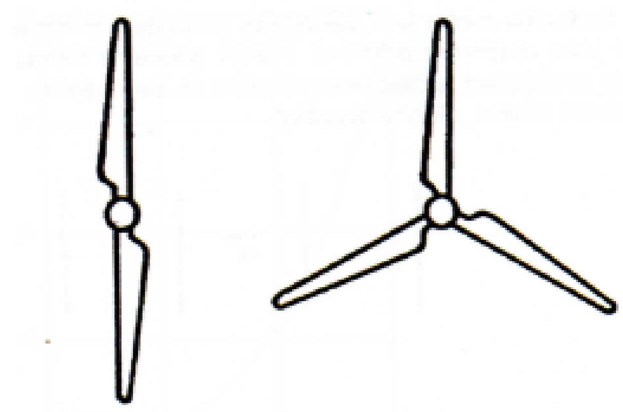
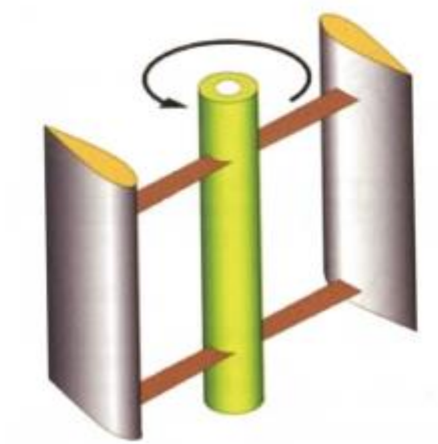
Drag-based engines

+ Simple structure
+ Independent on the direction of wind
+ Direct transfer of torque to the shaft
+ Broad range of applicable wind speed
– Low RPM
– High torque impressed on the shaft
– Low efficiency

Lift-based engine

- The majority of lift-based engines employs a horizontal axis
- The rotor is constructed with 2 or 3 wing-like blades in most cases
- High-speed lift-based engines reach the conversion efficiency of over 40 %
- Wind speed required to start up the engine is around 5 $m.s^{-1}$
- The most viable type of engine for electricity generation





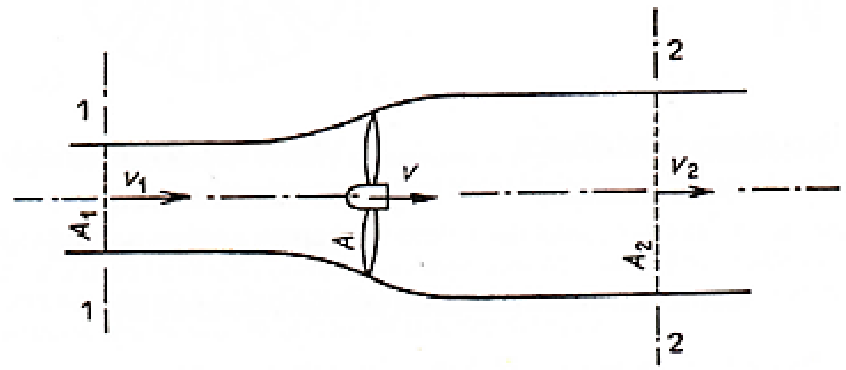
Darrieus wind turbine

Lift-based engine

- The continuum equation of a lift-based engine provides with two parameters v_1 and v_2:

$$v_1 \cdot A_1 = v \cdot A = v_2 \cdot A_2$$

where v_1 (m.s^{-1}) is steady wind speed in front of the engine and A_1 (m^2) is the relevant area through which the wind flows. Parameters v, A, v_2 and A_2 describe similar parameters in the vicinity of the turbine and in the area behind the turbine, respectively, as can be seen in the figure.



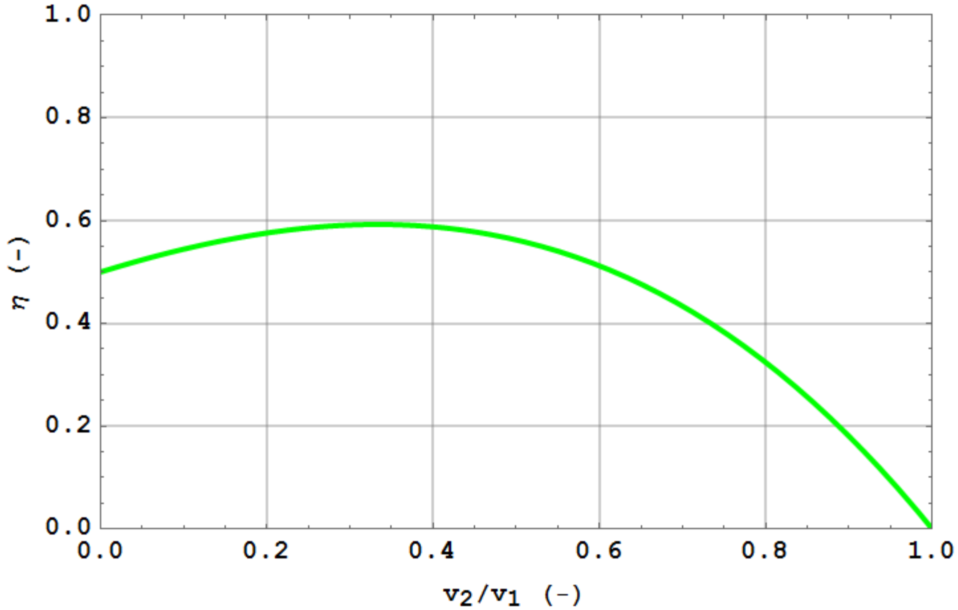
Lift-based engine

- Power and ideal efficiency of a lift-based engine is defined as:

$$P = \frac{1}{4} \cdot \rho \cdot A \cdot (v_1^2 - v_2^2) \cdot (v_1 + v_2) \text{ (W)}$$

$$\eta_i = \frac{(v_1^2 - v_2^2) \cdot (v_1 + v_2)}{2 \cdot v_1^3} \text{ (−)}$$

- The maximum theoretical conversion efficiency is given by Betz's law as $\eta_{i,M} = 0.59$ when $v_2/v_1 = 1/3$



Lift-based engine

- Electricity generation
  - Asynchronous generator
    - + Cheaper, simple construction, more reliable
  - Synchronous generator
    - + Broader range of potential rotor speed
  - Both require an AC/AC converter with a DC link

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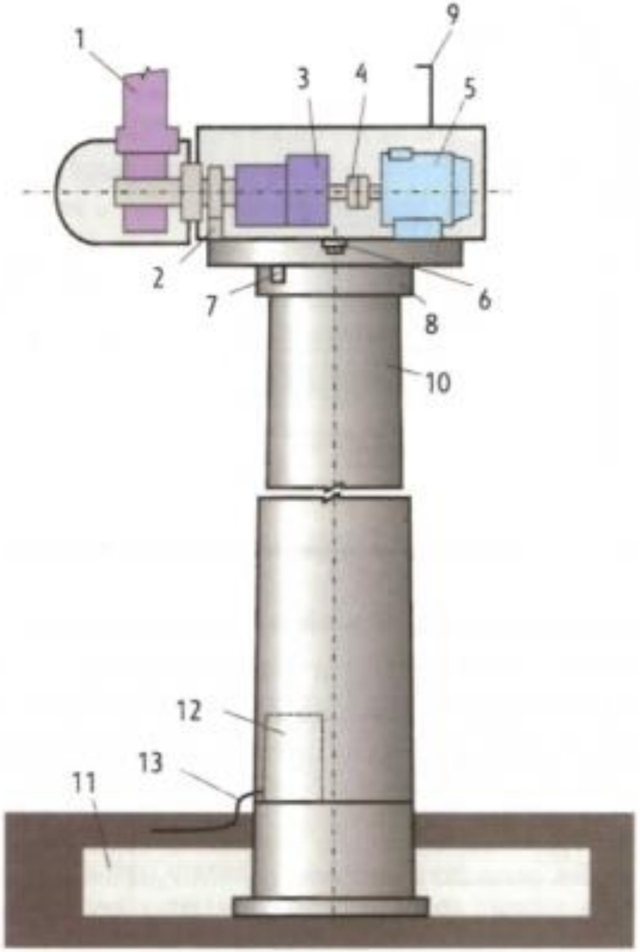
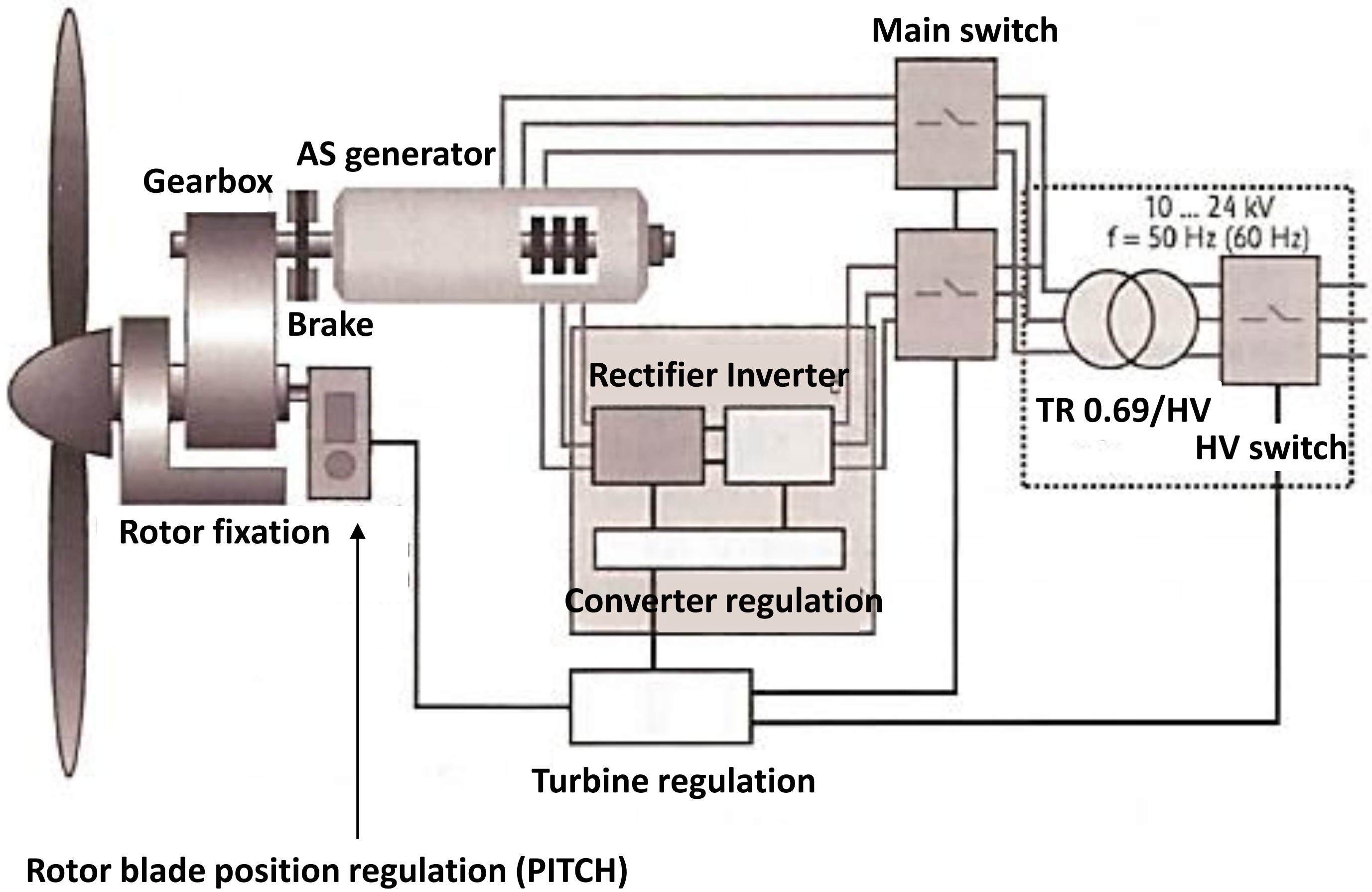
Construction of a wind turbine

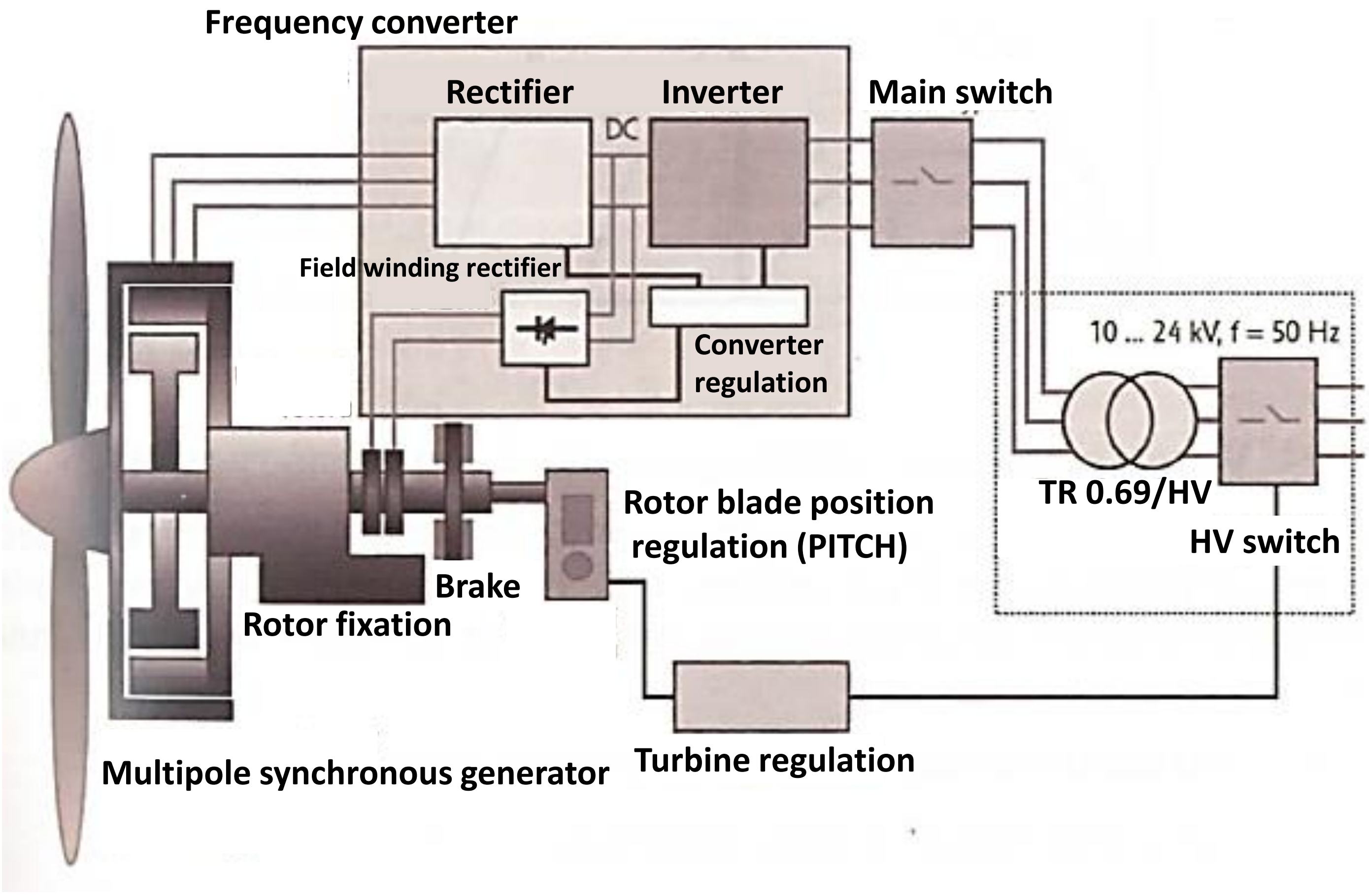


1 – Rotor (bearings, blades, nose cone)
2 – Rotor brake
3 – Gearbox
4 – Clutch
5 – Generator
6 – Engine room servomotor
7 – Engine room brake
8 – Engine room bearings
9 – Wind speed and direction sensor
10 – Tower
11 – Concrete foundation
12 – Distribution board
13 – Line conductors

Wind turbine block scheme (asynchronous)



Wind turbine block scheme (synchronous)



Wind turbine power regulation

- Power depends on wind speed: minimum 3 - 5.5 $m.s^{-1}$, nominal 13 - 15 $m.s^{-1}$, maximum 25 $m.s^{-1}$; higher wind speeds can cause damage to the turbine
- Different regulation methods for 2 basic types of blades:
  - With fixed bearing (STALL regulation)
  - With turntable bearing (PITCH regulation)

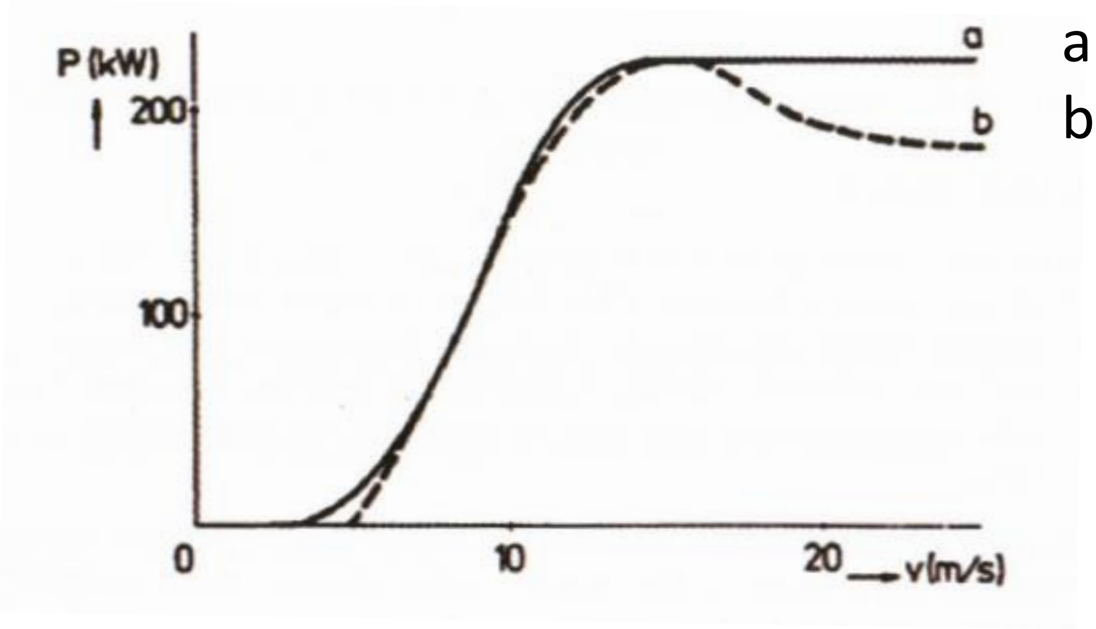
Wind turbine power regulation

- STALL
  - Fixed bearing requires gradual adjustment of elastic geometry of the blade's farther edge with rising speed of the wind.
  - The gradual change is achieved by blade's precise geometry, which gradually converts the air flow from laminar to turbulent at increased speed. It results in the reduction of aerodynamic lift, rotor torque, and power.

Wind turbine power regulation

- PITCH
  - Active regulation, blades may rotate around their axes via a turntable bearing.
  - Should wind speed, and thus rotor torque, approach potentially harmful level, the blades are turned in downwind direction, so the lift is reduced and drag is increased.
  - This reduces the rotor torque and therefore the power decreases.

Wind turbine power regulation



a – PITCH

b – STALL

Solar power

- The mean intensity of sunlight incident on Earth's upper atmosphere is 1 367 W/m^2 (the solar constant)
- About 20 % of the incident sunlight is absorbed in the atmosphere and approximately 10 % is scattered and reflected, letting 70 % to reach the ground directly.
- Therefore the maximum **direct** sunlight intensity reaching the ground is around 960 W/m^2 (assuming clear sky at solar noon).

Solar irradiance

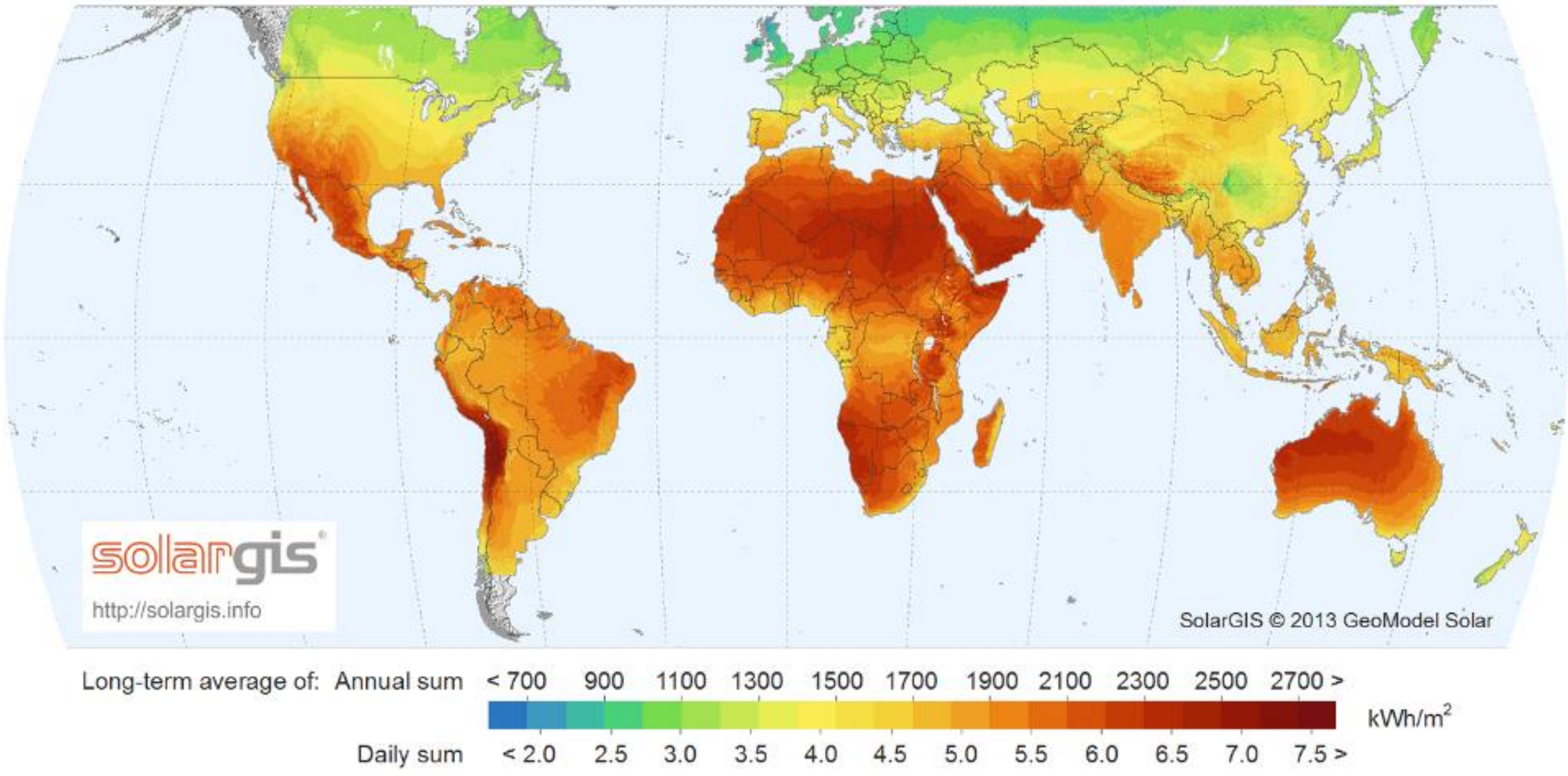
- The direct sunlight intensity is defined as:

$$I_D = I_0 \cdot 0.7^{AM} \cdot \cos\gamma$$

where I_0 = 1 367 W/m^2 is the solar constant, 0.7 is the fraction of incident sunlight directly reaching the surface, *AM* (-) is the atmospheric mass coefficient that reflects the total travel distance of a sunray through the atmosphere (minimal value is 1) and γ (°) is the angle between the incident sunray and the given surface.

- The total intensity is given by both direct and indirect sunlight (scattered and reflected sunlight reaching the ground).

Solar irradiance



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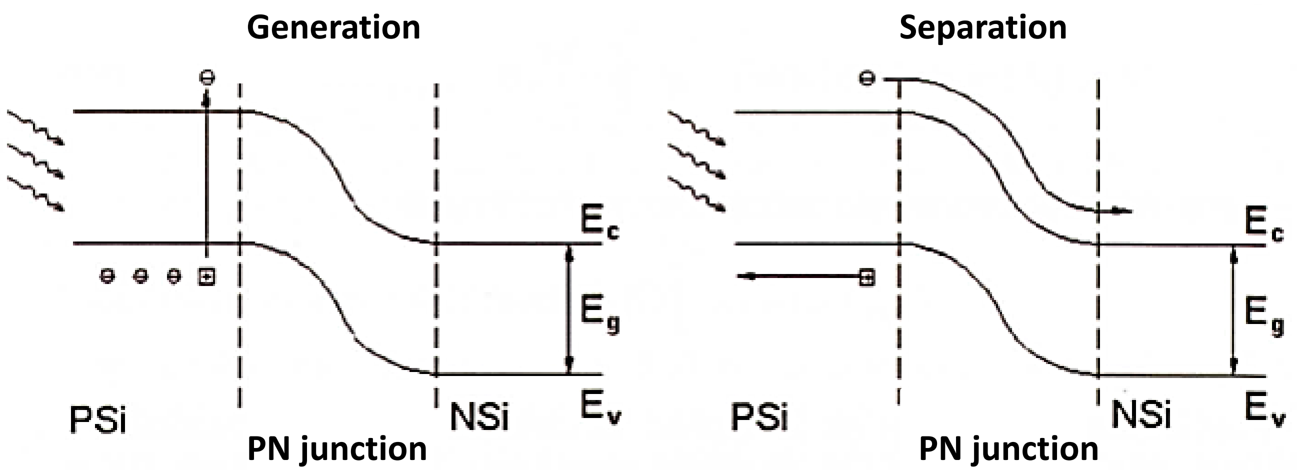
Photovoltaic effect

- When a photon is absorbed by material, it transfers some of its energy to the material's bound or unbound electrons, or to its lattice (should it exist).
- If the photon transfers enough energy to a bound electron, the electron then becomes unbound. Hence, a cation and an anion are created.
- When both ions are separated, they create difference in electric potentials, i.e. electric voltage.
- The easiest way to separate the ions is by employing a PN junction attracting the ions in opposite direction. Most of the time, it is implemented by monocrystalline or polycrystalline silicon with the p-doped and n-doped parts.

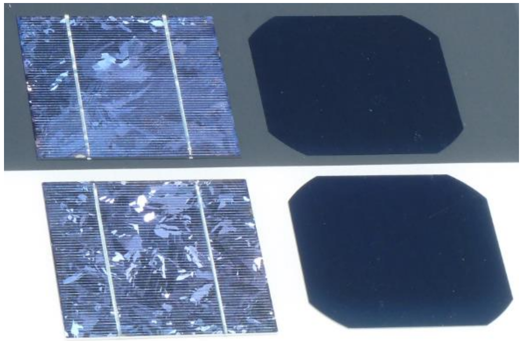
PN junction

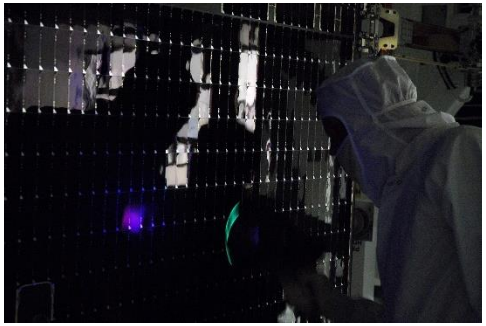


- Popis veličin
- E_g (eV) is the band gap, which refers to the minimum absorbed energy required for a bound electron to become unbound.

Photovoltaic cell

- Silicon monocrystalline and polycrystalline cells (c-Si)
  - Simple construction, but it requires a substantial amount of pure silicon
  - High conversion efficiency (15+ %)
  - Cheap, most widely used type of solar cells
- Thin-film cells
  - Small, compact construction
  - The active region's thickness is significantly reduced (about a thousandth of a crystalline silicon cell)
  - Lower efficiency (10 %), expensive or ecologically harmful materials (CdTe; Cu-In-Ga-Se; GaAs; amorphous silicon)
- Multi-junction cells (tandem)
  - Several PN junctions
  - Tandem of various materials with different band gap energies
  - Very expensive, generally require a solar concentrator to be economically viable.
  - Efficiency of up to 40 %





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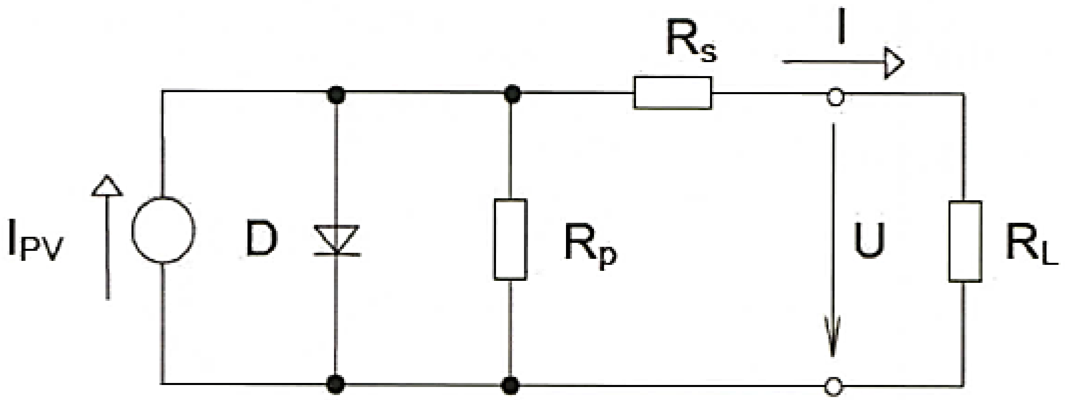
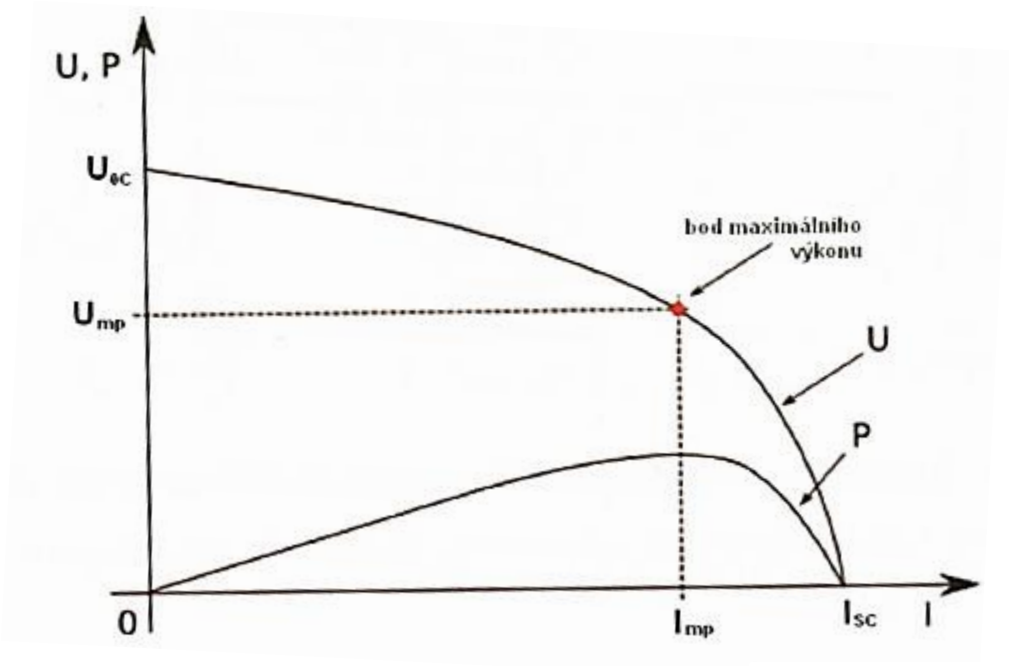
Circuit diagram of a photovoltaic cell



Where I_{PV} is the current source for ion generation through the incident sunlight, *D* is a diode that simulates the PN junction, R_P is a parallel resistance that represents the effect of technological imperfections of the actual PN junction, and R_S is resistance of the material and current collectors, respectively. Load is represented by resistance R_L.

Volt-ampere and power characteristics of a photovoltaic cell



Where U_{0C} (V) is the open-circuit voltage, U_{MP} (V) and I_{MP} (A) are the maximum power voltage and current, respectively, and I_{SC} (A) is the short-circuit current

Maximum power, fill factor and efficiency

- Maximum power is achieved at voltage U_{MP} and current I_{MP}:

$$P_M = U_{MP} \cdot I_{MP}$$

This occurs at the point of a power characteristic *P*(*I*) where

$$\frac{dP}{dI} = 0$$

- A fill factor of a photovoltaic cell is the mathematical representation of a perfect PV cell. The factor is defined in the following way:

$$FF = \frac{U_{MP} \cdot I_{MP}}{U_{OC} \cdot I_{SC}}$$

- Efficiency is determined at the maximum power as:

$$\eta = \frac{U_{MP} \cdot I_{MP}}{P_{IN}}$$

Where P_{IN} (W) is the total power of the incident sunlight.

STC, temperature dependency

- Standard Test Conditions (STC) of a photovoltaic cell are: ambient temperature ϑ_A = 25 °C, sunlight intensity I = 1 000 $W.m^{-2}$, and atmospheric mass coefficient AM = 1.5.
- The STC are particularly important as both power and efficiency significantly depend on the mentioned parameters.
- Since I_{SC} is practically independent on the temperature, the power is given almost exclusively by open-circuit voltage U_{OC}, which depends on temperature, as follows:

$$U_{OC} \approx \frac{k \cdot T}{e} \ln \frac{I_{PV}}{I_{01}}$$

Where

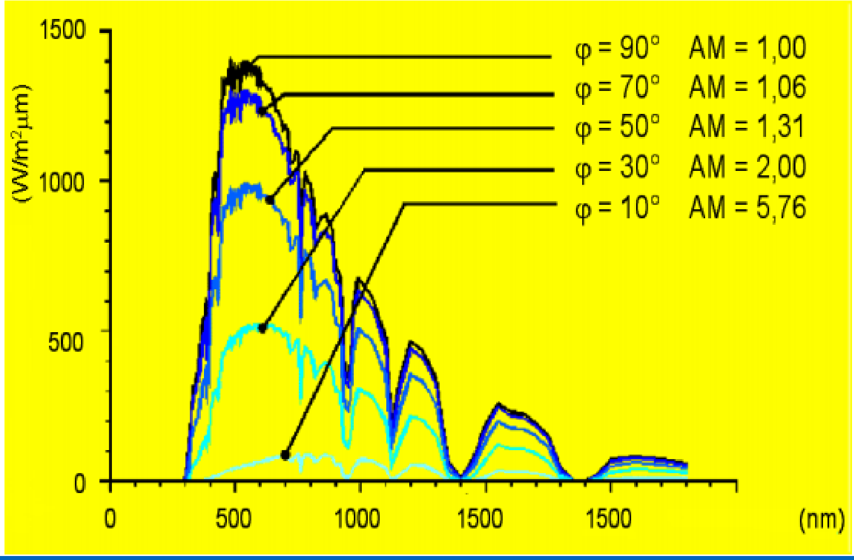
$$I_{01} \sim n_i^2 = B \cdot T^3 \cdot \exp\left\{-\frac{W_G}{k \cdot T}\right\}$$

Hence, it is evident that both power and efficiency decrease with temperature. For crystalline silicon, the drop is about 0.5 $\%.°C^{-1}$.

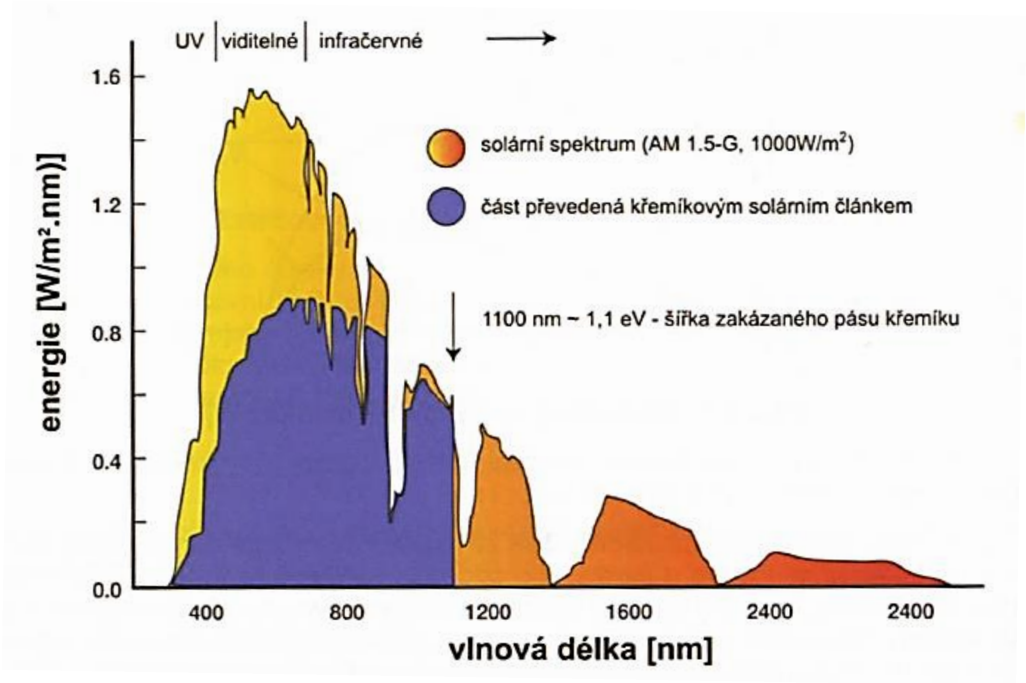
Irradiance intensity and *AM* dependency

- Based on the series resistance R_S, the efficiency can either increase or decrease with solar irradiance intensity.
  - Tandem PV cells have generally low value of R_S and hence their efficiency gradually increases. Therefore, they are often paired with solar concentrators.
  - The series resistance of c-Si cells is significantly larger. Hence, their efficiency drops with increasing intensity.

- The spectrum of incident light depends on the total travel distance through the atmosphere. For practical purposes, the spectrum is specified by atmospheric mass coefficient *AM.*
  – The coefficient is given by angle φ between the incident sunray and the normal of upper atmosphere surface. The values of AM are given in the figure.

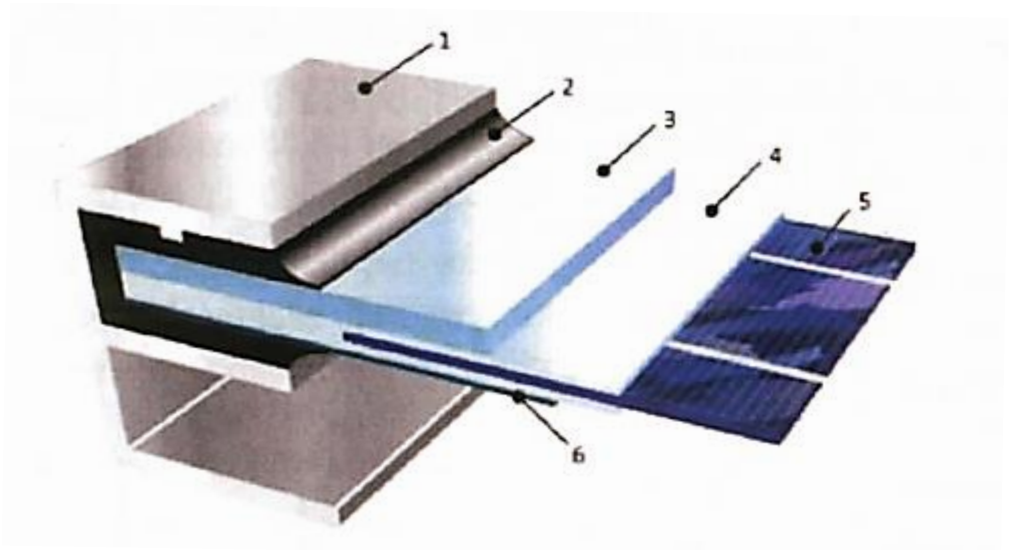


C-Si cell effective spectrum



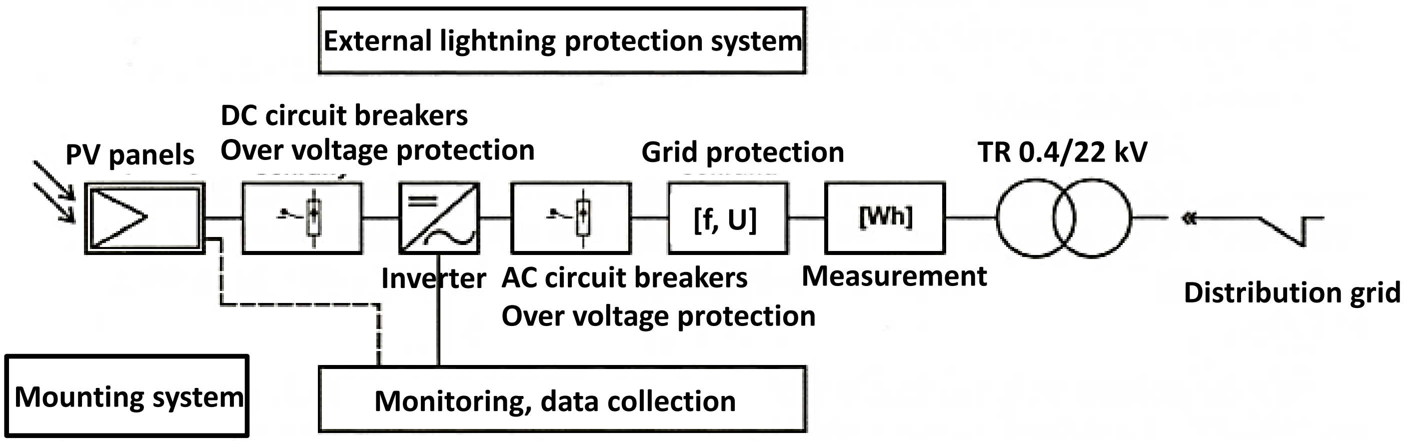
- The troughs in the figure correspond to the presence of H_2O and CO_2 molecules in the atmosphere, which absorb most of the sunlight at specific wavelengths.
- Without the atmosphere, the spectrum of light would be given only by black-body radiation of an object with surface temperature T = 5 800 K (the Sun).

C-Si panel structure



1 – Aluminum frame; 2 – Sealing, 3 – Tempered glass, 4 – Ethyl Vinyl Acetate (EVA); 5 – PV cell; 6 – Tedlar film

PV power station schematic diagram



PV power station

- There are several types that are determined by the following parameters:
  - Installed capacity:
    - < 100 kWp – generally employ many small inverters (1.5 – 8 kWp)
    - > 100 kWp – large central inverters (40 – 1 000 kWp)
  - Supporting structure of PV panels
    - Fixed construction
    - With tracking axis (axes)
      - 1 axis
      - 2 axes
  - Location
    - Rooftop
    - Integrated into building shells
    - Fields

PV power station

Other types of renewable energy sources

- Hydropower (see respective presentation) including tidal power
- Biomass
  - Chemical energy of plants, trees, manure (animal waste), etc. is indirectly transformed into electricity.
  - The most common representatives are wood pellets along with woodchips
- Geothermal energy
  - Thermal energy of deeper regions of Earth's crust is harnessed via heat pumps