Sustainable Energy Transformation Technologies, SH2706

Lecture No 18

Title:

Design and Operation of Solar Power

Henryk Anglart

Nuclear Engineering Division

Department of Physics, School of Engineering Sciences

KTH

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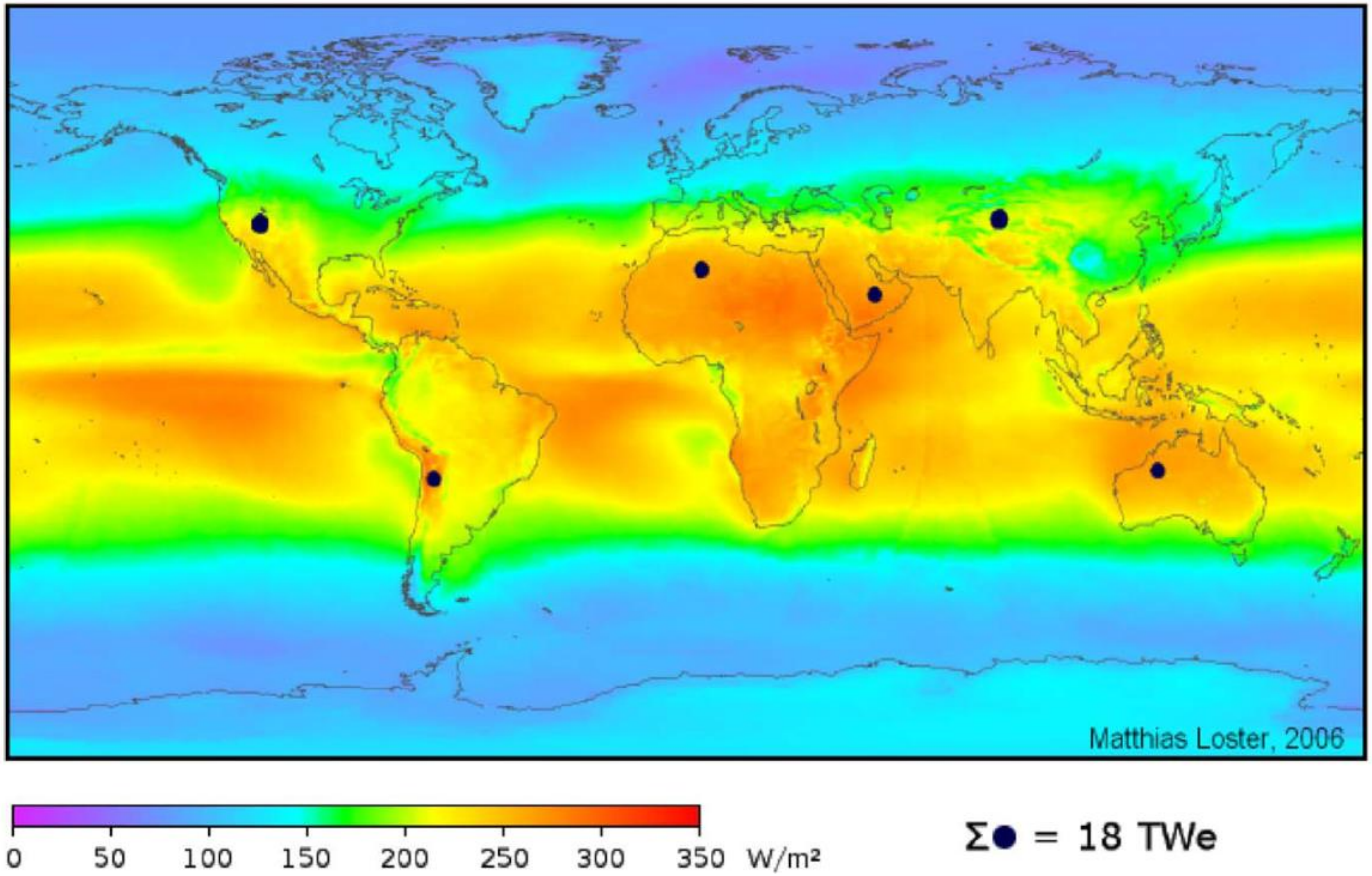
Outline

- Introduction
- Basics of solar energy
  - Solar production and radiation
  - Solar energy on Earth
- PV cell
  - Principles of operation
  - System efficiency
  - Future perspectives
- Solar thermal power
  - Principle of operation
  - Efficiency
  - Future perspectives

Introduction

- The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 EJ (exajoules, 10^{18}J) per year
- Photosynthesis captures about 3000 EJ per year
- Global primary energy use in 2010 was 539 EJ
- The potential solar energy that could be used by humans differs due to time variation, cloud cover and the land availability

Annual Solar Irradiance



NASA – Plotted from satellite data supplied by NASA Clouds and the Earth's Radiant Energy System – CERES; 2014. Ref. 1, p. 2

Energy of the Sunlight

- The Sun contains ~73.46% of hydrogen and 24.85% of helium. The rest includes oxygen, carbon, and other el.
- Sun energy results from the following fusion reaction

$$4\ {}_{1}^{1}p \rightarrow {}_{2}^{4}\alpha + 2\ e^{+} + 2\ \nu + \Delta E$$

proton helium's nucleus positron neutrino

- Mass defect of this reaction is Δm=0.0265 u, thus, the energy released in the reaction is $\Delta E = 3.955\mathrm{x}10^{-12}$ J

- During 1s the Sun is loosing a mass $\Delta m = 4.3\mathrm{x}10^{9}$ kg which corresponds to energy $Q_s = \Delta mc^2 = 3.845\mathrm{x}10^{26}$ J

Energy of the Sunlight

- The energy (heat) flux at the Sun surface can be found as $I_s = q_s/A_s = 63.11\ \mathrm{MW/m^2}$

- Assuming black-body radiation and using the Stefan-Boltzmann equation, we calculate the average temperature at the Sun surface as

$$T = \left(\frac{I_s}{\sigma}\right)^{1/4} = \left(\frac{61.11\cdot 10^{6}\ \mathrm{W\ m^{-2}}}{5.67051\cdot 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}}\right)^{1/4} \cong 5777\ \mathrm{K}$$

Solar Energy on Earth

- General characteristics of solar radiation
  - a varying and intermittent source of energy, influenced by such factors as weather, Earth rotation around own axis and Earth orbiting the Sun
- Position of the Sun
  - the position of the Sun in the sky is a function of both the time and the geographic location
- Effective radiation
  - hourly, daily and monthly clearness index
  - Radiation intensity on inclined surfaces

Solar Constant

- At the Earth's orbit (distance from the Sun L = 1.47÷1.52x10^8 km), the heat flux resulting from sunlight is

$$I_e = I_s \left(\frac{r_s}{L} \right)^2 = 1325 \div 1420 \text{ W m}^{-2}$$

- Its mean value, called **the Solar constant**, is:

$$G_{sc} = 1366 \text{ W m}^{-2}$$

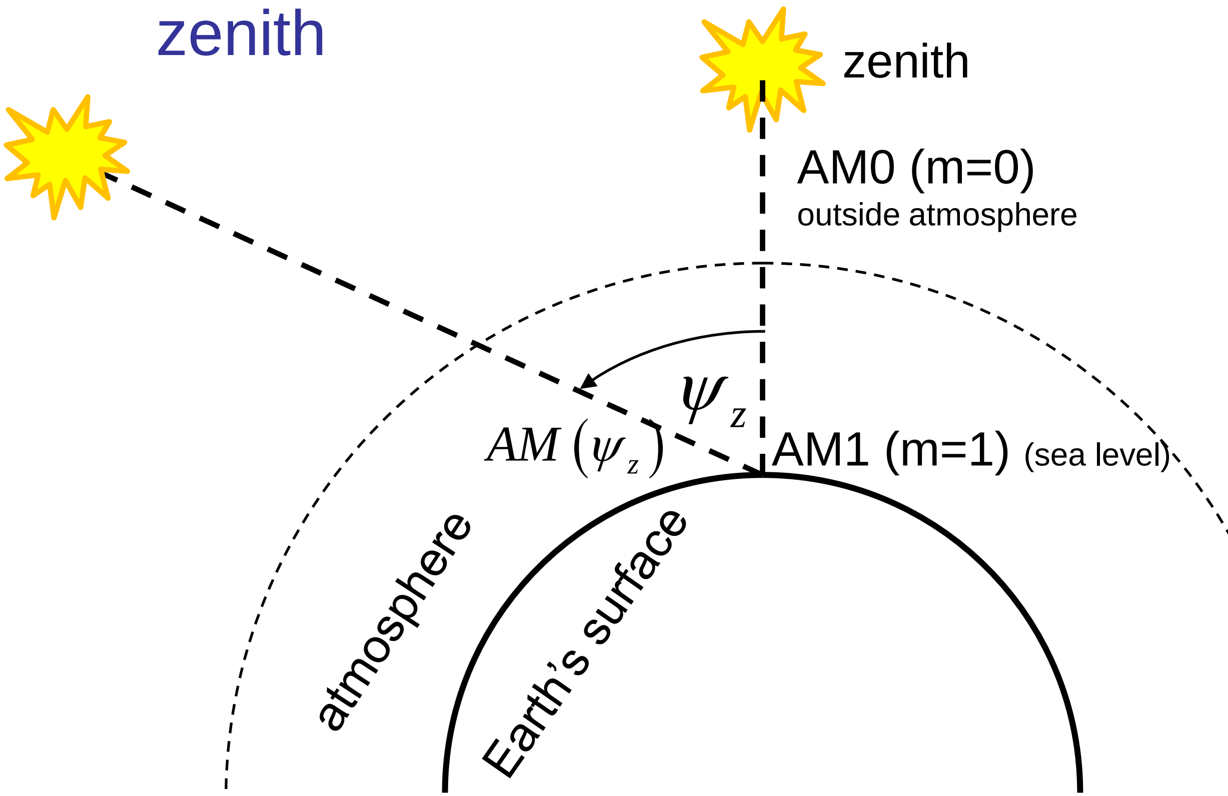
  - In reality G_{sc} is not a constant and is varying slightly with solar activity. Recent recalibrations of satellite observations indicate a lower value closer to 1361 W/m^2

Variation of the Sun Irradiation

- The variation of the Sun irradiation on Earth can be calculated from the following equation:
- $$I_e = G_{sc}\left[1+0.033412\cos\left(\frac{360°\left(N_d-3\right)}{365}\right)\right], \qquad G_{sc}=1366\ \mathrm{W\ m^{-2}}$$
- here N_d = 1,2, ..., 365 is the day number, starting from N_d = 1 on January, 1st
- N_d-3 is used in the equation since Earth's perihelion (the closest approach to the Sun) occurs around January 3rd and the aphelion – on July 4th

Air Mass Coefficient

- Air Mass (AM) coefficient defines the relative solar spectrum as compared to that when the Sun is at the zenith



AM coefficient is a function of angle ψ_z and approximately it is equal to

$$m = \left(\cos\psi_z\right)^{-1}$$

A more accurate value can be found as:

$$m = \left[\cos\psi_z + \frac{0.15}{\left(93.885 - \psi_z\right)^{1.253}}\right]^{-1} \frac{p}{p_0}$$

where p – pressure, p_0 = 101.3 kPa

Radiation correction $I = 1.1 \cdot I_0 \cdot 0.7^{\left(AM^{0.678}\right)}$

Solar Radiation Components

- **Beam radiation** (I_b) is the direct component of the solar radiation
- **Diffuse radiation** (I_d) is an indirect component of the solar radiation resulting from dispersion of the sunlight in the atmosphere
- The total radiation is a sum of the two

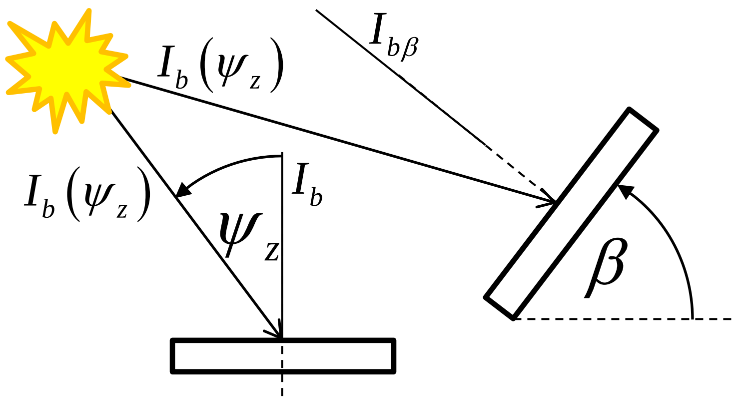
$$I = I_b + I_d$$

Radiation on Inclined Surface

- When surface is inclined to the horizontal position, additional radiation component can occur due to reflection from the ground

- Thus, the total radiation intensity I_β on the surface inclined with angle β consists of three terms

$$I_\beta = I_{b\beta} + I_{d\beta} + I_{r\beta}$$



- here:
- $I_{b\beta}$ - direct beam radiation intensity
- $I_{d\beta}$ - diffuse radiation intensity
- $I_{r\beta}$ - reflected radiation intensity

Radiation on Inclined Surface

- The radiation intensity on a inclined surface can be calculated as (for isotropic dispersed and reflected radiation)

$$I_\beta = I_b R_b + I_d \left(\frac{1+\cos\beta}{2} \right) + \left(I_b + I_d \right) \rho_g \left(\frac{1-\cos\beta}{2} \right)$$

- where

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\cos\omega + \sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta}$$

φ – local geographic latitude, δ – the Sun declination, ω – hour angle, β – collector inclination angle

ρ_g – reflectivity of the ground (depends on ground type, orientation, etc.)

Position of the Sun

- Position of the Sun can be found in three steps
  - calculate the Sun's position in the ecliptic coordinate system
  - convert to the equatorial coordinate system
  - convert to the horizontal coordinate system (at given time and location on Earth)

- In solar energy applications, we usually use correlations to determine the Sun coordinates in the sky:
  - the altitude of the Sun (ψ)
  - the azimuth of the Sun (α)
- These coordinates are functions of the local longitude and latitude, the solar declination and the hour angle

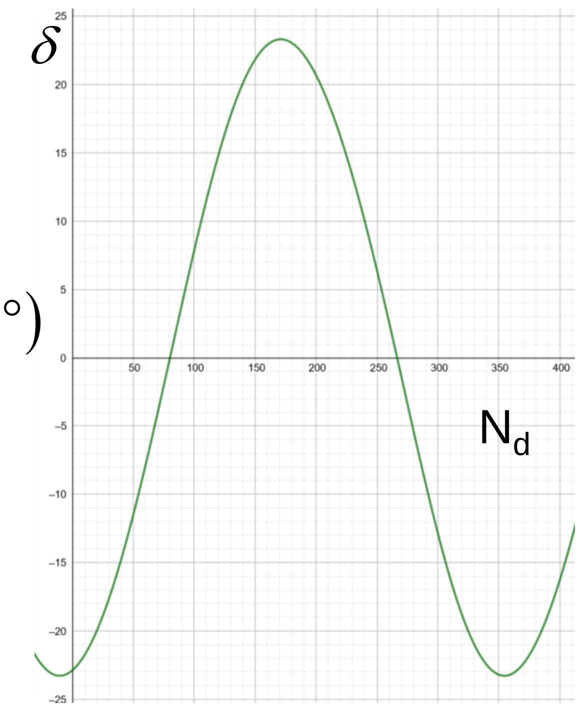
The Declination of the Sun

- The declination of the Sun is the angle between the ray of the Sun and the plane of the Earth’s equator. It varies from -23.45° (December 20) to 23.45° (June 21)

- The Sun’s declination is calculated as:

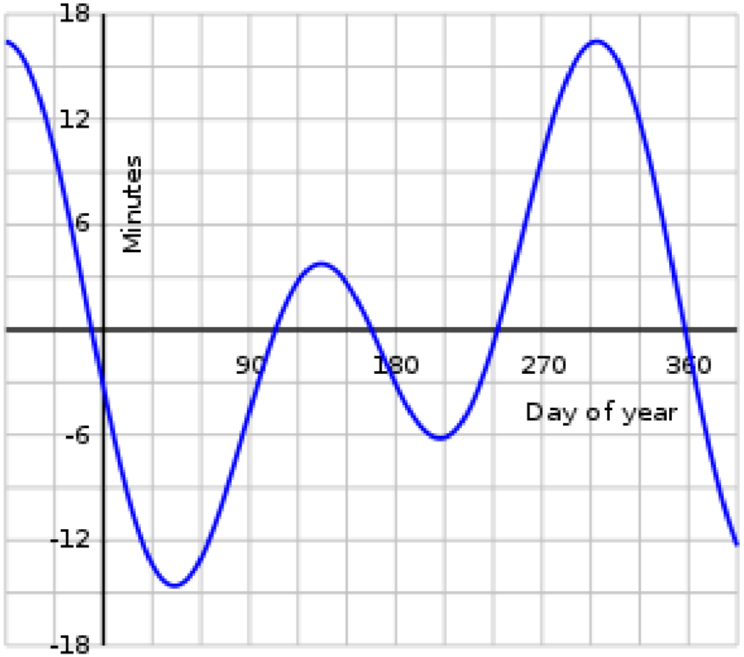
$$\delta = 0.3948 - 23.2559\cos\left(N_d' + 9.5°\right) - 0.3915\cos\left(2N_d' + 5.4°\right) - 0.1764\cos\left(3N_d' + 105.2°\right)$$

  - here $N_d' = 360° N_d / 365$; for leap year $N_d' = 360° N_d / 366$
  - N_d is the day number during the year, e.g. N_d = 1 for January 1



Equation of Time

- The equation of time ET describes the discrepancy between two kinds of solar time: the apparent solar time (direct tracked Sun motion) and the mean solar time (with noon 24 hours apart)
- It can be calculated as (in min):



$$\mathrm{ET} = 0.0066 + 7.3525\cos\left(N_d' + 85.9^\circ\right) + 9.9359\cos\left(2N_d' + 108.9^\circ\right) + 0.3387\cos\left(3N_d' + 105.2^\circ\right)$$

- here $N_d' = 360^\circ N_d / 365$
- or $N_d' = 360^\circ N_d / 366$

N_d - day number, e.g. for January 1st N_d=1

Solar Time

- Solar time is a measure of the passage of time based on the position of the Sun in the sky

- It can be found based on the known local time LT (e.g. Central European Time – CET, in most of EU countries) as:

$$\mathrm{ST} = \mathrm{LT} - 4\left(15^\circ - \lambda\right)\frac{\mathrm{min}}{\circ} + \mathrm{ET}$$

  - here ET is the Equation of Time [min] correction and λ is the local geographic longitude

Hour Angle

- The hour angle of a point is the angle between two planes: one containing the Earth's axis and the zenith (the meridian plane), and the other containing the Earth's axis and the given point

- It can be calculated as:

$$\omega = \left(12.00\,\mathrm{h} - \mathrm{ST}\right)\frac{15^\circ}{\mathrm{h}}$$

- here ST is the solar time

Hour angle is an angle "distance" to the noon.

When ST = 12.00h, $\omega=0$

$\omega > 0$ before the noon, and $\omega<0$ in the afternoon

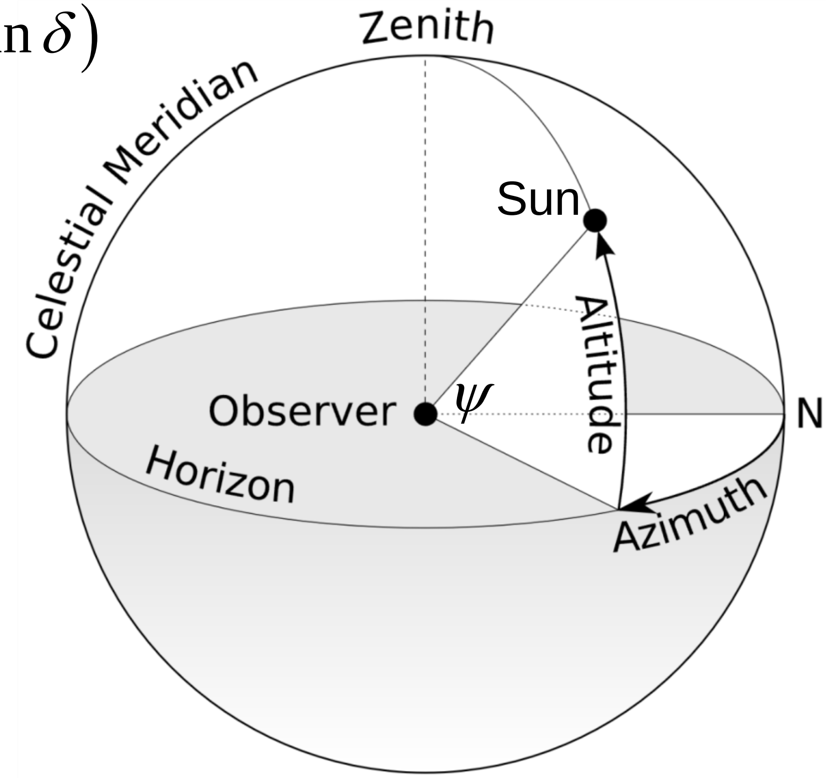
$\omega = 15^\circ$ corresponds to 1 h

Altitude of the Sun

- The altitude of the Sun can be found as

$$\psi = \arcsin\left(\cos\omega\cos\varphi\cos\delta + \sin\varphi\sin\delta\right)$$

  - here ω is the hour angle,
    φ is the local latitude, and
    δ is the declination of the Sun



Azimuth of the Sun

- The azimuth of the Sun can be found as

$$\alpha = \begin{cases} 180^\circ - \arccos\left(\dfrac{\sin\psi\sin\varphi - \sin\delta}{\cos\psi\cos\varphi}\right) & \text{for} \quad \mathrm{ST} \le 12.00\,\mathrm{h} \\ 180^\circ + \arccos\left(\dfrac{\sin\psi\sin\varphi - \sin\delta}{\cos\psi\cos\varphi}\right) & \text{for} \quad \mathrm{ST} > 12.00\,\mathrm{h} \end{cases}$$

  - here ψ is the altitude of the Sun, φ is the local latitude, and δ is the declination of the Sun.
  - ST is the local solar time

Passive/Active Solar Energy

- Passive solar technologies
  - Direct solar gain
  - Indirect solar gain
  - Isolated solar gain

No transformation of sunlight energy into other energy forms

- Active solar technologies
  - Photovoltaic
  - Solar thermal
  - Concentrated solar power

Transformation of sunlight energy into other energy forms takes place

- In this course we focus on the active solar technologies

Active Solar Energy Technologies

- Two major technologies are applied in solar power:

    - Solar thermal collectors, where heat due to sunlight is converted into electricity using a thermodynamic cycle

    - Solar photovoltaic systems in which sunlight is directly converted into electricity

Active Solar Technologies

- Photovoltaic
  - 1st generation (monocrystalline & polycrystalline silicon)
  - 2nd generation (amorphous silicon thin film, CdTe thin film, etc)
  - 3rd generation (organic, multi-junction or tandem)
- Solar thermal
  - Non-concentrating (flat-plate collector, evacuated tube collector)
  - Concentrating (compound parabolic concentrator, parabolic trough collector, linear Fresnel reflector, parabolic dish collector)

Photovoltaic Solar Energy

- Photovoltaics (PV) is a method for generating electric power by using solar cells to convert energy from the Sun into a flow of electrons by the photovoltaic effect
- PV power generation uses solar panels composed of a number of solar cells containing photovoltaic material
- PV power capacity is measured as maximum power output under standardized test conditions (STC) in “Wp” (watts peak). The real output can be less or greater of this (“rated”) value

Current Development

- To increase generated power, solar trackers are moving PV panels to follow the Sun
- This can increase the power by 20% in winter and up to 50% in summer
- Static mounted systems can be optimized by analysis of the Sun path. Adjustments for winter and summer is performed
- New inexpensive materials (such as perovskite) are used to replace the expensive crystalline silicon, which is part of the standard PV cells build today

perovskite – a yellow, brown or greyish-black mineral consisting of an oxide of calcium and titanium and sometime containing rare elements

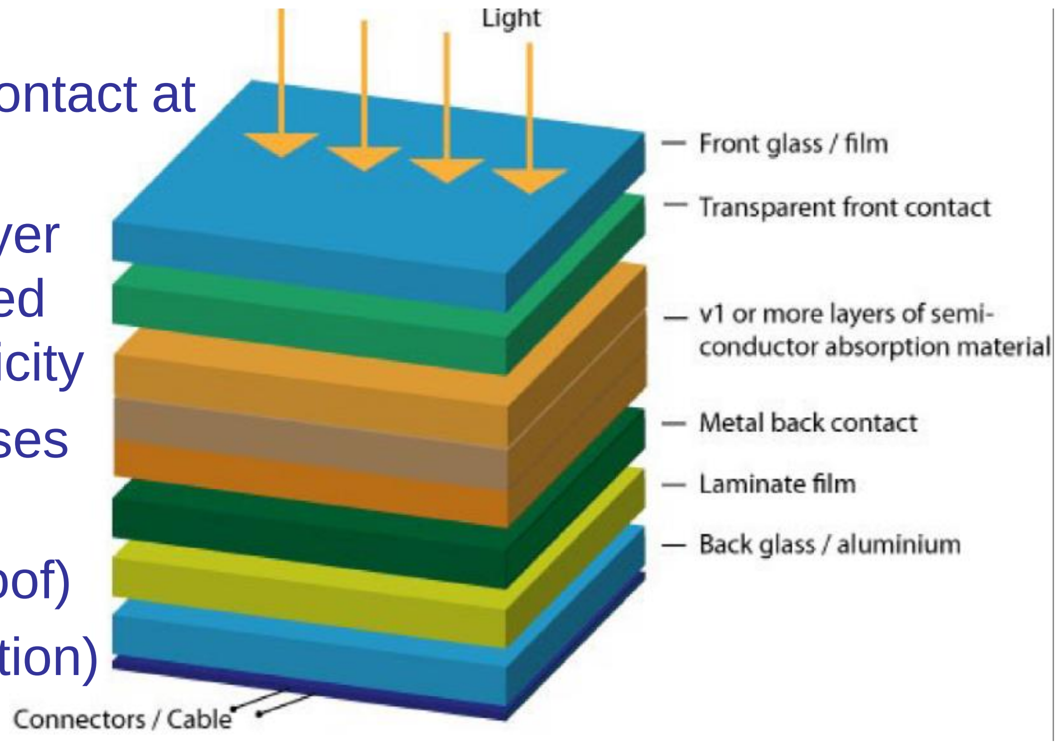
Current Development

- Concentrator photovoltaics (CPV) uses lenses and curved mirrors to focus sunlight onto small, but highly efficient multi-junction solar cells
- This can be combined with solar trackers and cooling systems to further improve the efficiency
- Hybrid systems containing photovoltaic and thermal solar. Heat retrieved from cooling of PV is used in thermal to increase over-all efficiency and decrease exergy losses
- Solar farms are constructed with high output (as 579 MW in Solar Star, California)

Satellite view of the Topaz Solar Farm, 550 MW_{AC} , California

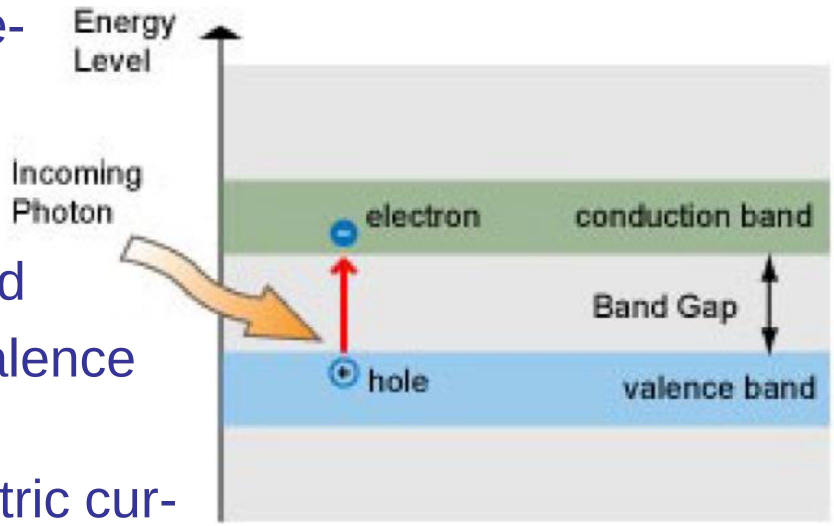
Principles of PV

- All PV-modules contain a number of layers (from the light-facing side to the back):
  - **protection layer** (usually from glass, or transparent plastic in thin-film modules)
  - **Front contact** (electric contact at the front - transparent)
  - **Absorption material** (layer where the light is absorbed and converted into electricity
  - **Metal back contact** (closes the electric circuit)
  - **Laminate film** (water-proof)
  - **Back glass** (back protection)
  - **Connectors**



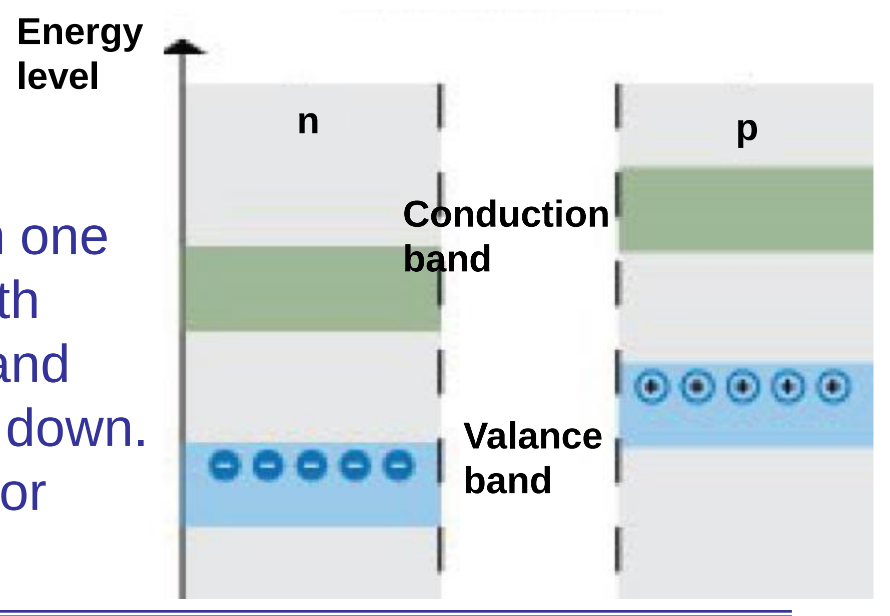
The Photovoltaic Effect (1)

- In simple terms, the photovoltaic effect describes the conversion of light into an electric current
- This process looks differently in intrinsic semiconductors, doped semiconductors and p-n junctions
  - In a pure semi-conductor the outemost electron of the atom is not heavily bound and incoming photon promotes it from the valence band to the conduction band
  - This leaves positive hole in the valence band
  - In intrinsic semiconductor no electric current results since the holes recombine with the electrons



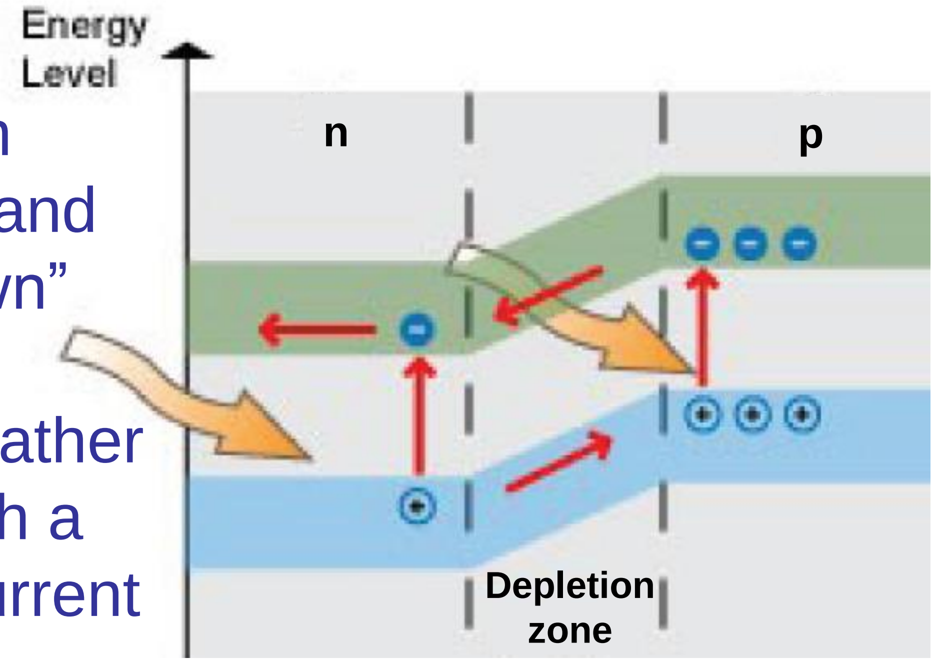
The Photovoltaic Effect (2)

- In doped semiconductors, a small addition of foreign atoms is present in regular crystal lattice of the semiconductor
  - **p-type:** when adding atoms with one electron less, a layer is created with fewer negative electrons in the valence band, pushing the overall energy level up. In silicon add boron, gallium or aluminium
  - **n-type:** when adding atoms with one electron more creates a layer with more electrons in the valence band pushing the overall energy level down. In silicon add antimony, arsenic or phosphorous



The Photovoltaic Effect (3)

- Where p-type and n-type layers join at the p-n junction, electrons and holes diffuse to create the charge-free depletion zone
- The junction creates a slope in the resulting energy bands
- When a photon promotes an electron to the conduction band it can subsequently “roll down” through the depletion zone into the lower energy band rather then instantly recombine with a hole – and this generates current



The Photovoltaic Effect (4)

- The band gap, which is the minimum energy required to promote an electron from the valence band varies by material
- It is usually expressed in units eV (electron Volts)
- To convert electron-Volts into wavelength of incoming light we use the formula:

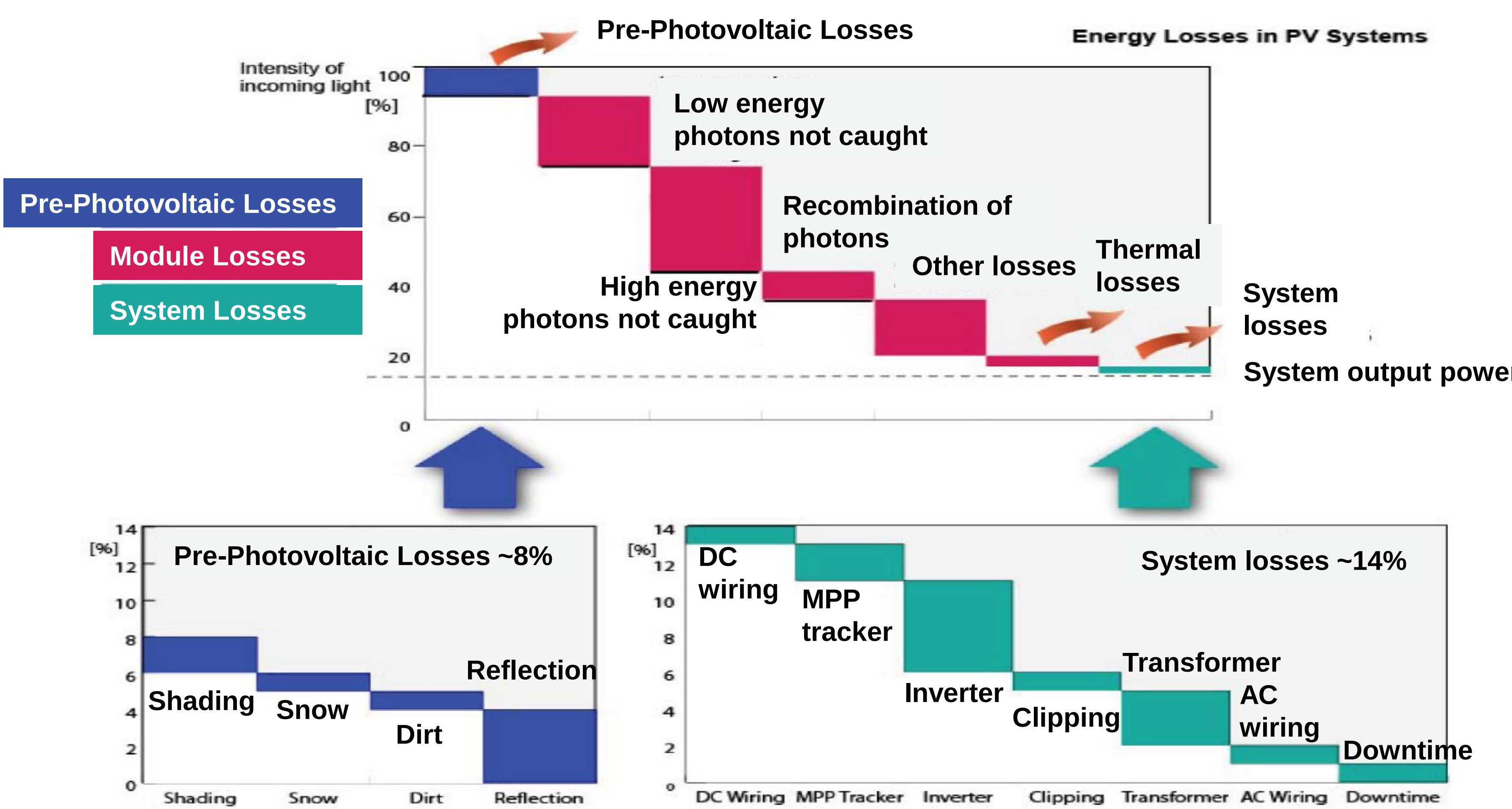
$$\lambda = c\frac{h}{e}\frac{1}{b}$$

  - where:
    $c = 299792458$ m/s (speed of light), $h = 6.63 \cdot 10^{-34}$ Js (Planck constant), $e = 1.609 \cdot 10^{-19}$ C (elementary charge), b – band gap in eV and λ – wavelength in m

Energy Losses in PV Systems

- Pre-module losses
  - Tolerance of rated power (manufactures state it, often up to 5%)
  - Shadows (from trees, chimneys; for some cells: significant effect)
  - Dirt (up to 4% with frequent rains; up to 25% in arid regions)
  - Snow (depends on maintenance and location)
  - Reflection (increase with angle of incident, lesser with clouds)
- Module losses
  - Conversion (nominal value given by manufacture)
  - Thermal losses (increase with temperature; roughly ~8%)
- System losses (~14%)
  - wiring, MPP tracker, inverter, transformer
- Operation & maintenance (downtime low for PV)

Energy Losses in PV Systems



PV Cell Efficiency

- **Electrical efficiency** (also called conversion efficiency) is a physical parameter which determines how much electrical power a cell can produce for a given insolation
- It is defined as the ratio of the maximum power output (N_{max}) to the incident solar radiation power (radiation flux S_a times cell area A_{cell})

$$\eta = \frac{N_{\max}}{S_a \cdot A_{cell}}$$

- The efficiency is measured under ideal laboratory conditions and is the maximum achievable efficiency

PV Cell Efficiency

- The most efficient type of solar cell to date is a multi-junction concentrator solar cell with an efficiency of 46%
- The market-average efficiency is 12-18%

- Recent developments in organic photovoltaic cells (OPV) have made significant advancements in power conversion efficiency from 3% to over 15% since their introduction in 1980s. For perovskite OPV this efficiency reached 21%

Growth

- Solar PV is growing rapidly
- Worldwide installed capacity reached about 300 GW at the end of 2016
- The total power output since 2014 is above 200 TWh of electricity per year
- This represents 1% of the worldwide electricity demand
- More than 100 countries use solar PV
- China, Japan and US are fastest growing markets
- Germany remains the worlds largest producer, with 7% of the national electricity demand

Top 10 PV Countries in 2015

#	Nation	Total Capacity	Added Capacity
1	China	43,530	15,150
2	Germany	39,700	1,450
3	Japan	34,410	11,000
4	United States	25,620	7,300
5	Italy	18,920	300
6	United Kingdom	8,780	3,510
7	France	6,580	879
8	Spain	5,400	56
9	Australia	5,070	935
10	India	5,050	2,000

Capacity in MW   Source: IEA

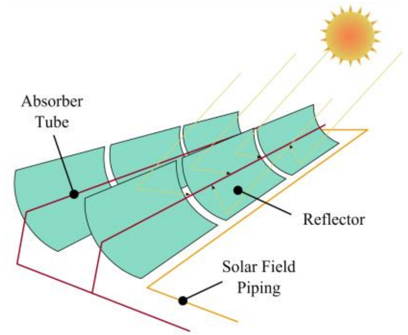
Solar Thermal Energy

- The worldwide total installed capacity of solar thermal energy in 2014 was about 400 GW and corresponded to average power generation of 39 GW during 2014
- Most collectors in first decade of 21st century were low temperature collectors operating at temperatures below 80ºC (mostly used for domestic purposes)
- Increasing development and deployment of intermediate-temperature solar collectors (80ºC-250ºC) could greatly increase the renewable share of industrial energy use

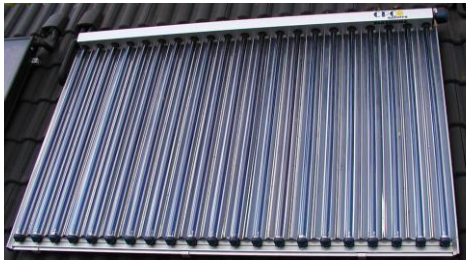
Solar Thermal Technologies

- Main two technologies:
  - Non-concentrating (flat-plate collector, evacuated tube collector)
  - Concentrating (compound parabolic concentrator, parabolic trough collector, linear Fresnel reflector, parabolic dish collector)

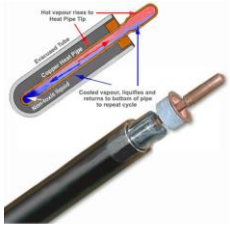
Flat-plate collector



Parabolic through collector



Evacuated tube collector



Glass-glass evacuated tube

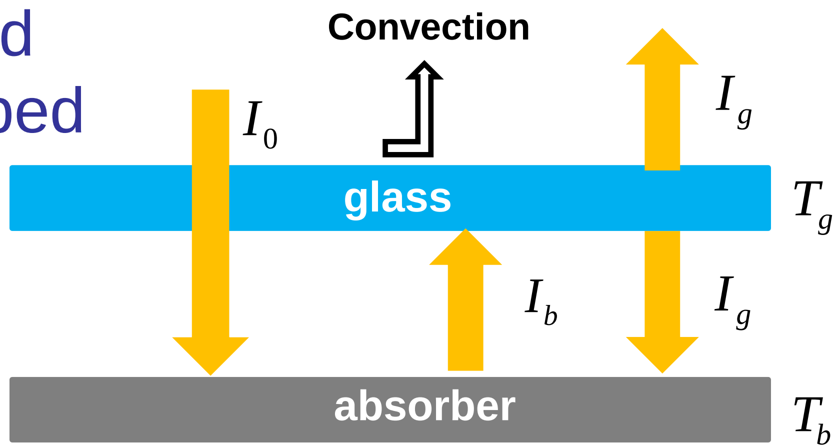
Solar thermal dish collector

Solar Absorption

- Radiative balance
  - thermal equilibrium in which radiation is the only means by which the object loses energy

$$I_0 = \sigma T_b^4 \qquad T_b = \sqrt[4]{I_0/\sigma}$$

- Heat trapping – the greenhouse effect. Assume incoming radiation I_0 perfectly transmitted through glass layer and absorbed in the absorber. Absorber emits radiation I_b in infrared range which is absorbed by glass, heated to temp. T_g



Solar Absorption

- The glass is heated up to temperature T_g and emits radiation to both sides as $I_g = \sigma T_g^4$
- The heat balance for the absorber is:

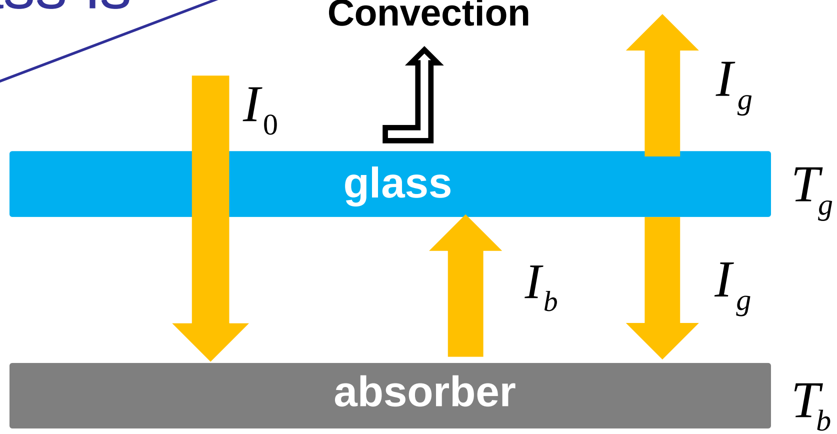
$$\sigma T_b^4 = I_0 + \sigma T_g^4$$

In simple models we assume $T_g = T_{amb}$

- The energy balance for the glass is

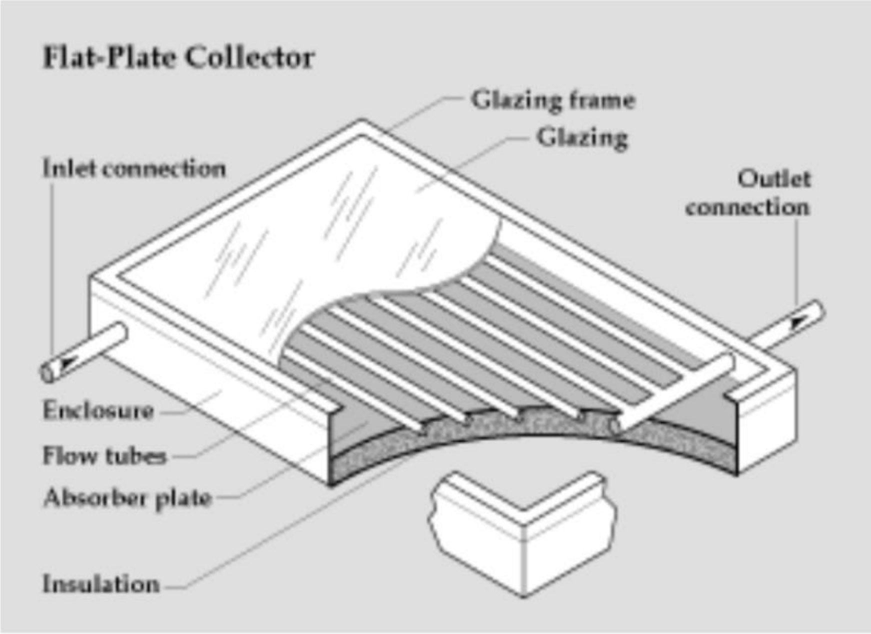
$$\sigma T_b^4 = 2\sigma T_g^4 + h_c \left(T_g - T_{amb} \right)$$

- If the heat transfer coefficient h_c is known, the equations are solved for T_b and T_g



Low-Temperature Collectors

- The simplest low-temperature solar collector is the flat-plate collector
- Pipes are run through a dark absorber plate
- The pipes carry fluid such as water, pumped through the system
- Transparent glazing over the absorber traps heat through greenhouse effect
- Operation temp. 80-120ºC

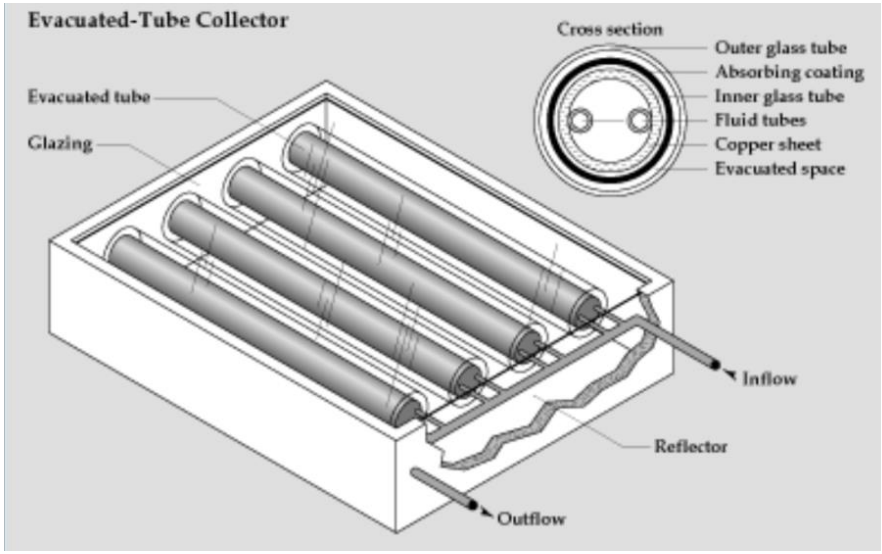


Flat plate collector. Credit: US Dept of Energy.

Collector efficiency is defined as $\eta = I_{useful}/I_0$ where $I_{useful} = I_0 + I_g - I_b$ (removed by coolant)

Medium-Temperature Collectors

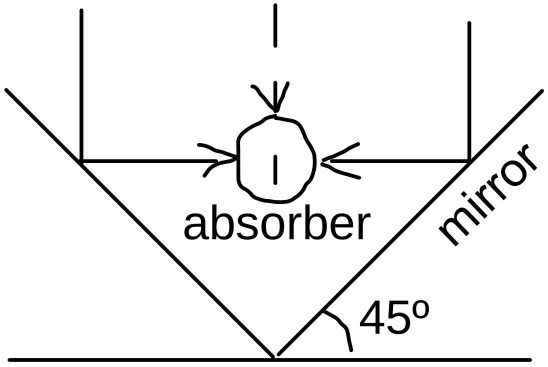
- For commercial and industrial heating and cooling applications higher temperatures are needed
- Intermediate-temperature collectors operate with working fluid heated to temperatures 80-250ºC
- By evacuating the space between glazing and absorber, losses are significantly reduced



If the absorber is painted with a material having emissivity e=0.9 for incoming near-visible radiation, and an emissivity e=0.1 in the infrared, than the radiative balance equation becomes: $0.1\cdot\sigma T_b^4 = 0.1\cdot\sigma T_{atm}^4 + 0.9\cdot I_0$

Concentrators

- In order to achieve much higher temperatures needed to generate electricity, it is necessary to concentrate the incoming solar radiation
- Simple concentrators are based on planar mirrors, tilted at 45º from the horizontal, with a cylindrical absorber



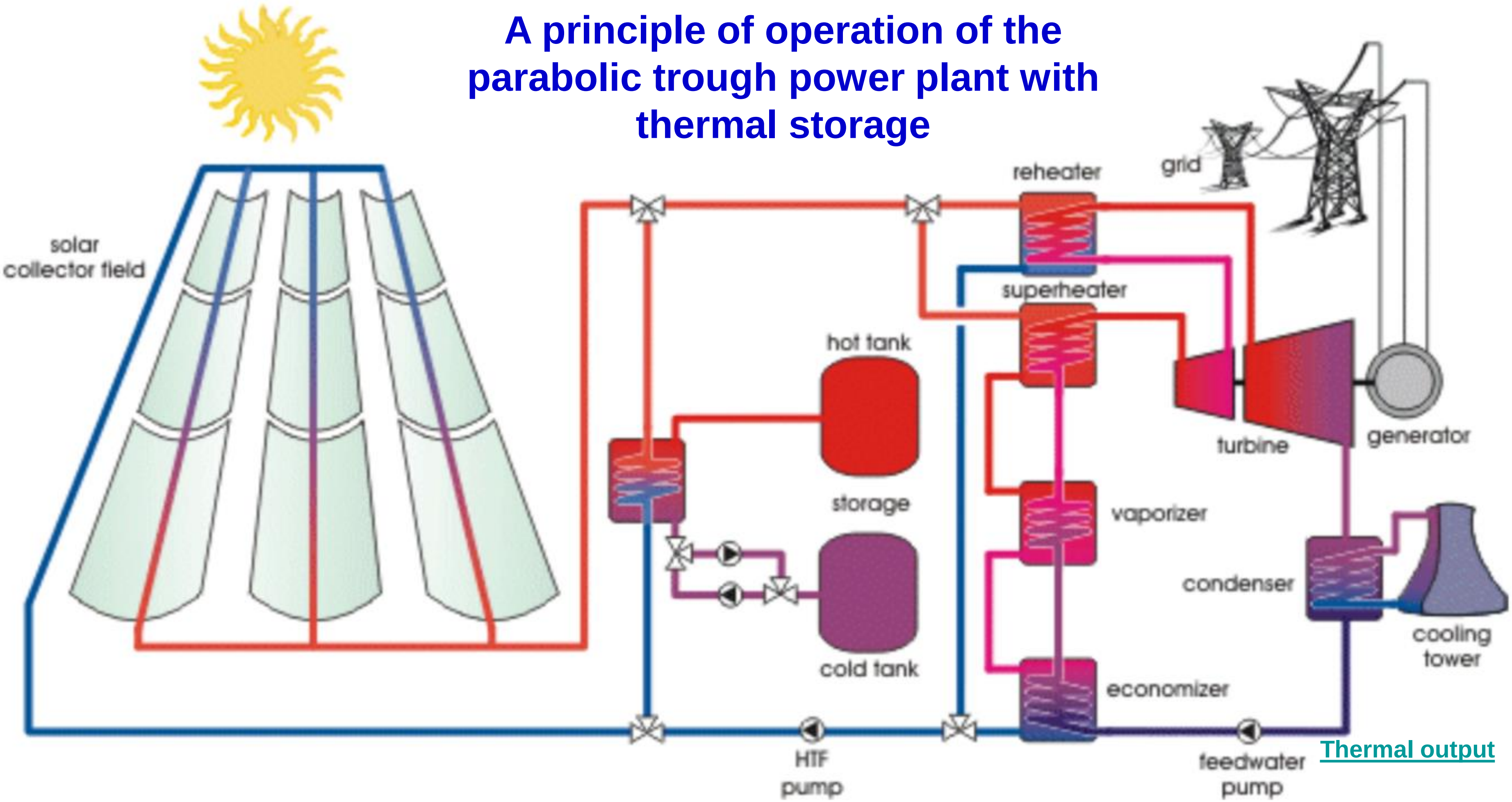
- Many concentrators use a system of mirrors based on a parabolic geometry, which concentrate all incoming light rays parallel to the axis of symmetry to a single focal point

Solar Thermal Electricity

- Solar thermal electricity (STE) power plants use concentrators in various geometries to focus direct sunlight on an absorber
- The resulting thermal energy is used to generate electricity
- STE has the advantage that the thermal energy can be stored for later use thus reducing the variability of the solar power
- Siting of STE is limited to locations with the least cloud cover and haze because only direct sunlight can be concentrated

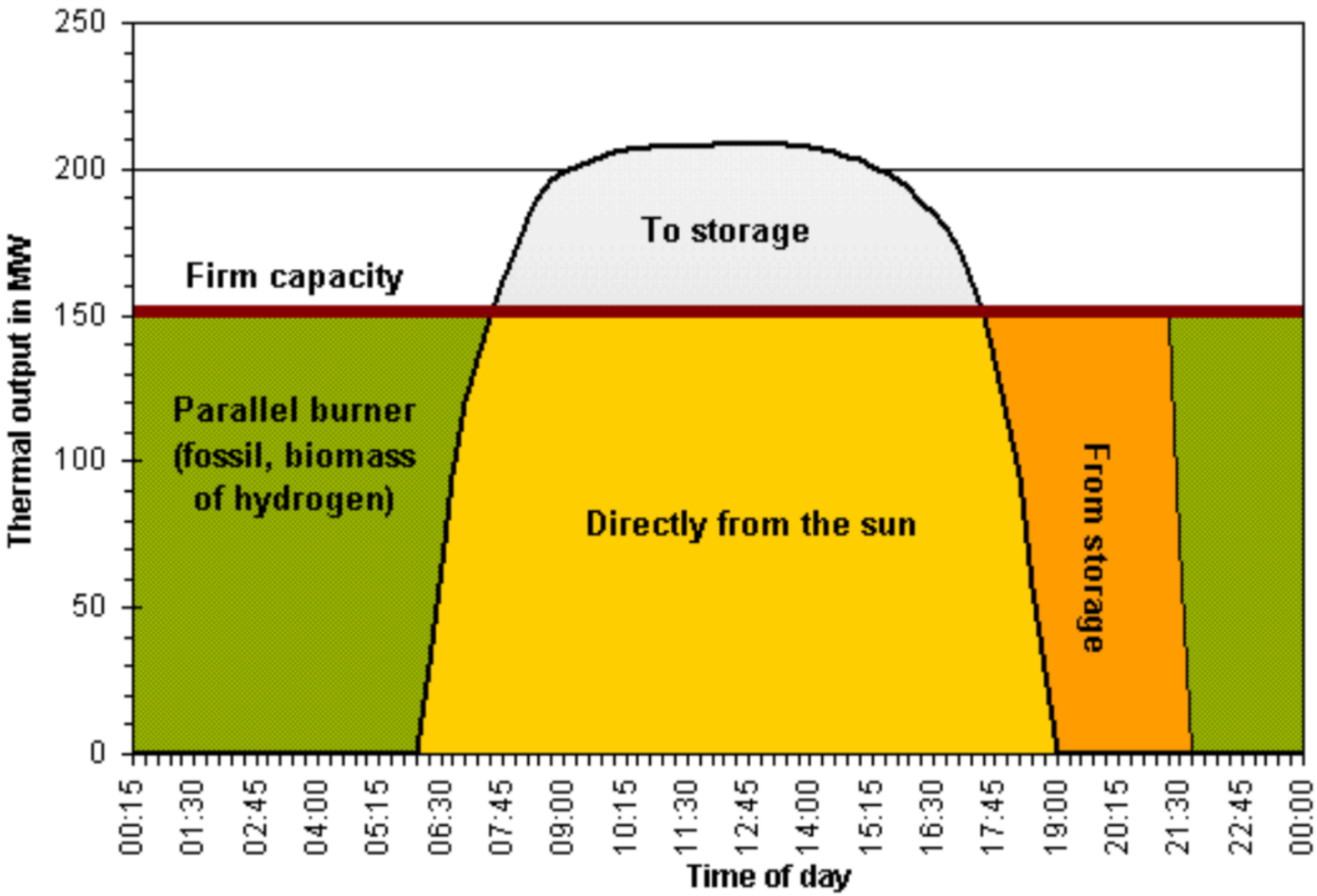
Concentrated Solar Thermal Power

A principle of operation of the parabolic trough power plant with thermal storage



Thermal output

Solar Thermal Power with Storage



Expected output of a solar thermal power plant with two-hour thermal storage and backup heater on a sunny day

Energy Losses in Solar Thermal