Renewable and Alternative Energies

Topic 2. Solar energy (I)

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Contents

Topic 2. Solar energy

- **2.1.** Solar radiation.
- **2.2.** Solar thermal collectors.
- **2.3.** Solar thermal utilization.
- **2.4.** Solar thermal power plants.
- **2.5.** Solar panels.
- **2.6.** Photovoltaic applications.

Topic 2. Solar energy

- **2.1. Solar radiation**.
- **2.2.** Solar thermal collectors.
- **2.3.** Solar thermal utilization.
- **2.4.** Solar thermal power plants.
- **2.5.** Solar panels.
- **2.6.** Photovoltaic applications.

2.1. Solar radiation

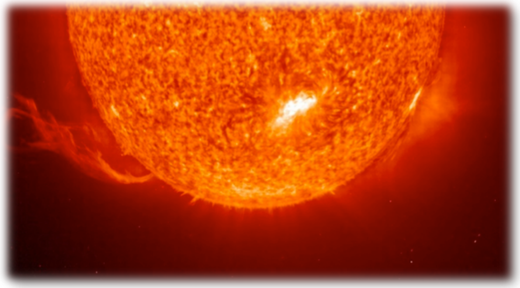
- The sun is the **main source** of all alternative energies on the earth's surface.

- Wind energy, bioenergy, ocean energy, and hydro energy are **derived from the sun**.
- However, the term **solar energy refers** to the energy that is **harvested directly from the sun** using solar cells, solar concentrators, etc.
- Although solar energy is abundant on the earth's surface, **harvesting it** into a useful energy form **is challenging and often costly**.
- Solar energy can be used either as a **source of thermal energy** when using solar concentrators, or for **direct electricity generation** when using photovoltaics.

2.1. Solar radiation

Extraterrestrial solar radiation

- Solar radiation reaches the Earth's surface at a maximum flux density of about 1 kW.m^{-2} in a wavelength band between 0.3 and 2.5 μm. This is called **short wave radiation** and includes the visible spectrum.
- The **spectral distribution is determined by the 6000 K** surface temperature of the Sun.
- The outward radiant energy fluxes emitted by the Earth's atmosphere and surfaces are also of the order of 1 kW.m^{-2}, but occur in an infrared wavelength band between about 5 and 25 μm, called **long wave radiation.**
- The proportion of **solar radiation that reaches** a device **depends on geometric factors**, such as latitude, and on **atmospheric characteristics**, such as infrared radiation absorption by water vapor, carbon dioxide…

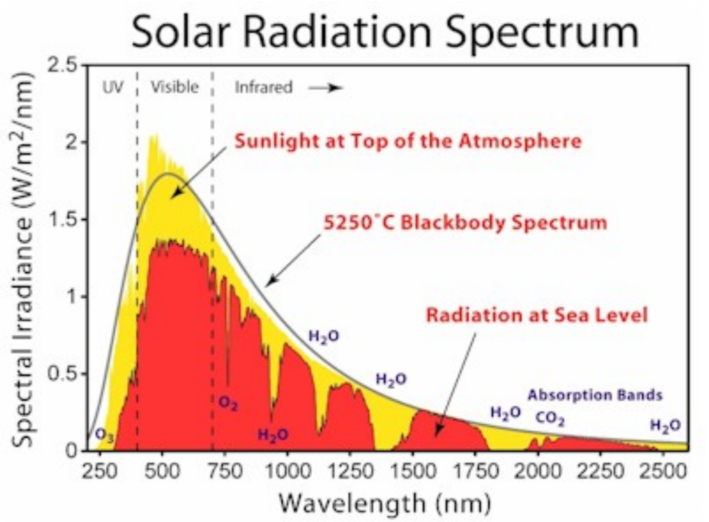


2.1. Solar radiation

Extraterrestrial solar radiation

- The figure shows the **spectral distribution of the solar irradiance** at the Earth's mean distance (yellow), uninfluenced by any atmosphere.

- Note how similar this distribution is to that from a **black body** at 5250 ºC in shape, peak wavelength and total power emitted.



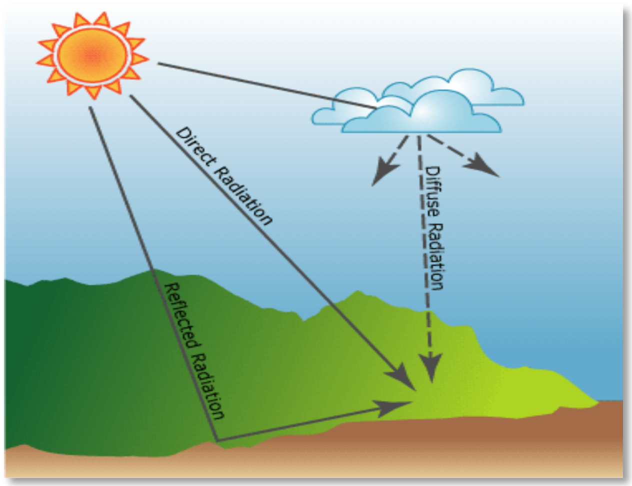
- The area beneath this curve the **solar constant** $G_0^* = 1367\ W \cdot m^{-2}$.

- The solar **spectrum** can be divided into **three** main **regions:**
  1. Ultraviolet region λ< 0.4 μm ~5% of irradiance.
  2. Visible region 0.4 μm < λ < 0.7 μm ~43% of irradiance.
  3. Infrared region λ > 0.7 μm ~52% of irradiance.

2.1. Solar radiation

Components of radiation

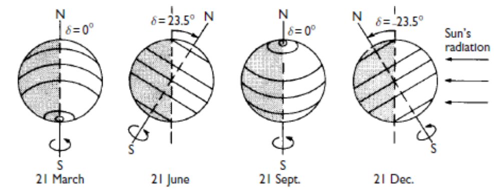
- Solar radiation incident on the atmosphere from the direction of the Sun is the **solar extraterrestrial beam radiation G.**
- Beneath the atmosphere, at the Earth's surface, the radiation will be observable from the direction of the Sun's disc in the **direct beam G_b (direct radiation)**, and also from other directions as **diffuse radiation G_d**.
- Note that even on a cloudless, clear day, there is always **at least 10% diffuse irradiance** from the molecules in the atmosphere.
- The practical distinction between the two components is that **only the beam radiation can be focused**.



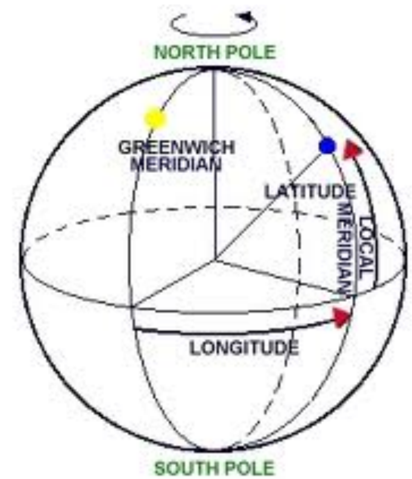
2.1. Solar radiation

Geometry of the Earth and Sun

- The axis of the poles is normal to the earth's **equatorial plane**.



- A **point** on the Earth's surface is **determined** by its **latitude Φ and longitude Ψ**.



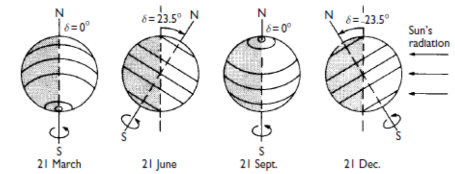
- **Latitude** is defined **positive for points north of the equator**, negative south of the equator.

- By international agreement **longitude is measured positive eastwards from Greenwich**, England.

- The **direction of earth's axis** remains **fixed** in space, at an angle δ_0 **= 23.45°** away from the normal to the plane of revolution.

2.1. Solar radiation

Geometry of the Earth and Sun



Declination δ

- This is the angle between the Sun's direction and the equatorial plane, which gradually varies from **$+\delta_0$ = 23.45°** at midsummer in the northern hemisphere, to **$-\delta_0$ = –23.45°** at northern midwinter.

$$\delta = \delta_0 * sin\left[\frac{360° * (284+n)}{365}\right]$$

n: the day in the year.

Hours between sunrise and sunset, N.

The number of hours between sunrise and sunset is:

$$N = \frac{2}{15} * cos^{-1}(-tan\Phi * tan\,\delta)$$

Φ: latitude.

2.1. Solar radiation

Geometry of the Earth and Sun

- The **daily insolation H** is total energy per unit area received in one day from the Sun.H varies with latitude and season. Its seasonal variation arises from three main factors:

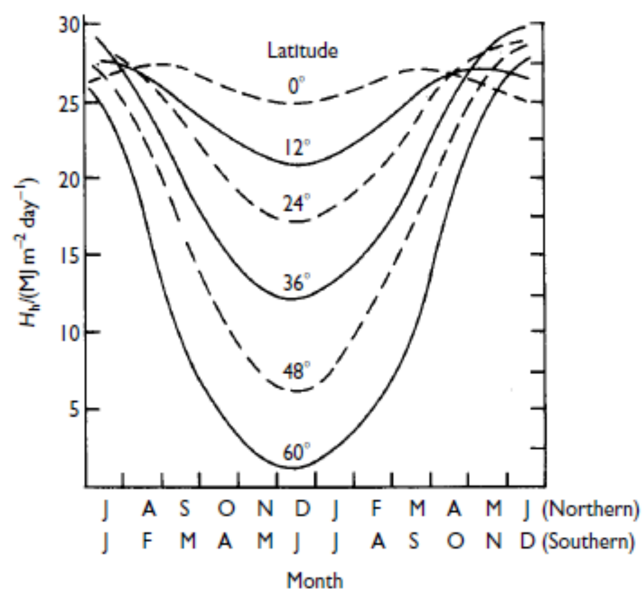
$$H = \int_{t=0h}^{t=24h} G\,dt$$

- H **varies with latitude and season**. Its **seasonal variation** arises from **three main factors:**

  1) Variation in the length of the day.

  2) Orientation of receiving surface.

  3) Variation in atmospheric absorption.



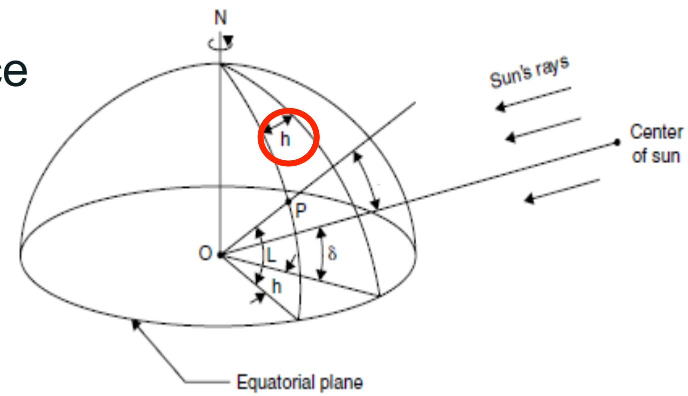
2.1. Solar radiation

Geometry of the Earth and Sun

Hour angle, h:

The hour angle, h, of a point on the earth's surface is defined as the angle through which the earth would turn to bring the meridian of the point directly under the sun.

The figure shows the hour angle of point P as the angle measured on the earth's equatorial plane between the projection of OP and the projection of the sun-earth center to center line.



The hour angle at local solar noon is zero, with each 360/24 or 15° of longitude equivalent to 1 h, afternoon hours being designated as positive. Expressed symbolically, the hour angle in degrees is:

h = ±0.25* (number of minutes from local solar noon).

Where the plus sign applies to afternoon hours and the minus sign to morning hours.

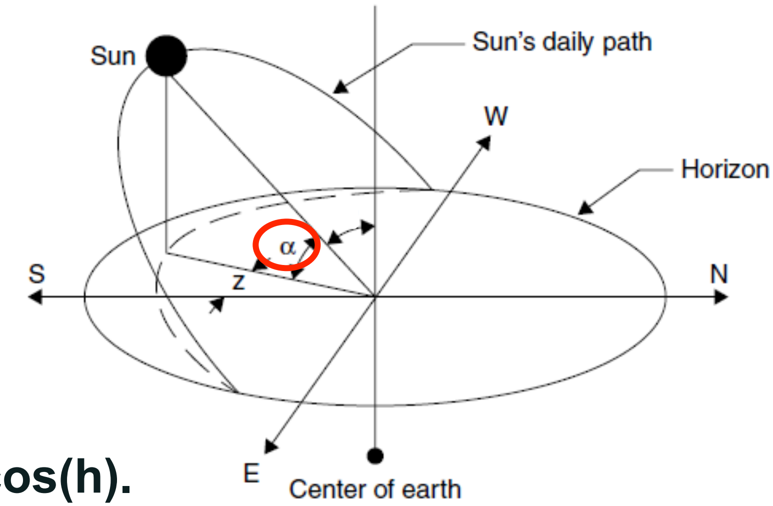
2.1. Solar radiation

Geometry of the Earth and Sun

Solar altitude angle, α:

The solar altitude angle is the angle between the Sun's rays and a horizontal plane.

The mathematical expression for the solar altitude angle is:



$$\sin(\alpha) = \sin(\Phi) \cdot \sin(\delta) + \cos(\Phi) \cdot \cos(\delta) \cdot \cos(h).$$

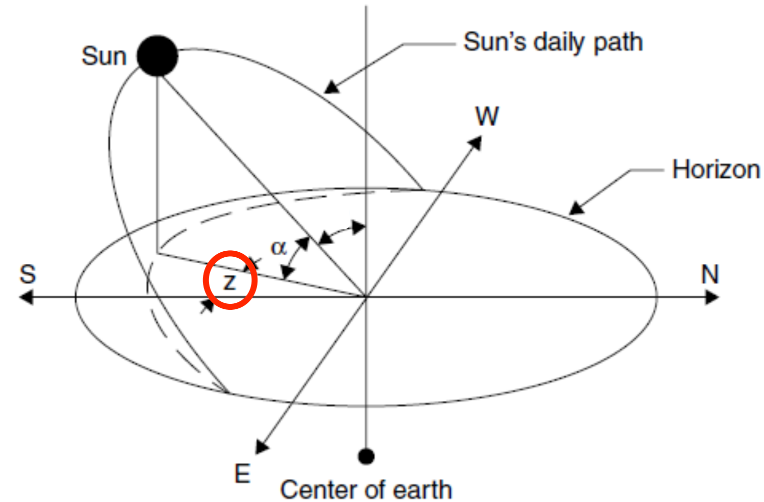
Φ: latitude.
δ: declination.
h: hour angle.

Values north of the equator are positive and those south are negative.

2.1. Solar radiation

Geometry of the Earth and Sun

Solar azimuth angle, Z:



The solar azimuth angle, Z, is the angle of the Sun's rays mesasured in the horizontal plane from due south (true south) for the Northem Hemisphere or due north for the Southern Hemisphere; westward is designated as positive.

The mathematical expression for the solar azimuth angle is:

$$\sin(Z) = \frac{\cos(\delta) * \sin(h)}{\cos(\alpha)}$$

α: solar altitude angle.

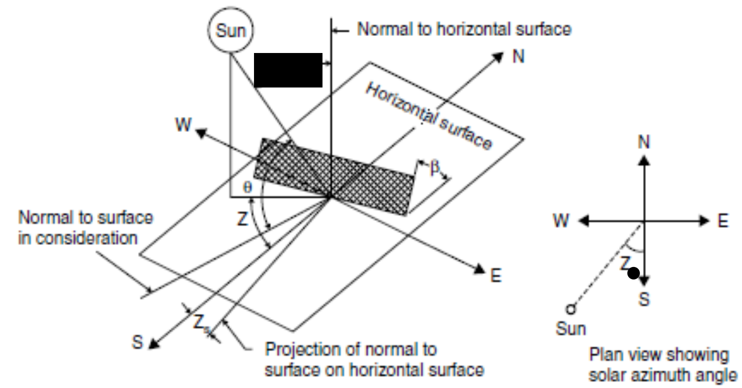
h: hour angle.

2.1. Solar radiation

Geometry of the Earth and Sun

Incidence angle, θ:

The solar incidence angle, θ, is the angle between the Sun's rays and the normal to a surface:



$$\cos(\theta) = \sin(\Phi) \cdot \sin(\delta) \cdot \cos(\beta) - \cos(\Phi) \cdot \sin(\delta) \cdot \sin(\beta) \cdot \cos(Z_s) + \cos(\Phi) \cdot \cos(\delta) \cdot \cos(h) \cdot \cos(\beta) + \sin(\Phi) \cdot \cos(\delta) \cdot \cos(h) \cdot \sin(\beta) \cdot \cos(Z_s) + \cos(\delta) \cdot \sin(h) \cdot \sin(\beta) \cdot \sin(Z_s)$$

Φ: latitude.

δ: declination.

h: hour angle.

β: surface tilt angle from the horizontal.

Z_s: surface azimuth angle, the angle between the normal to the surface from true south, westward is designated as positive.

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2.2. Solar thermal collectors

- Solar energy **collectors are** a special kind of **heat exchangers** that transform solar radiation energy to internal energy of the transport medium.
- They absorb the incoming solar radiation, convert it into heat, and transfer this heat to a fluid (usually air, water, or oil) flowing through the collectors.
- The solar energy thus collected is carried from the circulating fluid either directly to the hot water or to a thermal energy storage tank.

2.2. Solar thermal collectors

Types of collectors

Solar collectors can by classified by:

- The solar radiation caption: non-concentrating and concentrating.
- The motion: stationary, single-axis tracking and two-axes tracking.
- By the operating temperature: Low, medium and high temperature.

Motion	Collector Type	Absorber type	Concentration ratio	Indicative temperature range (ºC)
Stationary	Flat plate collector (FPC) Evacuated tube collector (ETC) Compound parabolic collector (CPC)	Flat Flat Tubular	1 1 1-5	30-80 50-200 60-240
Single-axis Tracking	Linear Fresnel reflector (LFR) Parabolic trough collector (PTC) Cylindrical trough collector (CTC)	Tubular Tubular Tubular	10-40 15-45 10-50	60-250 60-300 60-300
Two-axes Tracking	Parabolic dish reflector (PDR) Heliostat field collector (HFC)	Point Point	100-1000 100-1500	100-500 150-2000

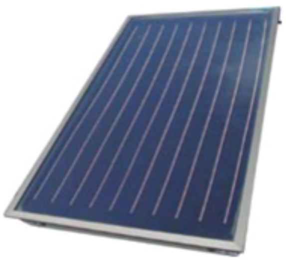
Note: concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.

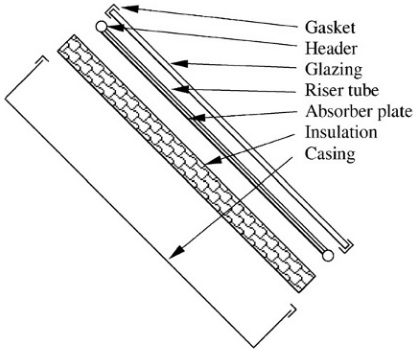
2.2. Solar thermal collectors

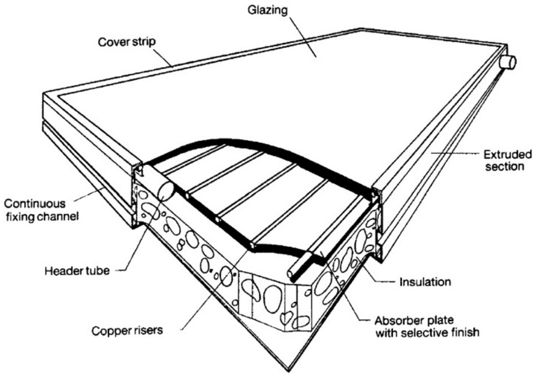
Stationary collectors: Flat-plate collectors (FPC)

A FPC generally consists of the following components:

- Glazing. One or more sheets of glass or other diathermanous (radiation-transmitting) material.
- Tubes, fins, or passages. To conduct or direct the heat transfer fluid from the inlet to the outlet.
- Absorber plates. Flat or corrugated plates to which the tubes are attached.
- Headers or manifolds. To admit and discharge the fluid.
- Insulation. To minimize the heat loss from the back and sides of the collector.
- Container or casing. To surround the other components and keep them free from dust, moisture, etc.







2.2. Solar thermal collectors

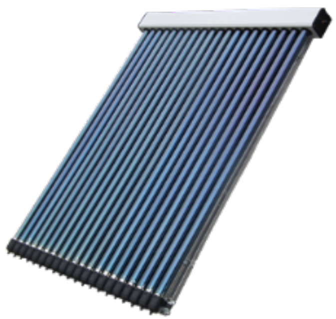
Stationary collectors: Flat-plate collectors (FPC)

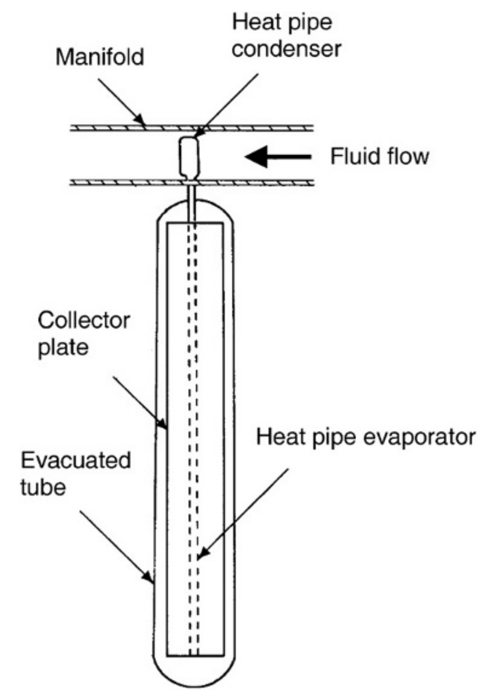
- When solar radiation passes through the transparent cover, a large portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use.
- The underside of the absorber plate and the side of casing are well insulated to reduce conduction losses.
- The liquid tubes are connected at both ends by large diameter header tubes.
- The transparent cover is used to reduce convection losses and radiation losses from the collector as the glass is transparent to the short wave radiation received from the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect).
- The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern hemisphere. The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10°–15° more or less depending on the application.

2.2. Solar thermal collectors

Stationary collectors: Evacuated tube collectors (ETC)

- These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in the figure.
- ETC have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures.
- The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than FPC.
- Like FPC, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles.
- ETC use liquid–vapor phase change materials to transfer heat at high efficiency.





2.2. Solar thermal collectors

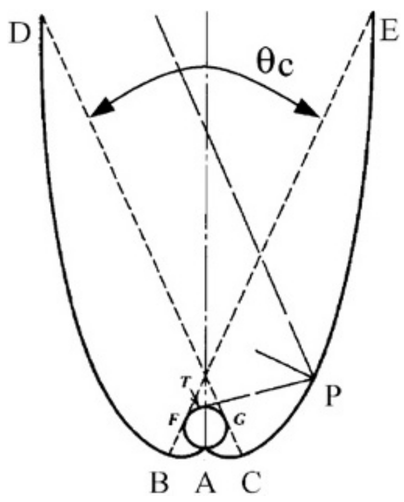
Stationary collectors: Evacuated tube collectors (ETC)

- These collectors feature a heat pipe (a highly efficient thermal conductor) placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate).
- Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser).
- The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapor travels to the heat sink region where it condenses and releases its latent heat.
- The condensed fluid returns back to the solar collector and the process is repeated.
- The heated liquid circulates through another heat exchanger and gives off its heat to a process or to water that is stored in a solar storage tank.

2.2. Solar thermal collectors

Stationary collectors: Compound parabolic collectors (CPC)

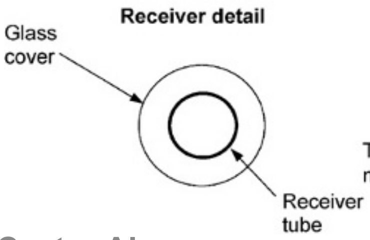
- The absorber can take a variety of configurations. It can be cylindrical or flat. In the CPC shown in the figure, the lower portion of the reflector (AB and AC) is circular, while the upper portions (BD and CE) are parabolic.
- These have the capability of reflecting to the absorber all of the incident radiation within wide limits.
- By using multiple internal reflections, any radiation that is entering the aperture, within the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector.
- CPCs are usually covered with glass to avoid dust and other materials from entering the collector and thus reducing the reflectivity of its walls.

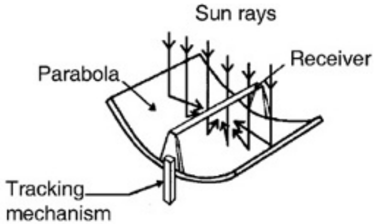


2.2. Solar thermal collectors

Sun tracking concentrating collectors: Parabolic trough collectors (PTC)

- PTCs are made by bending a sheet of reflective material into a parabolic shape. A black metal tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver.
- When the parabola is pointed towards the sun, parallel rays incident on the reflector are reflected onto the receiver tube.
- It is sufficient to use a single axis tracking of the sun and thus long collector modules are produced.
- PTCs are the most mature solar technology for generating heat at temperatures up to 400 ºC for solar thermal electricity generation or process heat applications.

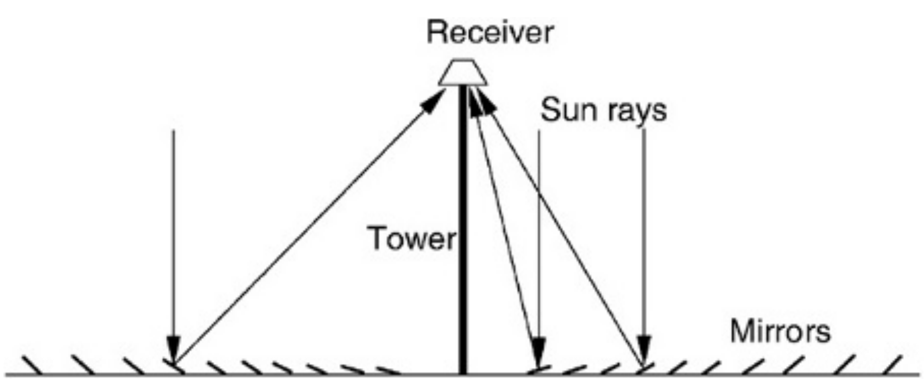




2.2. Solar thermal collectors

Sun tracking concentrating collectors: Linear Fresnel reflector (LFR)

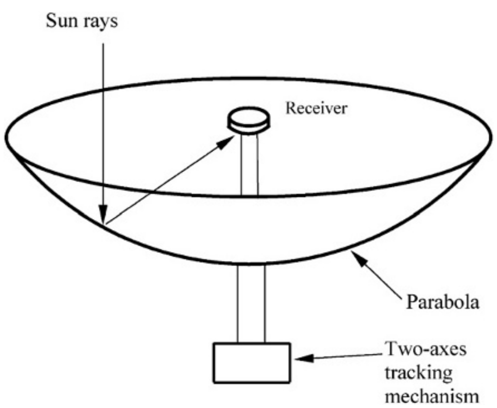
- LFR technology relies on an array of linear mirror strips which concentrate light onto a fixed receiver mounted on a linear tower.
- The LFR field can be imagined as a broken-up parabolic trough collector but it does not have to be of parabolic shape and large absorbers can be constructed and the absorber does not have to move.
- One difficulty with LFR technology is that the avoidance of shading and blocking between adjacent reflectors leads to an increased spacing between reflectors.



2.2. Solar thermal collectors

Sun tracking concentrating collectors: Parabolic dish reflector (PDR)

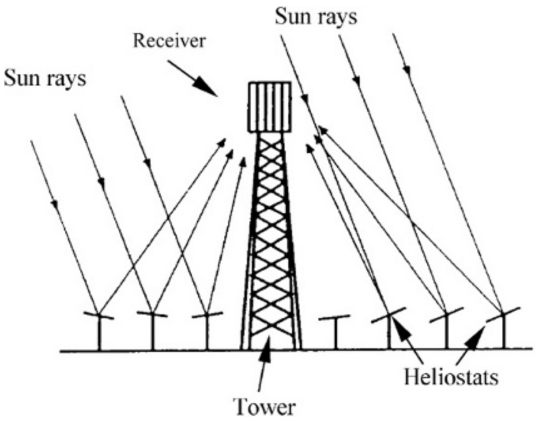
- A PDR is a point-focus collector that tracks the sun on two axes, concentrating solar energy onto a receiver located at the focal point of the dish.
- Parabolic-dish systems can achieve temperatures in excess of 1500°C.
- Because they are always pointing at the sun, they are the most efficient of all collector systems.
- The main use of this type of concentrator is for parabolic dish engines.



2.2. Solar thermal collectors

Sun tracking concentrating collectors: Heliostat field collector (HFC)

- A multiplicity of flat mirrors, or heliostats used to reflect their incident direct solar radiation onto a common target.
- Large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure, minimizing thermal-energy transport requirements.
- They are highly efficient both in collecting energy and in converting it into electricity.
- They are quite large (generally more than 10 MW) and thus benefit from economies of scale.



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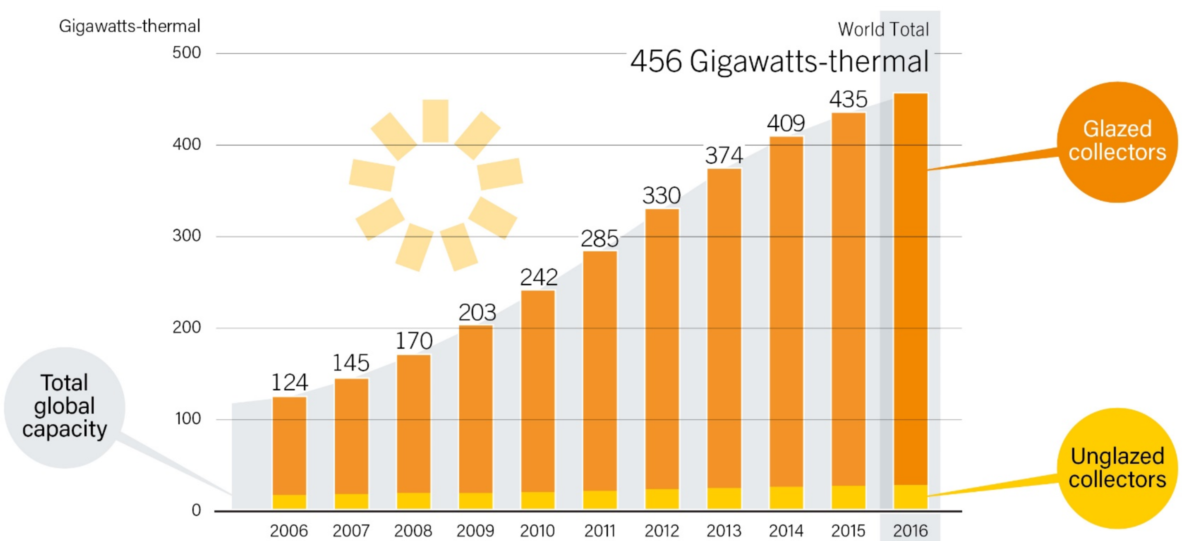
2.3. Solar thermal utilization

Solar Thermal Energy Utilization Worldwide

- In 2016, the newly installed capacity increased by 5%.
- These additions brought total global solar thermal capacity to an estimated 456 GWth at the end of 2016.

Solar Water Heating Collectors Global Capacity, 2006-2016

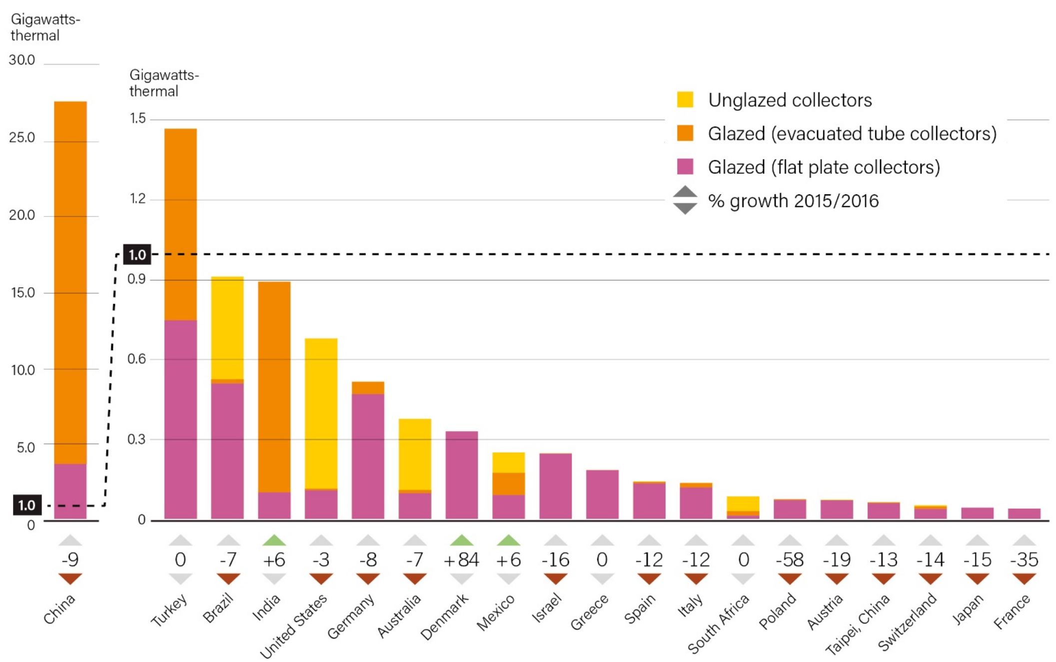


2.3. Solar thermal utilization

Solar Thermal Energy Utilization Worldwide

- Significant market growth in Denmark: 84%, Mexico: 6% and India: 6%. The total gross addition in 2016 was 36.7 GWth.

Solar Water Heating Collector Additions, Top 20 Countries for Capacity Added, 2016

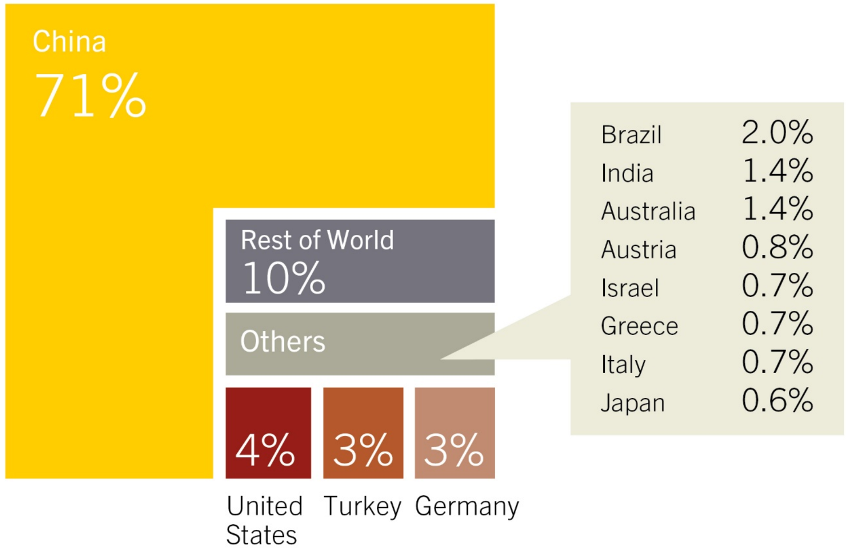


2.3. Solar thermal utilization

Solar Thermal Energy Utilization Worldwide

- The top five countries for cumulative capacity at year-end were China, the United States, Germany, Turkey and Brazil.

Solar Water Heating Collectors Global Capacity, Shares of Top 12 Countries and Rest of World, 2015

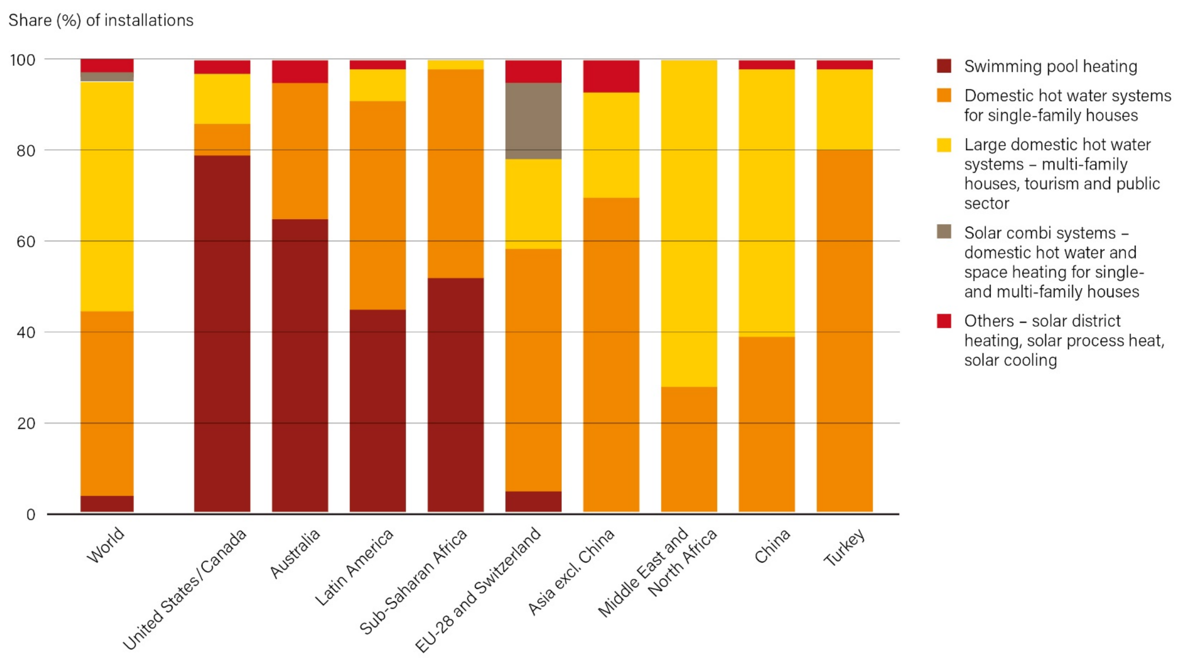


2.3. Solar thermal utilization

Solar Thermal Energy Utilization Worldwide

- Residential sector accounted for 63% of total installed collector capacity at the end of 2015.
- Markets transitioning to large-scale systems.

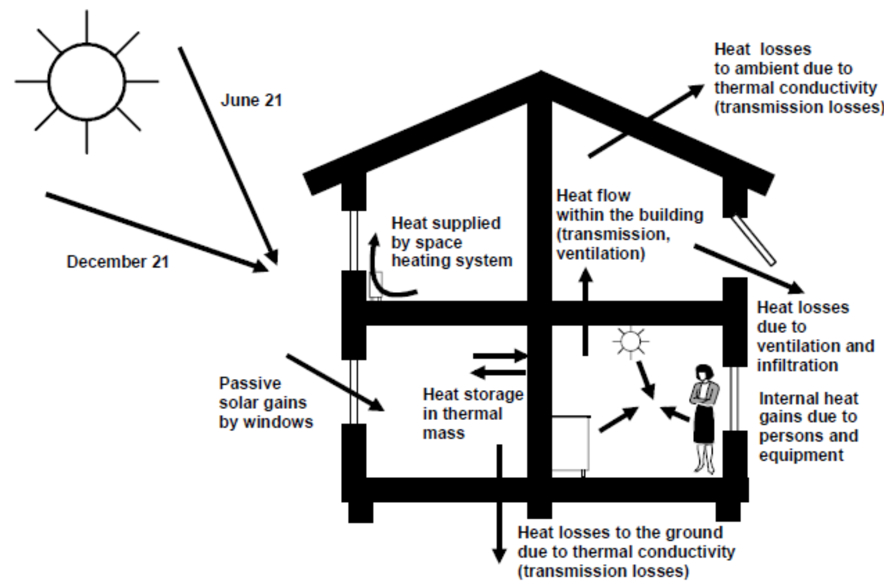
Solar Water Heater Applications for Newly Installed Capacity, by Economic Region, 2015



2.3. Solar thermal utilization

Utilization of Passive Solar Energy

- Passive solar systems **convert solar radiation into heat by** means of **the building** structure itself.
- It is characterized by **the use of the building envelope as an absorber** and the building structure as a heat store.
- It is based on the **absorption of short wave solar radiation**, either by the building interior, as solar radiation penetrates through the transparent external structural elements, or by the building envelope.
- The **energy is released back** into the exterior **by convection and long wave radiation**.



2.3. Solar thermal utilization

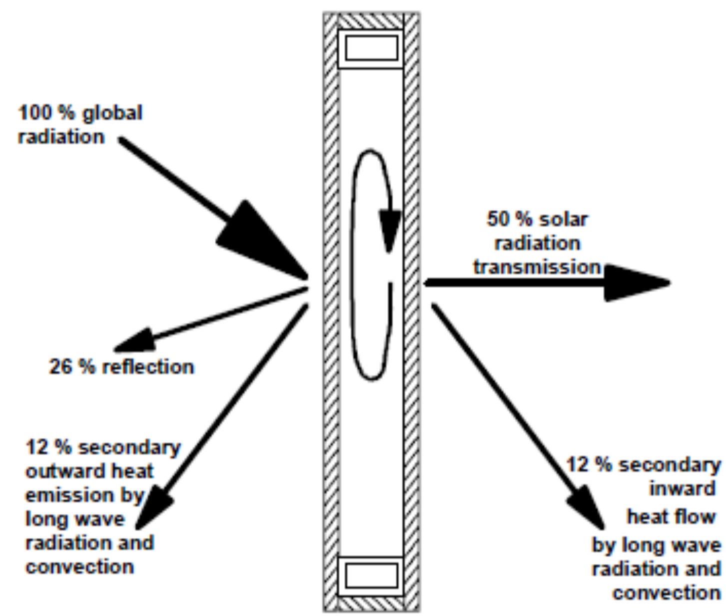
Utilization of Passive Solar Energy

System components:

- Passive solar systems may consist of transparent covers (such as windows, transparent thermal insulation), absorbers, heat stores and/or shading devices.

Transparent covers:

- They serve to transmit a maximum share of solar radiation to the interior and ensure at the same time utmost insulation from the outside.
- Typically, these two properties are expressed by the g-value (energy transmittance factor) and the U-value (thermal transmittance coefficient).
- Good transparent covers are characterized by high g-values and low U-values.



2.3. Solar thermal utilization

Utilization of Passive Solar Energy

System components:

Absorber and heat storage:

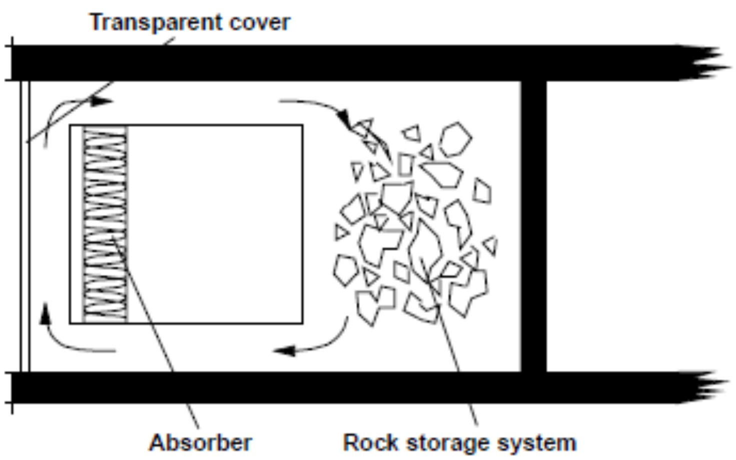
– They are integrated into the building structure.

– The room envelopes with solar radiation exposure, serve as absorber surfaces.

– Passive solar systems should offer well-absorbing outer surfaces and a heat-storing building structure which is well-adapted to the solar system.

– In most indirect gain systems only the outer wall is used for heat storage, which is thus of solid design, whereas the outer wall surface serves as an absorber.

– For this purpose the surface is either painted black or covered with black absorber foil.



2.3. Solar thermal utilization

Utilization of Passive Solar Energy

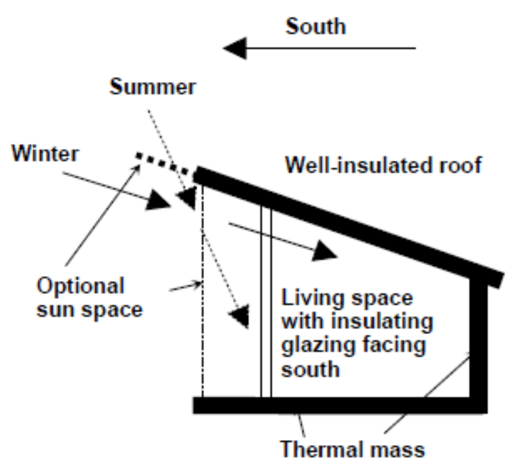
System components:

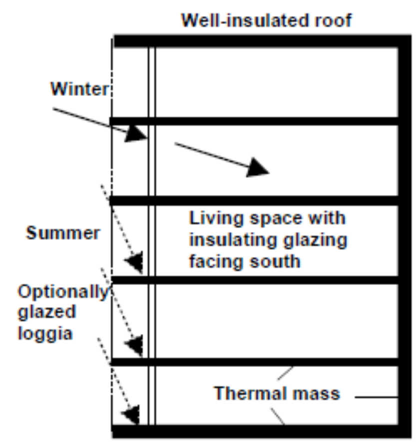
Shading devices:

- Adequate shading protection from high-angle sun in summer can be provided without incurring any additional costs using balconies and projections.

- The advantages of shading devices are simplicity and permanent function.

- They should be south-facing to ensure good shading in summertime and high irradiation into the building by the low-angle sun in the winter.





2.3. Solar thermal utilization

Solar thermal heat utilization

Physical principles of energy conversion for solar thermal heat utilization:

- **Solar thermal heat systems** are installations **converting solar radiation into heat** in order to heat swimming pools, produce domestic hot water, cover the demand for space heating or supply other heat consumers.
- The **basic principle** of solar thermal utilization is the **conversion of short-wave solar radiation into heat**.
- A body's capacity to absorb radiation is called absorbing capacity or **absorption** α, where α reflects the share of absorbed radiation as part of the entire radiation on matter.
- An ideal **black body** absorbs radiation at every wavelength and therefore has an **absorption coefficient equal to one**.
- The **emission** ε **represents the power radiated by a body**.

2.3. Solar thermal utilization

Solar thermal heat utilization

Physical principles of energy conversion for solar thermal heat utilization:

- The **relationship** between absorption α and emission ε is definided by **Kirchhoff's law**.

$$\varepsilon(\lambda, T) = \alpha(\lambda, T)$$

- The **ratio of** specific **radiation** and the **absorption coefficient** is constant at a given temperature and exclusively a **functionality of temperature and wavelength**.
- Matter with a **high absorption** capacity within a **defined wave range** also has a **high emission** capacity within that **same wave range**.
- The **deflection coefficient** ρ describes the **ratio of the reflected** to the inicident radiation.
- The **transmission coefficient** τ defines the **ratio of the radiation transmitted** through a given material to the entire radiation incident.
- The sum of absorption, reflection and transmission is one.

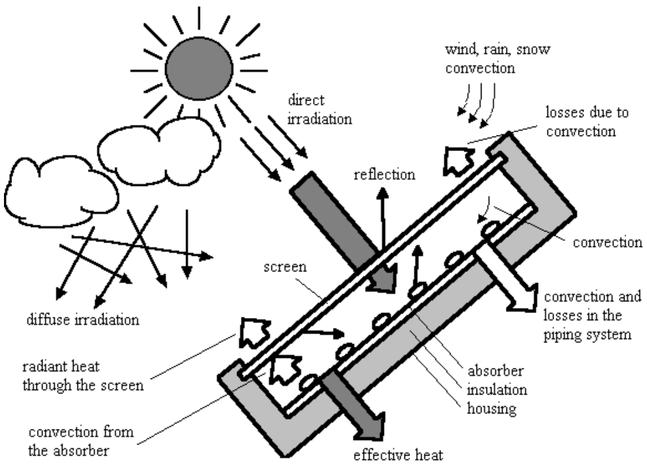
$$\alpha + \rho + \tau = 1$$

2.3. Solar thermal utilization

Solar thermal heat utilization

Optical features of absorbers:

- **Absorbers** have to absorb radiation and convert it into heat. They are characterized by **being opaque for radiation (τ = 0)**.
- An **ideal absorber** does **not reflect any short-wave radiation (ρ = 0)** so it **completely absorbs solar radiation** within this wave range **(α = 1)**.

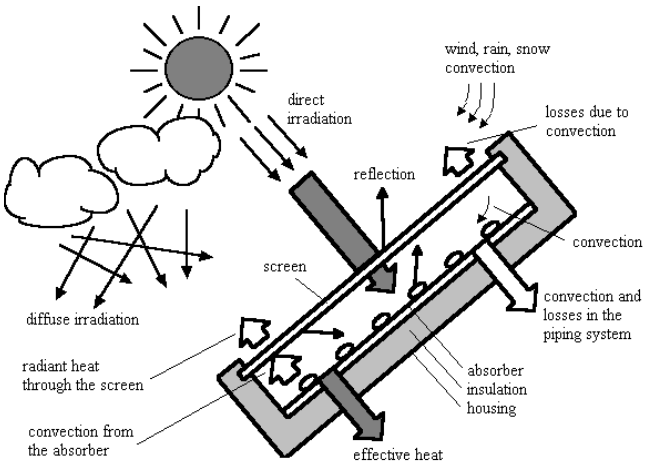


- **For long-wave radiation** above a certain boundary wavelength, **the situation** is exactly the **opposite**. Given an **ideal absorber**, it **reflects all of the radiation and** does **not absorb any at all**. Accordingly, the **emission** in this wave range **is zero** (Kirchhoff's law).
- Ideal scenarios cannot be completely recreated in real life. So-called **selective surfaces** (or selective coatings) **are close to the optimal absorber** features.

2.3. Solar thermal utilization

Solar thermal heat utilization

Optical features of covers:

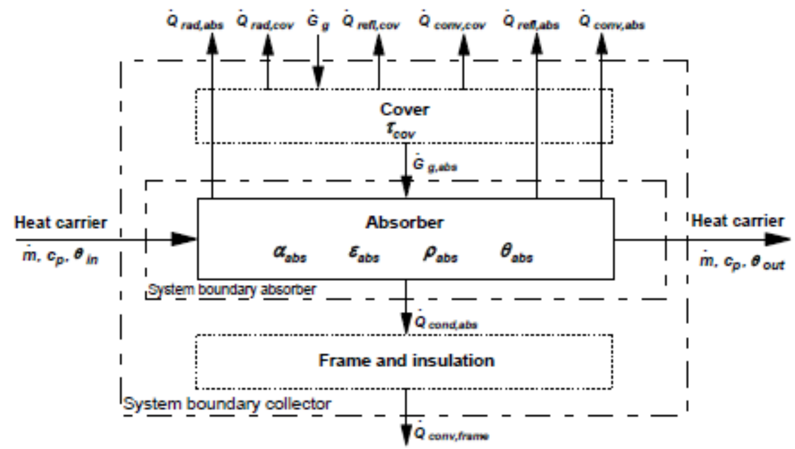


- In order **to reduce the convective** thermal **losses** of the absorber to the environment, in many cases **absorbers** used in solar thermal systems **have a** transparent **cover**.
- **Ideal covers have a transmission coefficient of one** in the range of solar radiation, whereas **reflection and absorption coefficient equal zero** in this spectrum.
- In **real life** such **conditions cannot be achieved**. **Glass fulfills** the required optical features within the luminous spectrum **very well**.
- **If** the degree of **absorption is high**, the **radiation losses** to the environment are high but can be **reduced by vacuum-coating** of layers that reflect infrared light.

2.3. Solar thermal utilization

Solar thermal heat utilization

Energy balance of a flat plate collector:



- A collector removes the utilizable heat by a heat transfer medium flowing through the collector.

- The difference between the energy at the inlet and the outlet of the heat transfer medium is the thermal flow removed by the transfer medium:

$$\dot{Q}_{useful} = c_p * \dot{m} * (\theta_{out} - \theta_{in})$$

  Where C_p is the specific heat capacity, $\dot{m}$ is the mass flow θ_{in} and θ_{out} are the inlet and the outlet temperature of the transfer medium.

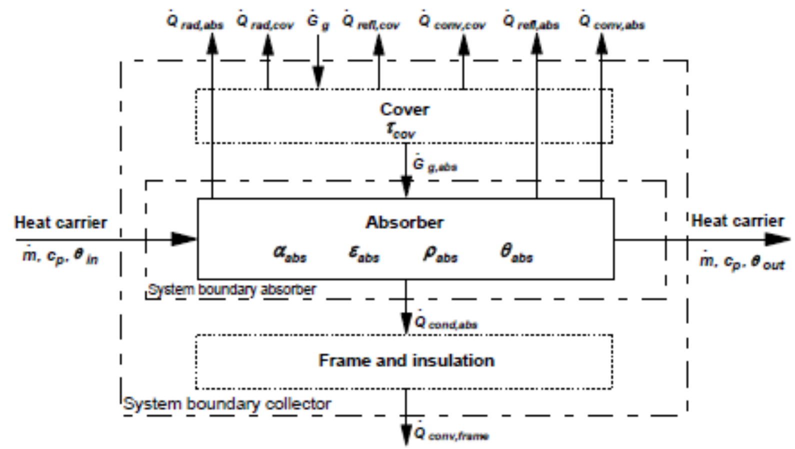
- This results in the following energy balance for the absorber of a collector:

$$\dot{G}_{g,abs} = c_p * \dot{m} * \theta_{out} - c_p * \dot{m} * \theta_{in} + \dot{Q}_{conv,abs} + \dot{Q}_{rad,abs} + \dot{Q}_{refl,abs} + \dot{Q}_{cond,abs}$$

2.3. Solar thermal utilization

Solar thermal heat utilization

Energy balance of a flat plate collector:



- $\dot{G}_{g,abs}$ is the **global radiation on the absorber** and defined by the total global radiation $\dot{G}_{g}$ on the collector cover and the corresponding transmission coefficient τ_{cov} :

- The **reflection losses of the absorber** $\dot{Q}_{refl,abs}$ is calculated with the radiation on the absorber and the reflection ρ_{abs}:

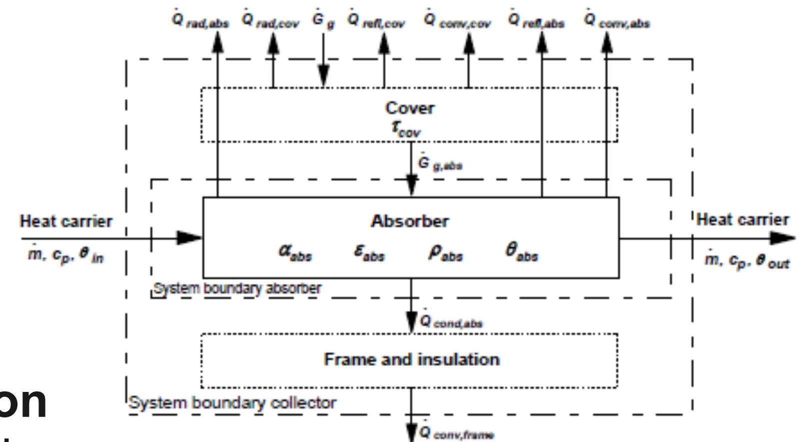
- The **radiation losses** $\dot{Q}_{rad,abs}$ result, according to the Stefan-Boltzmann radiation law, from the emission ε_{abs}, the absorber temperature θ_{abs} and the ambient external temperature θ_{e}, the Stefan-Boltzmann-constant σ and the radiating absorber area S_{abs}:

$$\dot{Q}_{rad,abs} = \varepsilon_{abs} * \sigma * \left(\theta_{abs}^4 - \theta_e^4\right) * S_{abs}$$

2.3. Solar thermal utilization

Solar thermal heat utilization

Energy balance of a flat plate collector:



- The **convective thermal losses** $\dot{Q}_{conv,abs}$ depends on absorber θ_{abs} and the ambient air temperature θ_e , and the heat transfer corfficient U^*_{coll} that is constant in the first approximation: $\dot{Q}_{conv,abs} = U^*_{coll} * (\theta_{abs} - \theta_e) * S_{abs}$
- The thermal flow due **to the heat conduction** $\dot{Q}_{cond,abs}$ from the absorber to the frame and the insulation is very small compared to the other thermal flows and **can be neglected**.
- So the energy balance for the heat transported by the heat transfer medium is:

$$\dot{Q}_{useful} = \tau_{cov} * \alpha_{abs} * \dot{G}_g - U^*_{coll} * (\theta_{abs} - \theta_e) * S_{abs} - \varepsilon_{abs} * \sigma * \left(\theta^4_{abs} - \theta^4_e\right) * S_{abs}$$

- The **efficiency** η of the collector is the ratio of the useful thermal flow transported by the heat transfer medium $\dot{Q}_{useful}$ to the global radiation incident on the collector $\dot{G}_g$:

$$\eta = \frac{\dot{Q}_{useful}}{\dot{G}_g}$$

2.3. Solar thermal utilization

Solar thermal heat utilization

Collector thermal efficiency:

- In reality the heat loss coefficient U_{coll} in previous equations is not constant but is a function of collector inlet and ambient temperatures. Therefore for flat-plate collectors the efficiency can be written as:

$$\eta = \eta_0 - a_1 \frac{\theta_{in} - \theta_a}{\dot{G}_g} - a_2 \frac{(\theta_{in} - \theta_a)^2}{\dot{G}_g}$$

- Where:

  η_0: maximum collection efficiency, called the optical efficiency.

  a_1: linear heat loss coefficient.

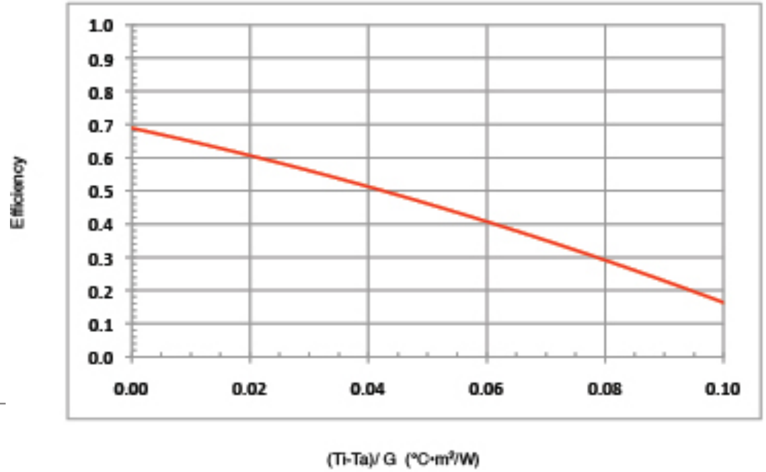
  a_2: quadratic heat loss coefficient.

2.3. Solar thermal utilization

Solar thermal heat utilization

Collector thermal efficiency:

$$\eta = \eta_0 - a_1 \frac{\theta_{in} - \theta_a}{\dot{G}_g} - a_2 \frac{(\theta_{in} - \theta_a)^2}{\dot{G}_g}$$



Technical Data

	K420-EM	K423-EM	K420-DH	K423-DH / AR
Absorberbauart Type of construction	Einfachmäander mit 12 mm Rohr Single meander with 12 mm tube		10 / 12 Harfenrohre mit 8 mm Rohr und 2 Sammelrohre mit 18 mm Rohr 10 / 12 harp tubes with 8 mm tube and 2 manifolds with 18 mm tube	
Abmessung des Kollektors Measurement of the collector	1870 x 1150 mm	2160 x 1150 mm	1870 x 1150 mm	2160 x 1150 mm
Bruttofläche des Kollektors Gross area	2,15 m²	2,51 m²	2,15 m²	2,51 m²
Höhe Height	75 mm		95 mm	
Aperturfläche (Absorber) Aparture area (absorber)	2,0 m²	2,3 m²	2,0 m²	2,3 m²
Masse ungefüllt Total Weight dry	34 kg	38 kg	34 kg	39 kg
Flüssigkeitsinhalt Liquid content	1,73 l	2,0 l	1,13 l	1,3 l / 1,4 l
Wirkungsgrad η_0 (Apertur) Efficiency η_0 (aperture)	80,3 %	80,3 %	80,1 %	78,1 % / 83,9 %
Wärmeverlustkoeffiz. a1 W/(m²xK) Heat loss coefficient a1 W/(m²xK)	4,11	4,11	3,65	3,60 / 3,71
Wärmeverlustkoeffiz. a2 W/(m² x K²) Heat loss coefficient a2 W/(m²x	0,0133	0,0133	0,0172	0,0155

2.3. Solar thermal utilization

Solar thermal heat utilization

Collector thermal efficiency. F-Chart method:

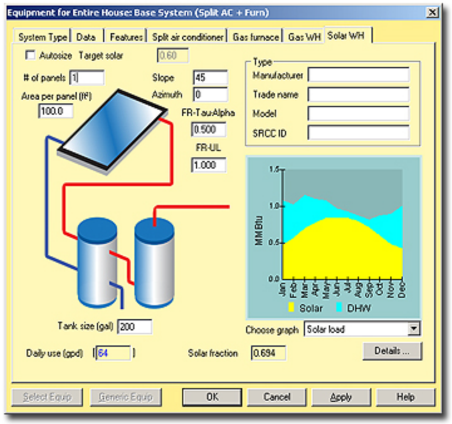
- **F-chart is** an authoritative solar system analysis and **design program** written by S.A. Klein & W.A Beckman, the originators of the F-chart method.
- This method provides a means of easily **determining the thermal performance of active solar heating systems** (using either liquid or air as the working fluid) and solar domestic hot water systems.
- It is essentially a **correlation of the results of hundreds of simulations** of solar heating systems. The conditions of the resulting correlations give f, **the fraction of the monthly heating load** (for space heating and hot water) supplied by solar energy **as a function of two dimensionless variables** involving collector characteristics, heating loads, and local weather.

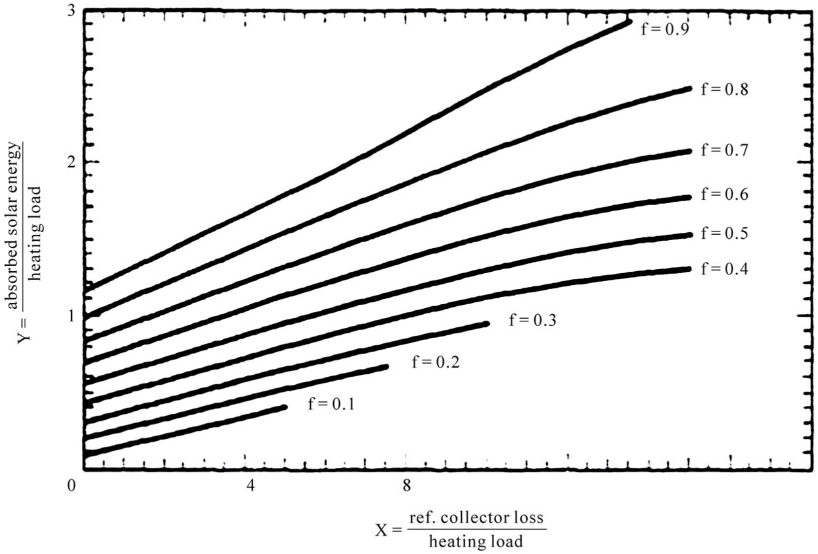
2.3. Solar thermal utilization

Solar thermal heat utilization

Collector thermal efficiency. F-Chart method:

- The f-chart method proceeds as follows:





- The dimensionless variables **X** and **Y** are calculated for each calendar month.
- The intersection of the **X** and **Y** values locates a value of **f** which is the fraction of the heating load supplied by solar energy for that month.
- The calculations are repeated for each month.

2.3. Solar thermal utilization

Solar thermal heat utilization

Further elements of solar thermal heat systems:

Heat store:

- A heat store has the heat accumulation medium, a solid cover with insulation material plus heat inlet and outlet devices to accumulate the heat generated in the collector by solar radiation, and store it for times when it is required.
- Because of the general non-correlation between the solar radiation supply and the demand for heat, heat stores are part of most solar thermal installations.
- The **heat capacity** is an important parameter for the heat accumulation medium. It is the amount of heat required to increase the temperature of a specific substance by 1 K.
- They can be differentiated by the type of heat accumulation (chemical, thermal) and the condition of the accumulative substance. In the segment of low-temperature heat storage mainly thermal heat accumulation is used. Liquid, solid-matter and latent heat stores can be distinguished.

2.3. Solar thermal utilization

Solar thermal heat utilization

Further elements of solar thermal heat systems:

Sensors and control systems:

- The number and the type of sensors and control instruments are largely dependent on the concept of the system.
- Natural circulation systems normally do not require any active regulation instruments.
- In forced circulation systems, the collector circuit is generally actively controlled by a temperature difference control device.
- Temperature sensors on or inside the collector, and on or inside the storage system, measure the temperature and convert it into electronic signals.

2.3. Solar thermal utilization

Solar thermal heat utilization

Further elements of solar thermal heat systems:

Heat transfer medium:

- Some of the requirements of a heat transfer medium are:
  - High specific heat capacity.
  - Low viscosity, i.e. good flow capability.
  - No freezing or boiling at operating temperature.
  - Non-corrosion in the conduit system.
  - Non-flammable and non-toxic and biologically degradable.
- Water fulfills most of these requirements very well.
- However, the danger of freezing at temperatures below 0°C can cause problems. Water without additives can thus only be used in the warmer zones of the Earth without the risk of frost.

2.3. Solar thermal utilization

Solar thermal heat utilization

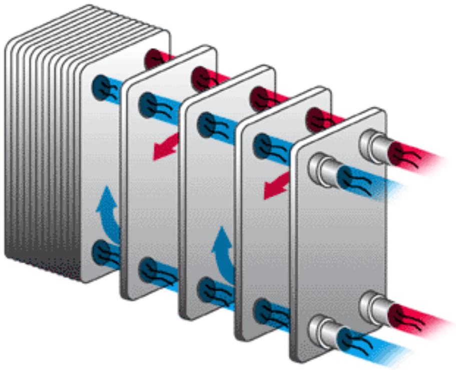
Further elements of solar thermal heat systems:

Pipes:

- The collector and the storage system are connected by pipes. The size of the system and the absorber material determine the material chosen for these pipes.
- Mostly hard or soft copper pipes or corrugated stainless steel pipes, and additionally, steel and polyethylene pipes are used.
- In order to reduce thermal losses, the pipes of the collector circuit have to be insulated.
- In standard solar thermal systems for domestic hot water supply, the thermal losses that still occur in the pipes, in spite of insulation, are 10 to 15 % of the energy released by the collector.

2.3. Solar thermal utilization

Solar thermal heat utilization



Further elements of solar thermal heat systems:

Heat exchanger:

- Heat exchangers serve to transfer heat from one medium to another while separating the media physically.
- They have to be used if the storage system is charged or discharged indirectly.
- The transferred heat depends on:
  - The temperature difference between the two media.
  - The area of the heat exchanger.
  - The heat transfer medium and the flow speed on both sides of the heat exchanger (heat transfer coefficient).
- External and internal heat exchangers are used for solar thermal systems.

2.3. Solar thermal utilization

Solar thermal heat utilization

Further elements of solar thermal heat systems:

Pumps:

- In solar thermal systems with a forced circulation, a pump is required to operate the collector circuit.
- For standard domestic solar thermal water systems, volume flow amounts of 30 to 50 l/h (m^2 collector area) are common (High-Flow). For Low-Flow systems the volume flows are between 10 and 15 l/h (m^2 collector area). The layout of the collector circuit pumps also depends on this volume flow rate.
- High-Flow systems always have simple centrifugal pumps, mostly equipped with a manual adjustable speed control.
- For Low-Flow, vane or gear pumps are used that still show good efficiencies at a higher pressure rise and a lower volume flow rate.

2.3. Solar thermal utilization

Solar thermal heat utilization: System design concepts

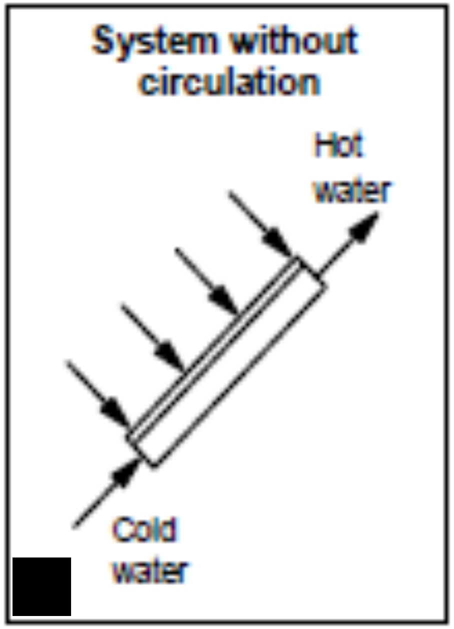
- The variety of different system installations can be described according to the type of heat transfer medium circulation:
  - Systems without circulation (storage collector).
  - Natural circulation systems (Thermo-siphon-systems).
  - Forced circulation systems.
- If the formation of the solar circuit is used for differentiation, there can be:
  - Open systems.
  - Closed systems.
- On the basis of these criteria, five basic principles of solar systems can be defined:
  - Systems without circulation.
  - Open natural circulation systems.
  - Closed natural circulation systems.
  - Open forced circulation systems.
  - Closed forced circulation systems.

2.3. Solar thermal utilization

Solar thermal heat utilization: System design concepts

Systems without circulation:

- In this most basic of all possible principles, the **heat transfer medium and the liquid** actually used by the consumer **are the same medium**.

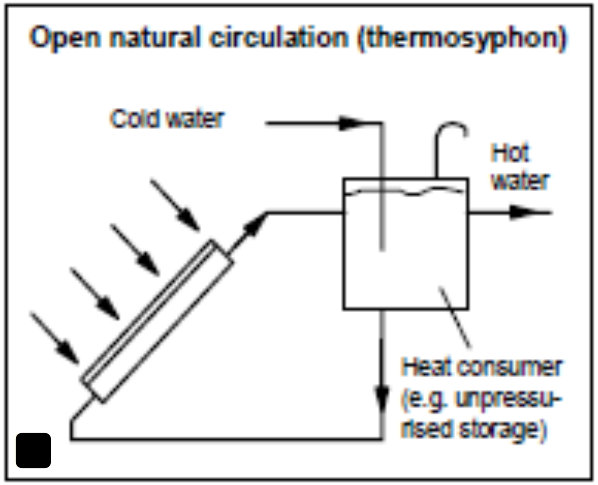


- Within the normal drinking or domestic water circuit, **a suitable collector is integrated**.
- When flowing through the collector, **the water is heated up and can be used afterwards**.

2.3. Solar thermal utilization

Solar thermal heat utilization: System design concepts

Open natural circulation systems:

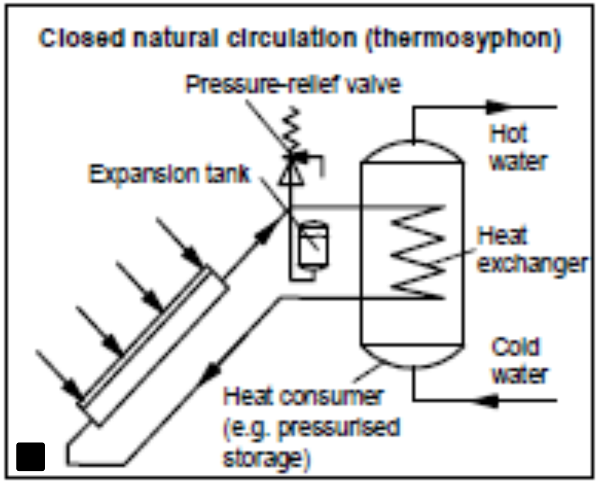


- This most basic of all circulation concepts consists of the collector, the flow and the return pipe and pressure free, open storage.
- The reason for the **natural circulation is the decrease in density** in a liquid with increasing temperature. These density differences create circulation within the system if the storage system with the colder medium is positioned above the collector.
- This is a **self-regulating system** that, at least in its basic form, can work without sensors and control instruments.
- The natural circulation system **is open** and the same liquid flows through the collector that is directly passed on to the user.
- The **collector circuit** has to be **resistant to corrosion** as drinking water generally flows through it.

2.3. Solar thermal utilization

Solar thermal heat utilization: System design concepts

Closed natural circulation systems:



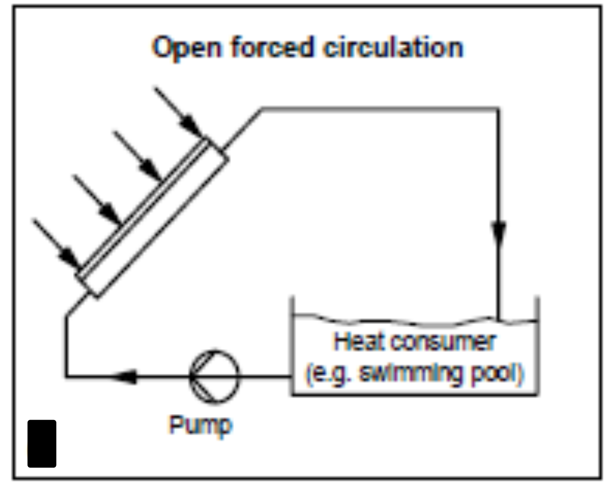
- In order to prevent freezing and corrosion, the **collector circuit can be closed** in natural circulation systems.
- This, however, **requires a heat transfer medium** that normally releases the heat in the collector circuit to a storage system that can distribute the heat further.
- As the circuit is sealed off from the environment, it is normally **under greater pressure**.
- In order to operate it **safely, an expansion tank** and a pressure control valve have to be installed within the primary circuit.
- If such systems are used in areas exposed to frost, **frost-resistant heat carriers have to be used** and the storage, the cold and the hot water service pipes must be protected against frost.

2.3. Solar thermal utilization

Solar thermal heat utilization: System design concepts

Open forced circulation systems:

- **If** the heat sink cannot be installed above the collectors, **circulation** of the heat transfer medium **has to be forced** by integration of a pump into the circuit.
- The given **advantage of orientating collectors and heat sink independent** from each other is of importance for heating open-air swimming pools, where the collectors are normally positioned on roofs or free spaces above the heat sink.

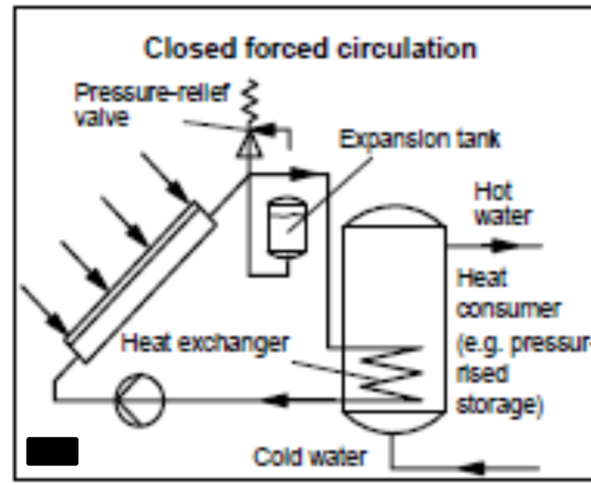


- If the fluid in the collector cools down more quickly than in the collector loop pipes, **the circulation might be reversed** during the night if the pump is not running.
- This can be prevented by e.g. **integrating a check** valve into the collector return flow pipe.

2.3. Solar thermal utilization

Solar thermal heat utilization: System design concepts

Closed forced circulation systems:



- In these systems, the medium flowing through the collector circuit is generally ordinary water. Therefore they are **exposed to** the same **frost** and corrosion risks as open natural circulation systems.
- In order to avoid freezing, the **forced circuit is sealed off** and a frost-resistant liquid flows through.
- This concept of closed forced circulation **is the most practical solution** for applications in Central and Northern Europe.
- If used within **buildings**, the **collector** is normally installed **on the roof**. The heat from the collector circuit is normally transferred to a heat store in the basement.
- An **expansion tank** and a pressure **control valve** are required. Additionally, a **check valve** also has to be installed.

Topic 2. Solar energy

- **2.1.** Solar radiation.
- **2.2.** Solar thermal collectors.
- **2.3.** Solar thermal utilization.
- **2.4. Solar thermal power plants**.
- **2.5.** Solar panels.
- **2.6.** Photovoltaic applications.

2.4. Solar thermal power plants

- The term "solar thermal power plant" comprises power plants which first **convert solar radiation into heat**.
- The resulting **thermal energy is** subsequently **transformed** into mechanical energy by a thermal engine, and then converted **into electricity**.
- For thermodynamic reasons **high temperatures are required** to achieve the highest efficiency. Such high temperatures are reached by increasing the energy flux density of the solar radiation incident on a collector.
- According to the type of solar radiation concentration, solar thermal power plants are subdivided into **concentrating and non-concentrating systems**.

Concentrating systems	Non-concentrating systems
• Solar tower power plants. • Dish/Stirling systems. • Parabolic trough and Fresnel trough power plants.	• Solar updraft tower power plants. • Solar pond power plants.

2.4. Solar thermal power plants

- Basically, the **process of solar thermal power generation** consists of the following **steps:**
  - Concentrating solar radiation by means of a collector system.
  - Increasing radiation flux density (i.e. concentrating the solar radiation onto a receiver), if applicable.
  - Absorption of the solar radiation (i.e. conversion of the radiation energy into thermal energy (i.e. heat) inside the receiver).
  - Transfer of thermal energy to an energy conversion unit.
  - Conversion of thermal energy into mechanical energy using a thermal engine (e.g. steam turbine).
  - Conversion of mechanical energy into electrical energy using a generator.

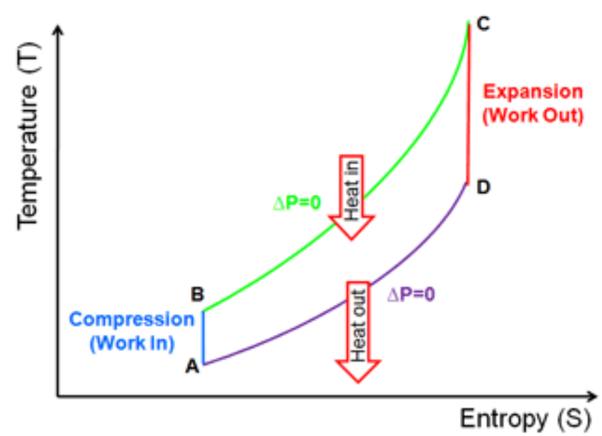
2.4. Solar thermal power plants

Thermodynamic cycles

For current industrial applications, **Joule and Rankine cycles** are most commonly applied. In both cycles **heat is first applied** to increase the volume flow of a gaseous working medium. Subsequently, during its expansion, this **volume flow performs mechanical work** in pressure engines.

The Joule cycle:

- It is composed of isentropic compression, isobaric heat addition, isentropic expansion and isobaric heat dissipation.
- The working medium "ambient air" is aspirated and compressed prior to adding heat. For solar applications heat is transferred directly from the absorber to the working medium of the energy conversion process.
- Since pressurized air is used as the working medium, the absorber must be of closed design.

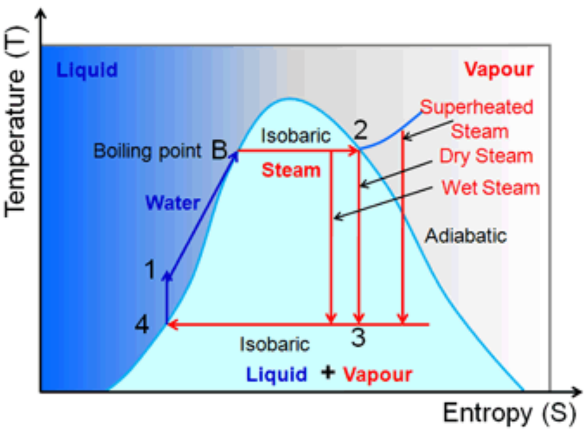


2.4. Solar thermal power plants

Thermodynamic cycles

The Clausius-Rankine cycle:

- It makes use of the phase transformation of matters. Such phase transformations correspond to isothermal heat addition and large additions of specific volume.
- It requires a phase change medium to allow for isothermal heat addition. In most cases water is applied, but there are also processes using organic working media for low-temperature applications.
- At the beginning, the liquid working medium is highly pressurized and undergoes a phase change while heat is added.
- The now gaseous material is subsequently expanded, possibly after further heat has been added.
- Afterwards condensation is performed under low pressure while heat is dissipated.



2.4. Solar thermal power plants

Concentrating systems: solar tower power plants

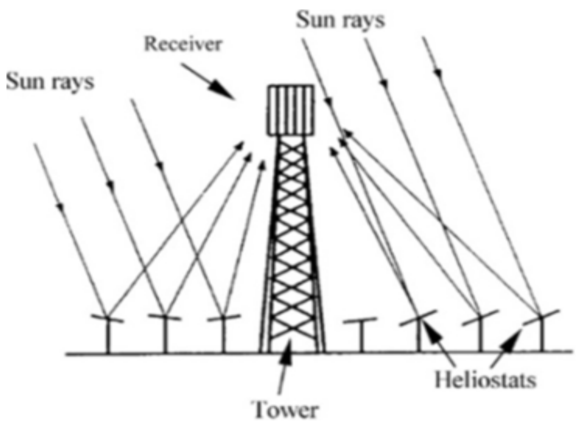
- **Mirrors tracking** the course of the **sun on two axes**, so-called heliostats, **reflect** the direct solar radiation **onto a receiver**, centrally positioned on a tower.
- There, **radiation energy is converted into heat and** transferred to a heat transfer medium (e.g. air, liquid salt, water/steam). This heat **drives a** conventional **thermal engine**.
- To ensure constant parameters and a constant flow of the working medium also at times of varying solar radiation, **a heat storage system** or an additional heat generator **can be incorporated** into the system.

2.4. Solar thermal power plants

Concentrating systems: solar tower power plants

System components:

- *Heliostats:* reflecting surfaces provided with a two-axis tracking system which ensures that the incident sunlight is reflected towards a certain target point throughout the day. They consist of the reflector surface, a sun-tracking system provided with drive motors, foundations and control electronics.
- *Tower:* the height of the tower, on which the receiver is mounted, is determined by technical and economic optimization. Higher towers are generally more favorable, since bigger and denser heliostat fields presenting lower shading losses may be applied. Common towers have a height of 80 to 100 m.
- *Receiver:* it serves to transform the radiation energy into technical useful energy. It is distinguished according to the applied heat transfer medium (e.g. air, molten salt, water/steam, liquid metal) and the receiver geometry (e.g. even, cavity, cylindrical or cone-shaped receivers).



2.4. Solar thermal power plants

Concentrating systems: Dish/Stirling systems

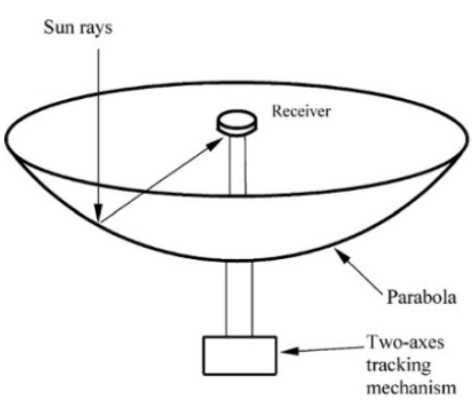
- Dish/Stirling systems mainly **consist of** the parabolically shaped **concentrator** (dish), a solar **receiver** and a **Stirling motor** as thermal engine with interconnected generator.
- The parabolic **concentrator tracks the sun on two axes**, so that it reflects the direct solar radiation onto a receiver positioned at the focus of the concentrator.
- The radiation energy transformed into heat within the receiver is **transferred to the Stirling motor**, which converts the thermal energy into mechanical energy.
- A generator is directly coupled to the **Stirling motor** shaft, which **converts** the mechanical energy **into** the desired **electrical energy**.
- For hybrid operation, the system may be **heated in parallel** or in addition **by a gas burner** (operating e.g. by natural gas or biogas).

2.4. Solar thermal power plants

Concentrating systems: Dish/Stirling systems

System components:

- *Parabolic concentrator (dish):* the dish concentrates sunlight onto a focal spot. The size of this spot depends on the concentrator precision, surface condition and focal distance. Common maximum diameters amount to 25 m.
- *Mounting structure:* this is determined by the shape of the reflector segments or the full-surface concentrator.
- *Solar tracking system:* point-focusing parabolic concentrators must be continuously tracking the sun's path to ensure that solar radiation is always parallel to the optical concentrator axis.
- *Receiver:* the receiver absorbs solar radiation reflected by the concentrator and converts it into technically useful heat.
- *Stirling motor:* thermal energy can be converted into electrical energy using a Stirling motor with coupled generator. It is based on the fact that gas changes its volume when subjected to a temperature change.
- *Video:* Infinia - Stirling solar generator.



2.4. Solar thermal power plants

Concentrating systems: parabolic trough power plants

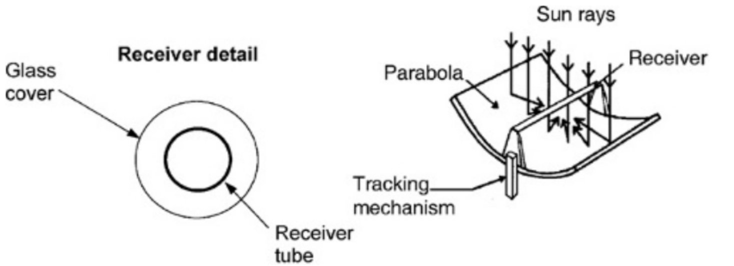
- The line-focusing solar fields of parabolic trough and linear Fresnel collectors **reflect the incident radiation on an absorber** positioned **in the focal line** of the concentrator.
- The **collector tracks the sun on one axis**. Due to this, the geometric concentration factors of 15 to 30 are lower than those of two-dimensional collectors and lower temperatures are achieved when compared to solar tower power plants.
- This disadvantage is compensated by **lower specific costs** as well as a **simpler structure** and maintenance.
- Because of its modular structure and the shape of the solar field, line-focusing solar power plants have been referred to as **"solar farms"**.

2.4. Solar thermal power plants

Concentrating systems: parabolic trough power plants

System components:

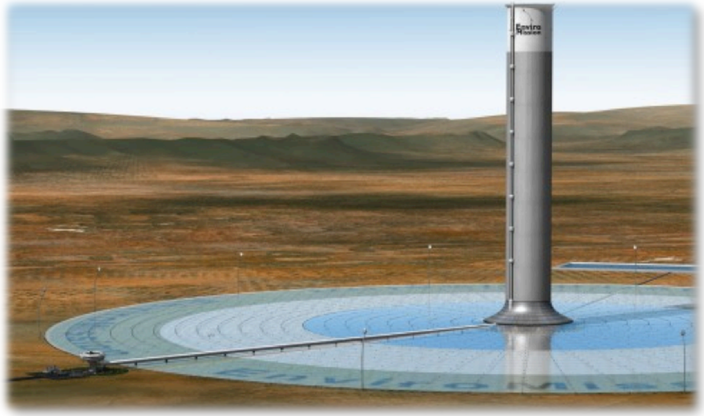
- *Collectors:* typically 100-150 m long, provided with single-axis solar tracking. After deduction of the optical and thermal losses inside the collector, 40 to 70% of the radiation incident on the mirrors can be used technically.
- *Absorber/Heat collecting element:* individual horizontal tubes are used as absorbers in the focal line of the collectors. For Fresnel collectors tube groups may also be used due to their wider focal line. Absorber tubes are enclosed in an evacuated glass tube to minimize heat losses.
- *Heat transfer medium:* to date, high-boiling, synthetic thermal oil has been applied. Due to the limited thermal stability of the oil, the maximum working temperature is 400°C. This temperature requires keeping the oil pressurized (approximately 12 to 16 bar).
- *Collector fields:* composed of a number of loops of an approximate length of 600 m each, north-south oriented to allow for high and constant energy yields.



2.4. Solar thermal power plants

Non-concentrating systems: solar updraft tower power plants

- The incident direct and diffuse solar radiation warms the air below a flat, circular glass roof, open at the circumference, which, in conjunction with the bottom underneath, forms an air collector.
- The middle of the roof is equipped with a vertical chimney provided with big openings for air supply. The roof is connected air-tight to the chimney bottom.
- Since warm air is of lower density than cold air, it rises to the top of the chimney tube and solar radiation ensures continuous updraft inside the chimney.
- The energy contained in the air flow can be converted into mechanical energy using pressure-staged turbines, located at the bottom of the chimney.

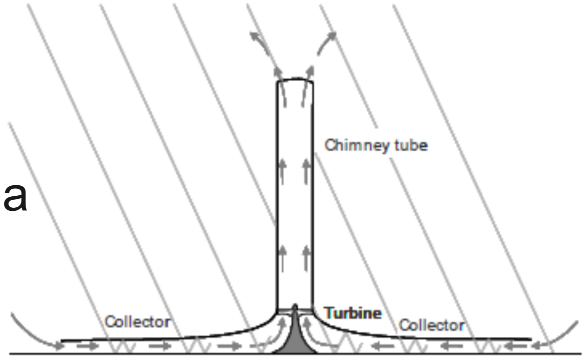


2.4. Solar thermal power plants

Non-concentrating systems: solar updraft tower power plants

System components:

- *Collector:* horizontal translucent glass or plastic roof located approximately 2 to 6 m above ground. It is permeable to solar radiation, but impermeable to the long-wave heat radiation emitted by the collector bottom. The height of the air-type collector increases towards the tower, so that friction losses are kept low.
- *Storage:* the solar energy can be stored intermediately using water-filled pipes or cushions placed on the collector bottom which improve the natural heat storage capacity of the ground.
- *Tower:* represents the actual thermal engine. The updraft of the air heated is proportional to the air temperature rise obtained inside the collector and to the height of the chimney. They are very big atmospheric cooling towers.
- *Turbines:* they are pressure-staged as wind turbo generator sets, and extract static pressure similar to a hydroelectric power plant.
- *Video:* EnviroMission - Solar tower.



2.4. Solar thermal power plants

Non-concentrating systems: solar pond power plants

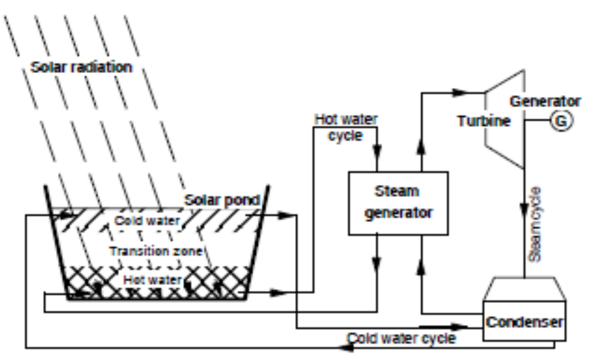
- Solar ponds are power plants that utilize the effect of water stratification as a basis for the collector.
- A basin filled with brine (i.e. a water/salt mixture) functions as collector and heat storage. The water at the bottom of the solar pond serves as primary heat storage from which heat is withdrawn.
- The deeper water layers and the bottom of the solar pond itself serve as absorber for the impinging direct and diffuse solar radiation.
- Due to the increase of the salt concentration towards the bottom of the basin, the resultant heat loss at the surface is minimized.
- Heat of an approximate temperature between 80 and 90°C can be extracted from the bottom using suitable thermodynamic cycles, then be used for power generation.

2.4. Solar thermal power plants

Non-concentrating systems: solar pond power plants

System components:

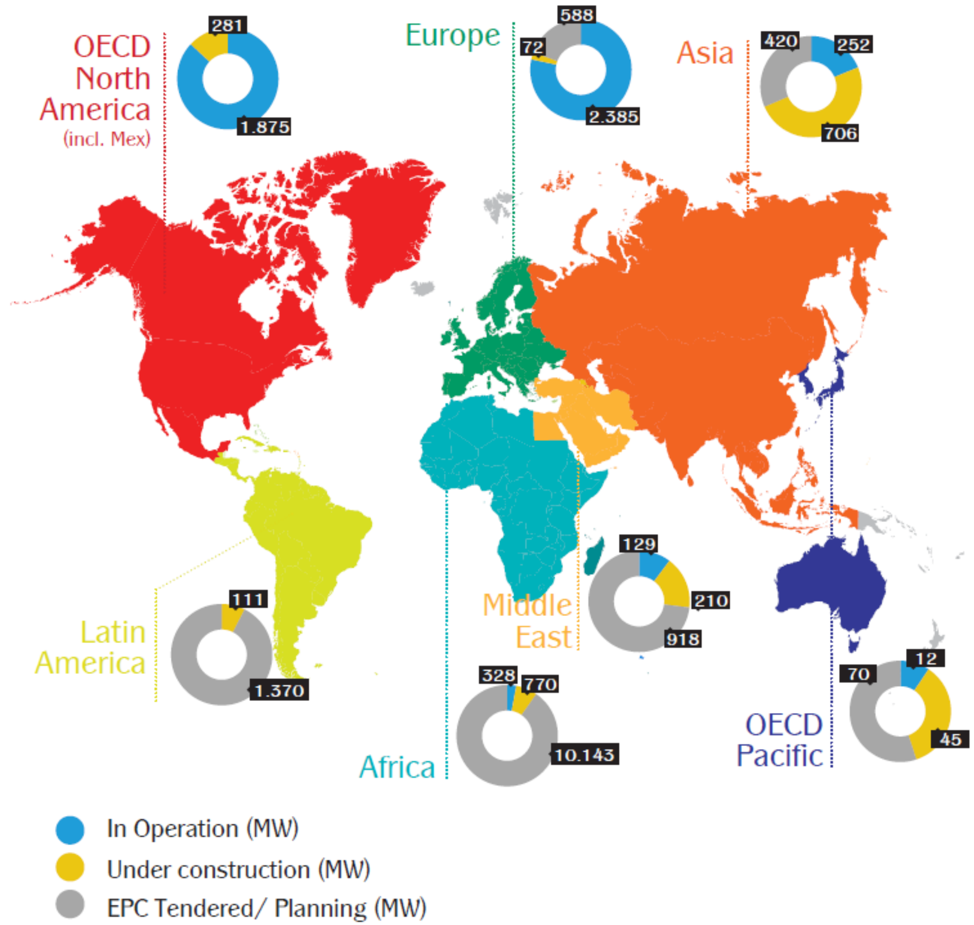
- *Pond collector:* natural or artificial lakes, ponds or basins that act as a flat-plate collector because of the different salt contents of water layers due to stratification. The upper water layer of relatively low salt is approximately 0.5 m thick. The adjacent transition zone has a thickness of 1 to 2 m, and the lower storage zone is of 1.5 to 5 m thickness.
- *Heat exchangers:* basically, there are two methods for withdrawing heat from a solar pond: The working fluid flows through tube bundle heat exchangers or it can also be pumped from the storage zone by means of an intake diffuser.
- *Thermal engine:* to convert solar thermal energy into mechanical and afterwards into electrical energy, usually Organic Rankine Cycles processes are applied. These are steam cycles which utilize a low-boiling cycle fluid. Such processes enable providing electrical energy also at low useful temperature differences.



2.4. Solar thermal power plants

Solar thermal electricity (STE) worldwide and Spain

- As of 2015, the installed capacity of STE increased to almost 5 GW with the connection of a number of large-scale solar thermal power plants to the grid.
- 110 MW of capacity came online in 2016.
- Total global capacity: 4.8 GW.
- 900 MW expected to enter operation during the course of 2017.

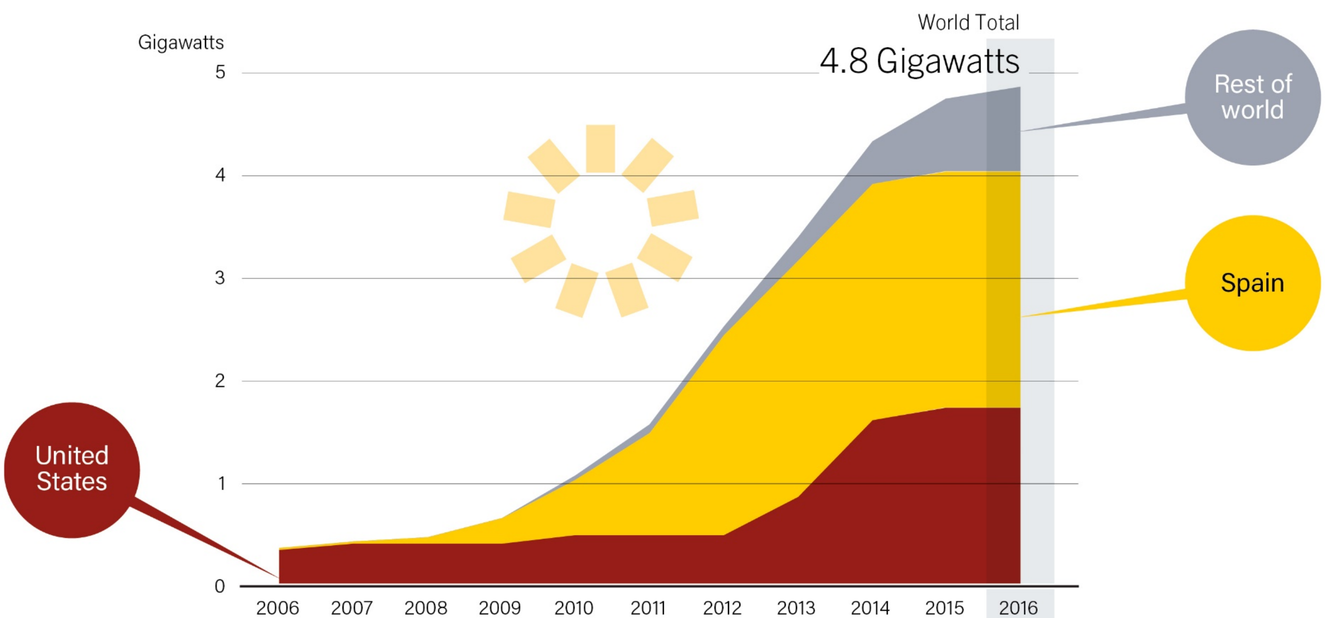


2.4. Solar thermal power plants

Solar thermal electricity (STE) worldwide and Spain

- Around 61% of operational STE plants are located in Spain, whereas 18% are located in the US.

Concentrating Solar Thermal Power Global Capacity, by Country and Region, 2006-2016

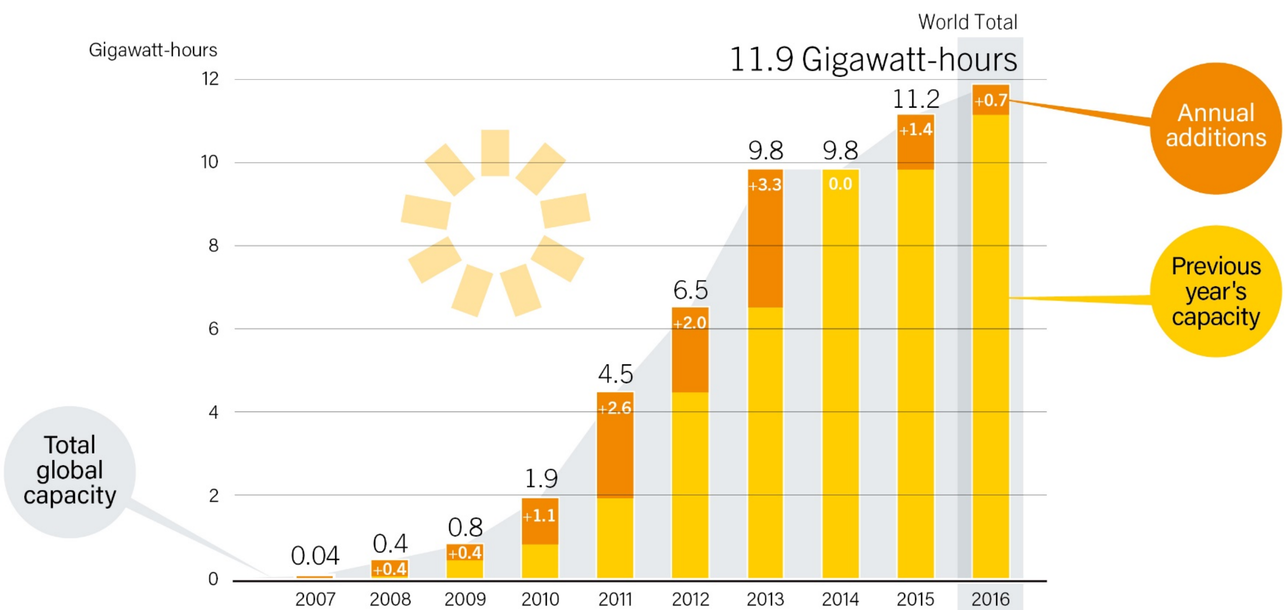


2.4. Solar thermal power plants

Solar thermal electricity (STE) worldwide and Spain

- Thermal energy storage. Annual additions: 0.7 GWh and world total: 11.9 GWh.
- All new facilities that came online incorporated thermal energy storage.

CSP Thermal Energy Storage Global Capacity and Annual Additions, 2007-2016

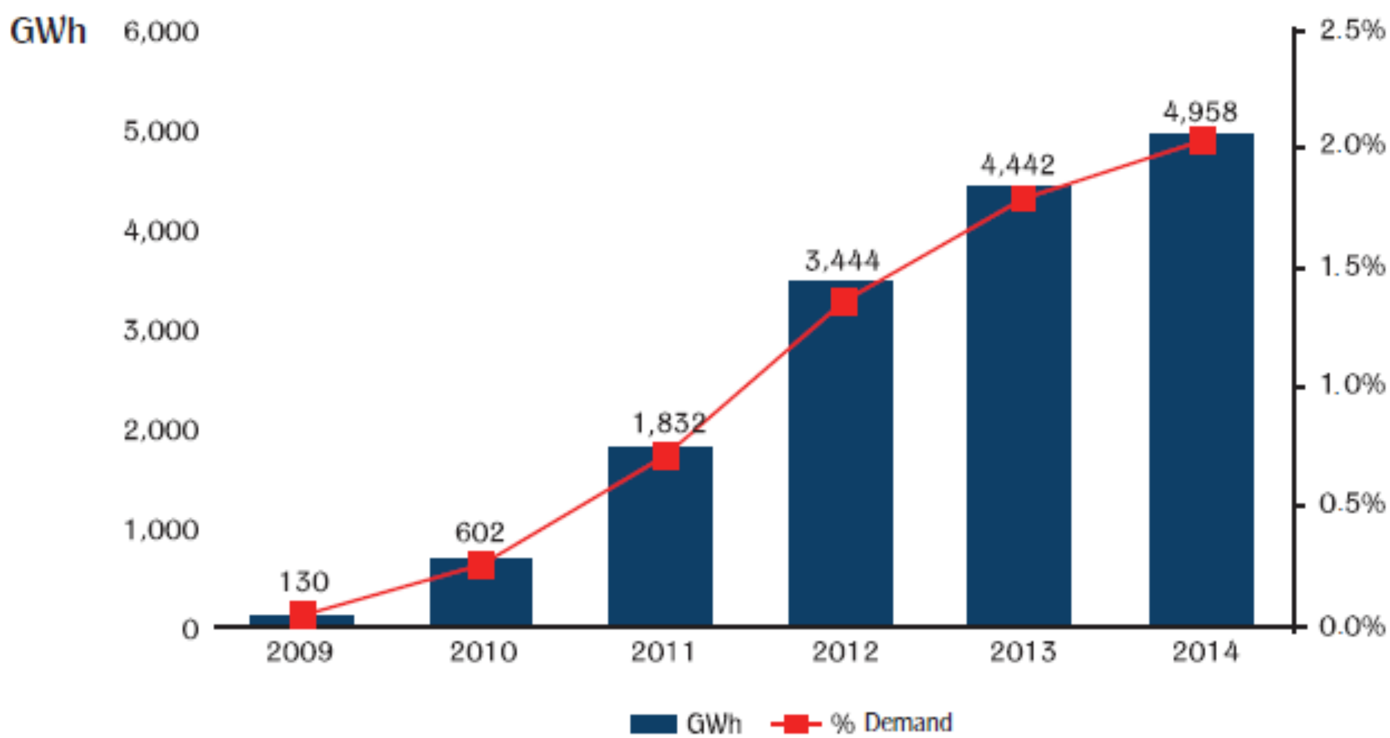


2.4. Solar thermal power plants

Solar thermal electricity (STE) worldwide and Spain

- Spain is the current STE market leader in installed capacity with 2,375 MW.

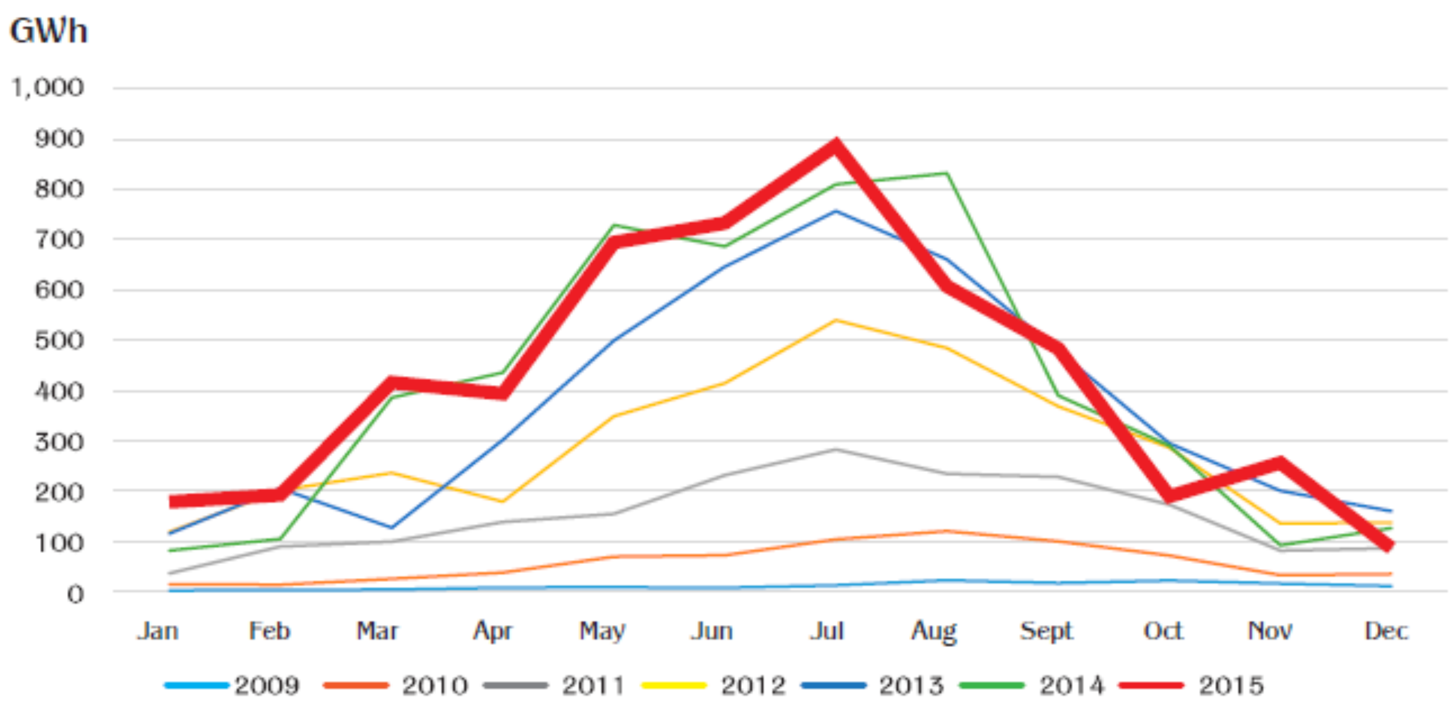
Annual production and demand share in Spain



2.4. Solar thermal power plants

Solar thermal electricity (STE) worldwide and Spain

Annual electricity production from solar thermal power plants in Spain over 12 months from 2009 to 2015



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