Solar thermal power plants

Utilising concentrated sunlight for generating energy
Straight to the point

The annual solar irradiation on the earth provides more than 8,000 times the world’s energy requirements. Mathematically speaking, about 1% of the surface area of the Sahara Desert is sufficient in order to meet the world’s electricity requirements with solar thermal power plants.

A solar thermal power plant was already constructed close to Cairo at the beginning of the 20th century. Using parabolic mirrors, the power plant captured and concentrated solar energy and used it to heat oil for boiling water. This in turn was used to drive steam turbines and produce electricity.

The PS10 solar tower power plant, which is located near Seville in the Andalusia region of Spain, has been providing about 11 MW of power since 2007, as has the Nevada Solar One 64-MW plant in Nevada in the United States. The Andasol I-III complex, which consists of three 50-MW power plants located in the Spanish province of Granada, went on line two years later. The market was developing very rapidly at this time, but has now slowed down considerably in comparison with a few years ago. Although the German research facilities and companies in the field of solar thermal power generation belong to the world’s best, they are currently in a difficult environment. High investment costs, the associated financial restrictions and political instability, such as in the MENA region (Middle East & North Africa), are just some of the reasons for this. Above all there is considerable competition with photovoltaics, since it is the price development that contributes to competitiveness. This means that it often takes considerably time for power plant projects to be implemented.

On the other hand, a positive trend can also be seen, with new markets about to be tapped. 2.5 GW of solar thermal capacity is currently in operation and about 1.5 GW is currently under construction.

The export-oriented key components developed in Germany, such as absorbers, collectors and mirrors, are being installed on a large scale in solar thermal power plants throughout the world. In addition, the news from Ouarzazate in Morocco shows that the expansion of solar thermal power plants is well under way. After all, they have long become standard practice.

This Themeninfo brochure examines the basics of solar thermal plants, their technical components and their application potential, and shows examples from practice.

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The market prepares itself

The sun provides copious amounts of energy. It has the potential to meet the needs of the entire population of the earth. According to the International Energy Agency, the worldwide installed capacity for solar thermal power plants will triple from 4 to 12 GW by 2020. The challenge is to utilise this climate-neutral energy in an efficient and cost-effective manner.

On the edge of the Sahara Desert near the southern Moroccan town of Ouarzazate, Morocco is planning to build its very first solar thermal parabolic trough power plant, which will also be the largest of its kind in the country. The planning has been completed, the funding is in place and the first groundbreaking ceremony is about to take place. Once the second construction phase has been completed, the plant in Ouarzazate is intended to provide up to 500 MW. The State Moroccan Energy Agency wants to take the first step in providing climate-friendly electricity supplies.

The technology of parabolic trough power plants has already proven itself with solar thermal power plants in the U.S. and Spain. Using giant parabolic mirrors, sunrays are concentrated on an absorber tube through which a heat transfer medium flows, which is mostly thermal oil. This is then fed into a power plant block where water is evaporated and, via steam turbines, used to generate electrical energy. Although the technology has already proven itself and is implemented on a commercial scale, intensive energy research is still being conducted in order to optimise the components and concepts.

This BINE-Themeninfo brochure presents the four main research areas for solar thermal power plants:

- Parabolic trough collector technology
- Fresnel systems
- Tower power plants
- Tests and quality assurance

More than 95% of the commercially operated solar thermal power plants are parabolic trough systems. It is intended to further reduce their costs by enhancing the collector design and by automating the operation and maintenance. The thermal oil that has been used until now as the heat transfer medium is considered to be problematic. It is aquatoxic and, should there be a leak in the pipeline system, it could seep into the groundwater and cause serious ecological damage. For this reason, it is intended to develop alternative heat transfer media to market readiness.

An alternative parabolic trough technology is provided by Fresnel systems, which currently operate with a worldwide capacity of about 45.5 MW. The research is currently focussing on components for parabolic trough, Fresnel and tower power plants in order to improve their economic efficiency. Research is also being conducted on receivers for tower power plants that enable both greater operating temperatures and more efficient power plant processes. Research projects are further developing and testing the concept of tower power plants with volumetric air receivers and the necessary components. An overarching theme is provided by storage systems, which will also make it possible to use the heat at night and produce electricity capable of meeting base loads.

The quality of components and systems in solar thermal power plants is a decisive criterion in achieving greater efficiencies and reducing costs. Researchers are therefore working on suitable measurement methods and devices in order to measure the quality and subsequently improve the weak points.
In solar thermal power plants, concentrating collectors are used to prepare high-temperature heat for the power plant block. This can supplement or completely replace fossil-fuel operation. Optical systems only concentrate direct solar radiation and have to track the sun in order to achieve a sufficient concentration. This technology is particularly used in large, central plants around the earth’s sun belt. The sunlight is concentrated by mirrors that bundle the light onto a heat exchanger, which transfers the absorbed energy to a heat transfer fluid.

A whole range of different concepts are currently available, where the heat transfer medium is either directly used in the power plant circuit, for example water vapour, or is first of all circulated in a secondary circuit (e.g. thermal oil). Current concepts are based on the experience garnered from the first systems to have enjoyed large-scale commercial success, which were built in the U.S. during the mid-1980s. However, it is only since 2007 that larger commercial market introductions have taken place in Spain and the United States.

About 2.5 GW of solar thermal capacity is currently in operation and about 1.5 GW is currently under construction. Further markets are currently developing, particularly in the MENA region (Middle East and North Africa) and in South Africa, India and China. Solar thermal power plants are also playing an important role as part of the DESERTEC concept. Here it is envisaged that by 2050 an integrated European-North African electricity network will provide substantial economic and socio-economic benefits as compared to a separate supply structure, and will also contribute to cost-effective and sustainable electricity supplies to Europe and Germany.

Line or point focus mirrors

Solar thermal power plants can be distinguished according to the arrangement of their concentrator mirrors (Fig. 3): line focus systems, such as parabolic trough or linear Fresnel systems, have to track the sun along a single axis in order to focus the sun’s rays onto an absorber tube. In practice it is possible to concentrate the sunlight by about 100 times. Point focus systems such as tower power plants use a large number of individually tracking heliostats in order to focus the sunlight onto a single receiver on the top of a central tower. These can concentrate the incident radiation from the sun by more than 1,000 times. However, to achieve this they require dual-axis tracking for the mirrors.

According to the laws of thermodynamics, the higher the temperature at which the collected heat is provided, the more effectively it can be transformed into mechanical work. On the other hand, the efficiency of the receiver sinks with increasing temperature owing to the greater heat losses. This is why every system has an optimum operating temperature at which the most favourable ratio of solar radiation to emission is achieved. With increasing concentration, greater efficiencies are achieved with greater optimum operating temperatures.

Thermally storing energy

Solar thermal power plants have the major advantage that they can integrate thermal energy storage systems (for example, storage tanks with hot, molten salt), which enable the plants to continue operating when clouds...
Fig. 3 The table shows the line and point focus systems used for solar thermal power plants. Source: DLR

**Transforming heat**

At the moment the collected thermal energy is predominantly transformed into electricity in steam power plants. These are suitable for capacity sizes from 10 MW upwards and for temperatures of up to about 600 °C, and can be coupled with parabolic trough, linear Fresnel and solar tower systems. Stirling engines are suitable for smaller capacities up to several tens of kilowatts, which are typical for dish concentrators. Gas turbines are available in a broad capacity range and are also capable of exploiting considerably higher temperatures up to 1,200 °C. With large capacities they can be coupled with steam processes to form so-called combined cycle power plants and, due to their high efficiency, generate the same output with a 25 % smaller collector surface area than conventional steam power plants. However, until now gas turbines have only been operated with solar energy in experimental systems.

**Consumption and costs**

As with all steam power plants, solar thermal power plants with steam circuits require water for the operation, mainly for efficiently cooling the circuit. Since water is a scarce commodity in the regions where the technology is deployed, the consumption can be reduced from about 3.6 to 0.25 l/kWh if the ambient air is used for cooling. However, this increases the investment costs and lowers the efficiency of the plants, which means that the electricity generation costs increase by about 3 to 7.5 %. As an alternative, seawater cooling or the operation of seawater desalination plants is possible for plants near the ocean. In the last five years, the electricity generation costs for solar thermal power plants have fallen by about one third to around 14 to 18 eurocents/kWh and, according to the European industry association ESTELA, have the potential to undercut the 10 eurocent mark during the next ten years. Compared with fluctuating electricity from wind and PV systems, the added value for the improved supply security for the grid operation achieved through energy storage systems currently amounts to 3 eurocents/kWh in some networks. This value will continue to increase in future along with the greater proportion of fluctuating energy in the grid.

The three main drivers lowering costs are the up-scaling to larger units, mass production of components and technological innovations. The latter are aimed at increasing the efficiency of power plants with greater operating temperatures, optimising the optical design as well as lowering the component costs, the need for water and the self-consumption of electricity.
Parabolic trough collector technology

More than 95 % of the commercially operated solar thermal power plants are parabolic trough systems. Researchers are working on further reducing their costs by enhancing the collector design and automating the operation and maintenance. In order to replace thermal oil as the heat transfer medium, alternative heat transfer media are being investigated, including water vapour and molten salts.

Parabolic trough collectors are assembled from three main functional units: the concentrator, a mirrored trough with a parabolic-shaped cross-section, uses a tracking device to track the course of the sun so that the incident radiation is concentrated along the focal line on the absorber tube or receiver tube. The collectors are normally aligned in a north-south orientation so that shortly after sunrise the light from the low-lying sun in the east is almost vertically incident on the parabolic opening, the so-called aperture. During the course of the day the sun (in the northern hemisphere) moves southwards and its light falls at an increasingly oblique angle on the collector (Fig. 6). The sunrays continue to focus through the tracking parabolic aperture onto the absorber tube but are reflected back across a longer distance. The inclined incident sunlight causes the radiation energy captured per unit area to be correspondingly reduced relative to the cosine of the incident angle (cosine effect, Fig. 5). In addition, the inclined reflected sunrays on the north end of the collector miss the absorber tube; this is known as end loss. In order to reduce the relative proportion of these end losses, the parabolic troughs are constructed to be as long as possible. Because the solar radiation during the mornings and evenings is weakened relative to midday as a result of the longer path through the atmosphere, on a cloudless day the usable energy per collector surface is fairly evenly spread across the day.

Highly concentrated

The most important properties for an efficient concentrator are a highly specular reflectance for light of all wavelengths in the solar spectrum as well as a precise parabolic shape. Specular reflectance means that as many rays as possible are reflected according to the “angle of incidence equals the angle of reflection” law and as few rays as possible are absorbed or scattered. Deviations in the parabolic shape cause the radiation to “miss” the absorber tube.

Tracking the sun

Only radiation that is vertically incident to the optical axis is concentrated on the focal point. This is why the concentrator has to continually track the path of the sun. Hydraulic drive systems are predominantly used for this purpose; smaller collectors also use electric motors. The drive systems are controlled either with sensors that determine the position of the collectors relative to
the sun’s elevation, or by numerically calculating the sun’s elevation and the position sensors for the collectors, or by using a combination of both.

The absorber tube

In the absorber tube the concentrated solar radiation is transformed into heat and transferred to the heat transfer medium flowing inside. The steel tube is coated with an optically selective coating that maintains high absorbance in the solar spectrum wavelength range but high reflectance in the infrared spectrum, i.e. it emits as little as possible. These days, absorption rates of 96% and emission rates of just 9% are achieved. In order to prevent heat losses to the ambient air, the absorber tube is surrounded by an evacuated glass envelope tube (Fig. 14). The different heat expansion in the glass and metal tube during operation, with temperatures of up to 500°C, is balanced out using metal bellows at the tube ends. Low-iron glass and anti-reflective coatings ensure that the concentrated radiation can penetrate through the glass tube and strike the absorber coating with as little loss as possible, whereby 96% transmission rates are achieved.

The collector system

Parabolic trough collectors have a modular structure. The concentrator collectors are mounted in rows on supporting pylons and are connected with one another so that they are torsionally stiff. Since the capturable solar power is proportional to the concentrator surface area, the collector structure is aimed at using as few components as possible, which include drive systems, moveable tube connections on the collector ends and absorber tubes. An extension of the collector length increases the surface area per drive system but requires torsionally stiff structures (Fig. 9 – 11) to transfer the superimposed weight and wind forces from the modules to the drive unit without causing performance-reducing deformations to the concentrator. Increasing the aperture width enables the number of absorber tubes per unit area to be reduced. However, as the surface area increases, so does the wind load, which needs to be taken into account when designing the structures.

Archimedes’ death ray

Archimedes’ heat ray device belongs to the ancient myths dating back to antiquity. During the Siege of Syracuse in the third century BC, Archimedes allegedly set fire to the Roman naval fleet using mirrors. It is said that mirrors made of polished bronze or glass were used to concentrate sunlight onto ships in the Roman fleet. According to the legend, these burst into flames one after the other. Physical arguments that refute such a version of events include the necessary minimum size and focal length of such mirrors, the minimum temperature required to set wood alight (about 300°C) and the time required to constantly illuminate the piece of wood being burnt. Numerous experiments have been conducted to test the likelihood. For example, researchers at the Massachusetts Institute of Technology (MIT) and the University of Arizona set out to discover the truth behind this ancient myth. They constructed two different mirrors and attempted to set fire to an 80-year-old fishing boat. However, the experiment failed. The roughly 30-square-metre mirror provided by the MIT scientists only singed timbers on the ship located 50 metres away. It was only when the distance was reduced to 25 metres that a relatively small flame was created, which, however, quickly went out on its own accord. The mirror constructed by scientists from the Arizona Lunar and Planetary Laboratory generated neither fire nor smoke. A second attempt in 2006 in the US TV show “MythBusters” produced similar results that were deemed to be a failure.

En passant
Successful parabolic trough technology

Until now parabolic trough collectors have been the commercially most successful technology used for solar thermal power plants. Since the mid-1980s, parabolic trough power plants have been operated in California whose total capacities were expanded to 354 MW, by 1990. Parallel to the construction of these SEGS-type plants (Solar Electricity Generating Systems) with rated capacities of 14 MW (SEGS I), 30 MW (SEGS II – VII) and 80 MW (SEGS VIII and IX), the components and system concepts were continually further developed. This development came to a preliminary end as a result of the sinking gas prices and the corresponding loss in revenue. Although the existing power plants were still able to operate at a profit, it was not until 2007 that new plants were built, particularly in Spain and the United States. This was as a result of the increasing importance of climate protection and sustainable energy supplies and the underlying economic conditions that were correspondingly created.

Higher process temperature – greater efficiency

In addition to the aforementioned optimisation of the collector system, further potential is provided by transforming the heat collected in the collector array into electricity as efficiently as possible through increasing the upper process temperature for the conversion process. Since the operating temperature of the predominantly used thermal oil is limited to just under 400 °C for thermal stability reasons, other heat transfer media are being investigated for their suitability. The most progress has been made with developments concerned with the use of direct steam generation in the collector array and molten salt as the heat transfer medium. Both have specific advantages and challenges.

Solar direct steam generation

Direct steam generation enables not only the process temperature to be optimised but also saves on all components in the thermal oil circuit including the associated costs and efficiency losses. The technological challenge here is that the entire tube system needs to be designed for the high pressures of about 100 bar that are desired for turbine operation. The two-phase flow also presents particular challenges in terms of the controllability and thermo-mechanical loads. The heat injection first of all creates small steam bubbles (Fig. 12) that collect to form larger bubbles above the liquid phase. As a result of the larger specific volume of the steam, the expanding steam bubbles accelerate to form so-called water slugs.

Because the heat transfer between the tube wall and the steam phase is considerably worse than between the tube wall and the fluid, the tube temperature increases after this so-called dry-out point. This can cause considerable thermal stress to the tube, since the dry-out point can very rapidly shift with fluctuating solar radiation. The temperature distribution in the tube cross-section shown in Fig. 13 can occur in the morning or evening. There is a clear temperature difference between the outer heated and the inner unwetted tube surfaces and the unheated moist section opposite.

In order to utilise the advantages of direct steam generation and simultaneously avoid the risks caused by...
undesired operating conditions, various process concepts have been developed: a feature of the forced once-through process is its simple structure. The water fed into the collector string is preheated, completely evaporated and then superheated in one passage. With the recirculation concept, rather than evaporating the entire injected water, a water-steam mixture is fed into a pressure vessel and separated there by means of gravity. This concept is very robust but incurs higher costs as a result of the necessary pressure vessel, the recirculation pump and losses in the recirculation system.

The first commercial parabolic trough power plant that dispenses with thermal oil and generates the steam directly in the absorber tubes commenced operation in Kanchanaburi (Thailand) at the end of 2011. The plant, which has a rated capacity of 5 MW, works at 30 bar and 330 °C. It is planned to increase both the plant size and the fresh steam parameters in already planned follow-up projects. The aerial view of the plant (Fig. 4) clearly shows the division of a larger sub-array for pre-heating and steam generation and a smaller superheater array.

Because cheap steam storage systems are not yet available, solar direct steam generation is initially most suitable for smaller systems or hybrid power plants that combine solar and fossil energy. The ability to adapt the steam conditions to the respective feed-in point enables the proportion of solar energy to be increased when integrated with combined cycle power plants. Concepts are also being developed for saving fuel and correspondingly avoiding CO₂ emissions in coal-fired power plants by integrating solar steam generation.

Molten salt as a heat transfer medium

Molten salt has already proved itself as a storage medium on a commercial scale. The use of similar salts as a heat transfer medium not only leads to considerable savings in the plant technology but also allows the operating temperature to be increased relative to thermal oil. This enables greater process efficiencies and higher storage capacities for the same storage volume.

The most commonly used salt is a mixture of sodium and potassium nitrate. It has a melting point of 238 °C.

In periods without irradiation, special precautions are therefore necessary in order to prevent the salt from freezing. The simplest measure is to permanently recirculate warm salt in order to keep the plant at the right temperature. This incurs corresponding heat losses. For this reason research is being conducted on developing salt mixtures with melting points that are as low as possible. Here it also needs to be ensured that these mixtures remain stable at high temperatures, are not corrosive and are cheap. Nitrate salt mixtures with three or more components look highly promising. Chloride mixtures are also being investigated, but these implicate increased corrosion problems.

Everything in a tube

As part of the “Once-through Concept – Development and Testing” project (DUKE), the existing DISS (Direct Solar Steam) test facility on the Plataforma Solar de Almería has been extended to 1000 metres and equipped with additional measurement technology. Steam is directly generated in the receiver tubes within the parabolic troughs for producing electricity. This allows higher temperatures and saves on plant components and intermediate stages.
In July 2010, ENEL and Archimede Solar launched the first application of this technology at the power plant scale in Priolo Gargallo in Sicily. The collector array has a collector surface area of about 30,000 m² and heats the molten salt to 550 °C. The steam generated with the hot molten salt is fed into the steam circuit belonging to ENEL’s neighbouring combined cycle power plant and contributes about 5 MW to the electricity generation. System studies show that there are particular economic advantages for plants with molten salt with large rated capacities (> 150 MW) and storage systems with capacities of 10 to 12 full-load hours.

Storage concepts

Heat storage systems have two main tasks in solar thermal power plants: on the one hand, relatively small storage systems can be used to balance out fluctuating irradiation and facilitate stable plant operation; on the other hand, large storage systems can extend the operating time of power plant blocks beyond the periods when there is irradiation or enable them to be completely decoupled. The storage size is often specified in full-load hours: that is the number of hours in which the power plant could be operated at full power solely from the storage system. Buffer storage systems typically have a capacity of ½ to 1 full-load hour, whereas large storage systems with 8 to 12 full-load hours enable power plant operation around the clock.

Commonly used are storage systems in which molten salt from a “cold” tank (about 290 °C) is heated to around 390 °C in a heat exchanger using heating oil from the solar array and then stored in a hot tank. The storage capacity depends on the temperature difference between hot and cold, the volume of the tank and the so-called specific thermal capacity of the storage medium. This is the thermal volume that a kilogram of the storage medium can absorb per degree increase in temperature. Since the storage costs are substantially determined by the volume of the storage material, storage media that are as cheap as possible and with a high thermal capacity are used, whereby the temperature difference between the charged and discharged conditions should be as high as possible.

With steam generation, a large proportion of the heat is required at a constant temperature for the phase change from liquid water to steam. That is why a storage system is desirable here which can also absorb and release heat at a constant temperature level. This property is provided by latent heat storage systems that use energy released in the phase change from liquid to solid. Such storage systems are charged using condensing steam. The released heat is transferred to the solid salt and begins to melt this. In the charged condition, the entire salt in the storage system is liquid (Fig. 17). To discharge the system, water is injected which extracts the heat from the molten salt so that this gradually hardens while the water evaporates. A considerable challenge when designing such storage systems is the fact that the hardening salt forms a crust on the evaporation tube that conducts heat poorly and so hinders an efficient discharge.
Current power

Current power plant concepts

The current state of technology is represented by the Andasol-type plants constructed in Spain (Fig. 19, above) with a capacity of 50 MW, and integrated thermal storage tanks providing about 8 full-load hours. Here steel structures with parabolic glass mirrors form concentrator modules with an aperture width of about 5.8 metres and a length of 12 metres, which are combined together to form 150-metre-long collectors. The absorber tubes have a selectively coated surface and are surrounded by an evacuated glass envelope tube. Thermal oil is used as the heat transfer medium and more cost-effective molten salt is deployed in the thermal storage tank. 18 plants using this technology, each with collector surface areas of approximately 500,000 m², are already connected to the grid in Spain. In addition, there are also another 22 plants without storage systems, which have correspondingly smaller collector arrays (each approximately 350,000 m²). Six plants are currently under construction so that about 2.3 GW of parabolic trough-produced electricity will be available in Spain by the end of 2013. A solar-hybrid power plant concept in which the fossil fuel is used as efficiently as possible is provided by combining a parabolic trough plant with a combined cycle power plant (CCPP). The additional steam generated by the solar plant is fed into the steam circuit for the CCPP with a solar portion) and the Martin Next Generation Solar Energy Center in Florida (total capacity of 3,780 MW with a 75 MW solar portion). There are also plans for sites in Mexico and India.

If you consider the enormous technical progress made by the CSP industry in the last five years alone, then it’s not difficult to predict that solar thermal power plants will increase their share of the electricity provision around the Mediterranean during the next 15 years. They play an important role in the renewable energy mix and thus offer enormous potential. The electricity that solar thermal power plants generate can be easily controlled and stored, and can therefore be adapted to meet the load profiles. This is highly significant for the poorly developed supply networks in North Africa. The industry will continue to invest in research & development in order to make the generation of CSP electricity even more economic. At the same time, the new power plant projects in the operator countries will help them develop their own industries and thus contribute to the economic growth in the regions.

Fig. 19 Comparison of Andasol and molten salt plants: In the upper case the heat from the thermal oil is transferred to the salt (green) for storage, in the other case the salt itself is used as the heat transfer medium in the collector circuit.

Source: DLR

In portrait

What role will solar thermal power plants play in 15 years?

Prof. Dr. Robert Pitz-Paal
Institute Director
at the Institute of Solar Research, DLR

Niels Bohr was certainly right when he said: “Prediction is very difficult, especially about the future.” Therefore I would prefer to explain the role that solar thermal power plants could play: more than 50 GW of solar thermal power plant capacity with storage technology could be implemented by 2028 that also ensure secure electricity provision in the evening hours and balance out the fluctuations from wind and PV electricity. The prices have dropped to such a level that a massive expansion of this technology is possible without comprehensive subsidies. This will therefore also make climate protection more economically attractive. Companies are involved as partners in the value creation and there are numerous collaborations with German companies and research institutes. This will only happen, however, if targeted investments are made today in such developments. To achieve this, substantial, long-term financial incentives are required now that set a clear signal to business.

Dr. Nikolaus Benz
Managing Director of SCHOTT Solar CSP GmbH

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Fresnel – The tilting linear system

An alternative parabolic trough technology is provided by Fresnel systems, which currently operate with a worldwide capacity of about 45.5 MW. The production costs are less than for parabolic troughs. The weaker concentration of the solar radiation means that Fresnel collectors have higher optical losses, which reduces the efficiency.

Fresnel collectors are linear-concentrating systems with receivers which, in contrast to parabolic trough plants, do not track the sun. Instead, the near-ground mirror segments – the primary mirrors – tilt about their north-south axis during the course of the day and concentrate the solar radiation onto the receivers fixed above them (Fig. 22). Depending on the design, the primary mirrors are flat or slightly curved and precisely track the sun using a motor or cable drive. Glass mirrors are normally used as the mirror material. They are fixed to a metal structure. The receiver is situated along the focal line and often consists of a metal tube that extends along the entire collector string. The tube is coated with a selective absorber coating to keep the conversion losses as low as possible. A secondary reflector is fixed above the absorber tube. It reflects back the radiation that does not directly strike the absorber. To minimise the absorber’s heat losses, the receiver is typically enclosed with a glass pane beneath the absorber so that the radiation from the primary mirrors can pass through unhindered while enabling the absorber to be protected from wind influences.

Cost-effective concept

Fresnel collectors can be manufactured more cheaply than parabolic trough collectors. Because the primary mirrors are fixed to the ground, they are easily accessible for repair and cleaning work and do not require such a complex mechanical structure as a result of the reduced wind forces. In addition, the collector array can have more modular parts and no or very little curvature of the glass mirrors is necessary. The foundations also do not have to absorb as much loads and, depending on the size of the collectors, can even be replaced with cheap ground anchors. The receiver above the mirror array can be supported with simple steel sheet profiles and fixed in position with cable struts. The use of a secondary reflector makes it possible to deploy cheaper non-evacuated receivers. Because the receiver is stationary, a smaller number of expansion bends and flexible connection points are required (e.g. ball joints). Last but not least, the more compact structure means that the specific land use is less, which besides lower land acquisition costs also reduces the ground preparation work.

However, the simpler and cheaper structure also has disadvantages relative to parabolic trough collectors of the same size. The annual yield of a Fresnel collector is considerably less, being about 71% of a parabolic trough collector of the same size. The greater shading losses during the morning and evening hours mean that the Fresnel collectors supply power more irregularly, which leads to more frequent partial-load periods for the turbines. This is because the mirror segments partially shade one another when the sun is low in the sky, which means that fewer rays are reflected on the receiver. In addition, with parabolic trough collectors the mirror’s main axial plane coincides with the plane of the sun’s position and the receiver, whereas with Fresnel collectors the main axis of each individual primary mirror is always the angle bisector of the sun’s position and the receiver orientation. That causes greater cosine losses. Further additional losses are caused by the longer focal lengths and by absorption and scattering on the secondary reflector.

Fresnel collectors should not exceed about 70% of the specific costs of parabolic trough collectors in order to remain competitive despite the lower yields. This is deemed possible owing to the potentially cheaper structure.

Following development and tests of prototypes, the first larger demonstration plants are being constructed or are already in operation. Fresnel systems can in principle use the same heat transfer media as parabolic trough...
Constant steam temperature

In addition to the cost-effective manufacture of the plants, the largest technical challenges lie in the provision of constant steam parameters and in controlling the high temperatures of around 500 °C on the receiver (Fig. 21). The steam quality at the outlets of the collector strings can be ensured using a so-called “once-through” control concept for the steam mass flow, which by regulating the mass flow is able to take account of fluctuations in the radiation or the collector efficiency caused by changes in the sun’s position. Additional water can also be injected at the hot end of the solar array to control the steam parameters. It is also possible to stabilise the steam parameters by deploying short-term steam storage systems or using hybridisation, i.e. the targeted cofiring of fossil fuels. In addition to the once-through control concept, in which the heating, evaporation and superheating all take place in one string, it is also possible to regulate with a split solar array. The heating and evaporation of the water takes place in the first section. The liquid and steam portions of the saturated steam are then separated in a steam separator. While the liquid portion recirculates, the steam portion is fed into the second section, the superheater.

There are currently no commercial storage systems available for the direct steam generation concepts that can bridge periods of several hours when there are overcast skies and provide longer operation in the evening hours when the sun no longer shines but there is still a large demand for electricity. For this reason, so-called phase change storage systems are currently being developed.

The process temperatures of up to 500 °C striven for in Fresnel systems with pressures of up to 100 bar at the turbine require corresponding wall thickness for the absorber tube (pressures of up to 130 bar at the inlet to the solar field). Since the temperature difference between the outer and inner surface increases relative to thin-walled tubes, the selective absorber coating is additionally stressed. However, the tube is also radiated somewhat more evenly around its circumference, which compensate this effect. The secondary reflector surrounds the receiver tube without any additional cooling and has to be able to withstand temperatures of about 200 °C on a permanent basis.

Spain’s first commercial Fresnel power plant

Puerto Errado 2 (PE2), which has been built by the manufacturer Novatec Solar, is the first commercial solar thermal power plant based on Fresnel technology and has been running since August 2012. The power plant consists of two separate 15-MW, power plants, each with its own solar field, turbine and BOP (balance of plant) with a feedwater supply, pumps and cooling systems (condenser). If required, it is possible to couple together the two solar field to control one turbine. In winter and with poorer solar radiation levels, this enables the power plant operator to drive one turbine at full load instead of two turbines in partial-load operation. The basic principle behind the power plant can be seen in the schematic diagram. Water is pumped into the solar array via a freshwater pump. The water is then heated and subsequently evaporated in the solar array. Because the PE2 power plant uses a saturated steam system, there is no superheating. At a temperature of about 270 °C and a pressure of 55 bar, the saturated steam flows along with any residual water through the outlet of the solar field into a steam drum. Via a steam separator, the dry saturated steam is then fed into the turbine. There the steam expands and the thermal energy is converted into kinetic energy, which in turn is transformed into electrical energy by means of a generator. The expanded steam is condensed in an air-cooled condenser and then collected in a return tank. The water is then fed back into the circuit via a deaerator. The liquid portion of the saturated steam is removed with a recirculation pump in the steam drum and is then returned to the solar array.
Solar tower power plants belong to the point focus systems. A feature of these systems is that the direct solar radiation is concentrated on a single spot – the focal point. Considerably higher concentration factors can be achieved than with line focus systems, which means that the optimum operating temperature in the receiver can also be increased. This enables power plant processes to be coupled with better process parameters and thus greater efficiencies. This in turn leads to higher overall efficiencies when transforming solar radiation into electricity, resulting in potentially lower electricity generation costs.

In solar tower power plants (Fig. 24), numerous dual-axis tracking concentrator mirrors – the heliostats (Fig. 25) – reflect sunlight onto the top of a tower. This is where a central receiver is located that absorbs the concentrated solar radiation and converts it into high-temperature heat. A heat transfer medium removes the heat and transfers it directly to the power plant process or to a storage system. In solar tower systems, the radiation is concentrated by 500 to 1,000 times, which enables receiver temperatures of up to 1,200 °C to be achieved. Solar tower power plants differ in terms of the type of heat transfer medium, the receiver and the power plant process. Depending on the requirements, thermal storage systems are integrated into the power plant in order to adapt the electricity generation to the current electricity needs. By installing an auxiliary burner, the power plant can also be operated, if necessary, without solar thermal heat, which dispenses with the need to maintain expensive reserve capacities in the electricity grid.

**Heliostats bundle the sun**

The direct solar radiation is concentrated using many heliostats, which mostly have a slightly curved glass surface. Using a dual-axis drive operated by an array control system, this surface tracks the sun so that the reflected solar radiation is concentrated on the receiver. Current heliostats are between 1 and 140 m² in size. In order to achieve the desired radiation concentration, heliostats require mirror surfaces with a high optical quality and precise tracking. Heliostats use rotary or linear electrical drives to track the sun. Several new developments use hydraulic actuators. System deviations in the tracking movement can be minimised using suitable calibration methods. Current heliostats are controlled and supplied with energy for the tracking via cables; new developments are moving towards using radio-controlled heliostats with local energy supplied via small PV modules.
At the moment water/steam, liquid salt and air are principally used as the heat transfer medium. Whereas steam can be directly used in a steam turbine process for generating electricity, with liquid salt and air the heat is transferred to the power plant process via heat exchangers. The use of liquid metals or ceramic particles is currently being investigated for achieving higher temperatures as part of innovative solar tower concepts.

The receiver

The receiver transforms the highly concentrated solar radiation into high-temperature heat and transfers this to the heat transfer medium. The type of receiver substantially depends on the selected heat transfer medium. In tube receivers, the medium flows directly through radiated, black-coated absorber tubes made of high-temperature metal alloys. To achieve the required output (up to several 100 MW per receiver), many parallel tubes are compiled and connected together to form panels similar to the boilers in fossil-fuelled steam generators.

For air, volumetric absorbers are deployed that absorb the radiation in the volume of a highly porous ceramic structure and thus heat the air flowing through it. For example, the Jülich solar demonstration power plant deploys parallel channel monoliths made of silicon carbide that use the absorbed solar radiation to heat the air to 680 °C.

Storing the solar energy

Thermal storage systems can absorb the collected solar heat and release it at a later time to the power plant process largely without loss. The type of storage system depends on the heat transfer medium used. For steam systems, steam storage systems are available which, owing to their limited storage duration, are generally used to balance out interruptions caused by passing clouds. Storage systems for steam systems with longer storage durations are still undergoing development, whereby a combination of sensible and latent storage is favoured. Two tank systems are currently being used for liquid salt, which is heated by the solar energy to 565 °C, collected in a “hot” storage tank and from there pumped to the power plant process for generating electricity. The liquid salt that is cooled to 290 °C...
in this process is collected in a second salt tank and, if enough solar energy is available, is heated up again to 565 °C in the receiver.

For air systems, so-called regenerator storage systems are deployed that mostly use ceramic storage elements in the form of a packed bed (stacked or heaped up elements). To charge the system, air flows through the packed bed from top to bottom, whereby the heat is transferred from the air to the storage medium. To discharge the system, air flows through the storage system in the opposite direction and is correspondingly heated up.

The power plant process

Current solar tower power plants deploy steam processes to generate electricity. Depending on the system and heat transfer medium, these steam processes currently achieve a thermal efficiency of about 42%. In the medium term researchers are endeavouring to increase the steam temperature even further by increasing the receiver temperature. The efficiency advantage offered by steam power plant technology can be used for further reducing the solar generation costs, as is already deployed in coal-fired power plants (600 to 620 °C). An alternative is provided by highly efficient solar-heated gas turbine systems which, as CCPP or recuperative gas turbine systems, can also achieve thermal efficiencies greater than 45%. In Spain, a demonstration power plant with solar-supported gas turbines began operation in 2012. Based on a 4.6-MW gas turbine, the receiver is situated between the compressor and the combustion chamber for the gas turbine. The tube receivers utilised can preheat the air to temperatures of up to 800 °C; additional combustion heats the air further to the nominal turbine input temperature of 1,160 °C.

Prospects

Solar tower technology is only just beginning to appear on the market. The capacities range from small-scale units with 100 kW, to large-scale power plants with several hundred megawatts of capacity. The first commercial plants with a total capacity of about 50 MW are already in operation while further solar tower power plants with a total capacity of almost 500 MW are under construction. Their further development is focussing on the one hand on reducing the investment costs by mass-producing and standardising the components and on the other on improving the components and subsystems to increase efficiency. In order to increase the overall efficiency, it is intended to increase the process temperatures and enhance the plant control system.
Tests and quality assurance

The quality of components and systems in solar thermal power plants is a decisive criterion in achieving greater efficiencies and reducing costs, whereby the focus is on developing suitable measurement methods and devices to identify weak points and subsequently improve them.

Quality assurance with suitable test and qualification methods is necessary before introducing new materials and components to the market or optimising the operation of complete plants. This is concerned not just with the corresponding instruments, test stands and measurement procedures but also with long-term aspects such as the ageing of components, which needs to be tested under realistic operating conditions. With the market introduction of solar thermal power plants, the importance of this area is increasing. Concentrator mirrors play a key role in using the technology efficiently. An important parameter for their measurement is the solar-weighted, specular reflection. This indicates which proportion of the incident radiation within a specific spatial angle is reflected and thus determines how much radiation strikes the receiver. The reflection is weighted with the actual solar spectrum in order to only incorporate the usable portion of the light.

The aim is to maintain a reflection that is as high and as long as possible. There are various types of mirror materials, whereby glass mirrors have proved to be particularly suitable. There are currently two groups of materials that provide an alternative to conventional glass mirrors: aluminium mirrors and films. The former consist of anodised aluminium sheets on which reflection-enhancing and protective coatings are applied. With the films, the coatings are applied to a very thin polymer layer. Both types look as if they can be produced more cheaply, more easily installed and deployed more flexibly.

Changes in the concentrator structure and new developments require that the quality of the concentrators is tested for long-term external use. For this purpose both extended weathering tests and accelerated ageing tests are conducted. Here environmental influences (for example, the temperature, humidity, UV radiation and pollution) are generally heightened in order to accelerate the naturally occurring degradation. The materials have to pass these tests for a specified duration without degrading too much. Degradation mechanisms include corrosion phenomena as well as surface changes (abrasion, soiling).

Tested quality

Since concentrating solar collectors are designed to reflect the incident solar radiation onto a receiver, it is not just the proportion of the reflected radiation that is significant (determined by the specular reflection) but also the direction of the reflected radiation. The latter is achieved by maintaining the ideal mirror shape and slope.

A deflectometry-based optical measurement process is used to precisely measure them. For this purpose a series of striped patterns are projected onto a flat target, the patterns reflected and deformed by the mirror are then photographed with a camera, and the deviations to the ideal mirror slope calculated. The process enables the measurement and assessment of individual mirrors of any geometry in the laboratory, during the mirror production and later in the solar array.

Current research activities are aimed at standardising the measurement boundary conditions (for example, orientation of the mirror in the test setup, mounting structure being used), transferring the laboratory findings to the installed condition and maintaining the correct
mirror shape at different operating points. For this purpose finite element models are being developed and the individual influencing factors investigated.

In order to ensure the quality of solar thermal power plants it is necessary not only to carry out quality testing on individual components but also quality assurance when assembling the collectors, the solar array and the entire power plant. In this regard, production-integrated measurement and qualification methods are generally preferable to field measurement procedures owing to their ability to directly and immediately influence the production parameters. However, the collector size means that not all qualification measures can be conducted in the production hall. For this reason, measurement procedures are also required for already built solar arrays. Field measurement procedures are also used for acceptance measurements when commissioning solar arrays or for conducting targeted maintenance work after several years of operation.

The more solar radiation strikes the receiver, the more radiation energy is collected by the collector system. If this maximisation of the so-called intercept factor is

Collector qualification from the air

Air-based measurement systems help when optically examining entire solar arrays. QFly (Fig. 34) is a measurement system consisting of a flying drone that can carry either a CCD or infrared camera. Depending on the assignment, QFly flies over the solar array using different routes and takes photographs in the visible or infrared range of the spectrum. Based on the images in the visible spectral range, the accuracy of the mirror surface can be determined using deflectometric methods (Fig. 35). To supplement this, photogrammetric methods are used to detect, among others, deviations of the absorber tube from the focal line. This in turn enables deformations in the structure to be identified. This data also enables the optical efficiency of the entire plant to be determined using ray tracing.

The infrared images can be used to determine the surface temperature of the glass envelope tubes in the absorbers. Even with a 400 °C operating temperature, these envelope tubes are in the ideal case only “hand warm” thanks to the selective coating and the vacuum inside. With defective absorbers the envelope tube temperature increases, which can then be identified in the IR images.
achieved without increasing the material used, the power plant can generate cheaper electrical energy.

Measuring mirror shapes

Curved mirror facets are frequently combined together on a supporting structure in order to form, for example, line focus parabolic trough plants or point focus heliostats for tower power plants. The mirror shape should be measured when developing prototype mirror facets and during the manufacturing process. When mounting the mirror facets, it must be ensured that the facets are correctly oriented on the mounting structure. In addition, the mounting structure must meet the geometrical requirements. Photogrammetric measurement methods are frequently used (Fig. 33) for measuring the shape and the deformation under, for example, gravitational influence. For this purpose markers are fixed to the collector structure being investigated and these are then photographed from different angles. Using these two-dimensional digital photos, photogrammetric software can then reconstruct the three-dimensional geometry and check whether the geometry of the collector structure lies within its tolerance.

Deflectometric measurement procedures are used to measure deviations in the mirror slope or shape relative to its target value. For this purpose a series of striped patterns reflected on the mirror surface (Fig. 35) are photographed with a camera and evaluated. With solar tower plants, the photograph can be made from a central point at tower height. With parabolic trough plants there is no central point but a focal length in which the receiver tube is installed. The reflex of this tube can be photographed on the parabolic trough mirrors and the data processed, whereby the camera can be fixed to the ground or moved across the solar array using a flying platform (Infobox QFly). With the QFly measurement system, photogrammetric and deflectometric techniques are used in combination with automatic image processing and evaluation.

Collectors on the test stand

The performance capability of receivers in parabolic trough plants is described by two properties: the optical efficiency and the thermal losses. These properties are measured in non-destructive tests on laboratory test stands in the DLR’s Quarz Centre (Fig. 37). To measure thermal losses, the receiver is heated to different operating temperatures. Based on the heat output it is then possible to determine the thermal losses at these temperatures. To assess the optical efficiency, the receiver is radiated in a solar simulator. The absorbed output is determined by means of the heated water flowing through it, i.e. calorimetrically. A particular challenge here is to achieve the necessary measurement accuracy of, at best, less than one per cent. In addition to having a high performance capability, sufficient durability is also required to prevent having to replace receivers installed throughout the solar array at a later date. To test the durability of the absorber layer, the receivers undergo accelerated ageing by overheating them across several weeks and then subsequently measuring their optical and thermal properties again.

The Kontas test stand (Fig. 38) was constructed in 2010 on the Plataforma Solar de Almería (PSA) to enable entire collector modules to be tested. It is located on a swivel platform on which parabolic trough collectors with a length of up to 20 metres can be installed. The test stand makes it possible to qualify all collector components, ranging from metal structures, reflectors, receivers and flexible tube connections to entire collectors. The dual-axis tracking provides it with considerable flexibility in terms of the solar radiation’s angle of incidence on the test collector. The test stand is equipped with high-precision sensors that enable efficiency measurements with an uncertainty of ±2 %.
Regional and technical focuses

In contrast to photovoltaics (PV) and wind energy, solar thermal plants with storage systems do not generate any fluctuating electricity. The deployment of solar thermal systems with storage systems can even enable more PV and wind energy to be fed into the grid. Due to the varying positions of the sun, this technology depends on the season, time of day and the cloud cover.

A considerable advantage of solar thermal energy over wind energy and photovoltaics is the ability to store the captured heat during periods with low electricity requirements in large concrete or salt thermal energy storage tanks installed directly on the power plant site. These enormous storage tanks therefore enable solar thermal power plants to balance out electricity fluctuations for several hours or even throughout the night. The use of such storage systems is already standard practice.

As with all renewable energies, solar thermal energy will also be increasingly expanded in future. In particular, solar thermal plants are being built and further developed in Spain and the United States. Cost-effective renewable electricity also provides the basis for sustainably supplying water in North African countries. The region requires its own provision of water almost more urgently than electricity. Solar thermal energy could therefore make sea water desalination, which is currently only operated in the oil-rich Gulf States, affordable in all countries in the Middle East and North Africa (MENA region), and in the long term this could also become an export factor for regional development.

Researchers particularly expect countries in North Africa to benefit from this and are observing an increasing proportion of local value creation from project to project: this means new jobs and less dependency on raw material imports. Many project concepts assume that there will be a gradual transfer of the technology and that a growing proportion of plant components can be built locally. As a result of the further expansion, solar and wind power may already become cheaper for many countries during the next ten years than importing oil and gas at world market prices.