Solar thermal power plants

Heat, electricity and fuels from concentrated solar power

Collector line at the Fresnel thermosolar power plant in Puerto Errado, Spain. Image: NOVATEC

Cover photo: Ouarzazate Noor I and II solar thermal power plant, Morocco. Image: SENER

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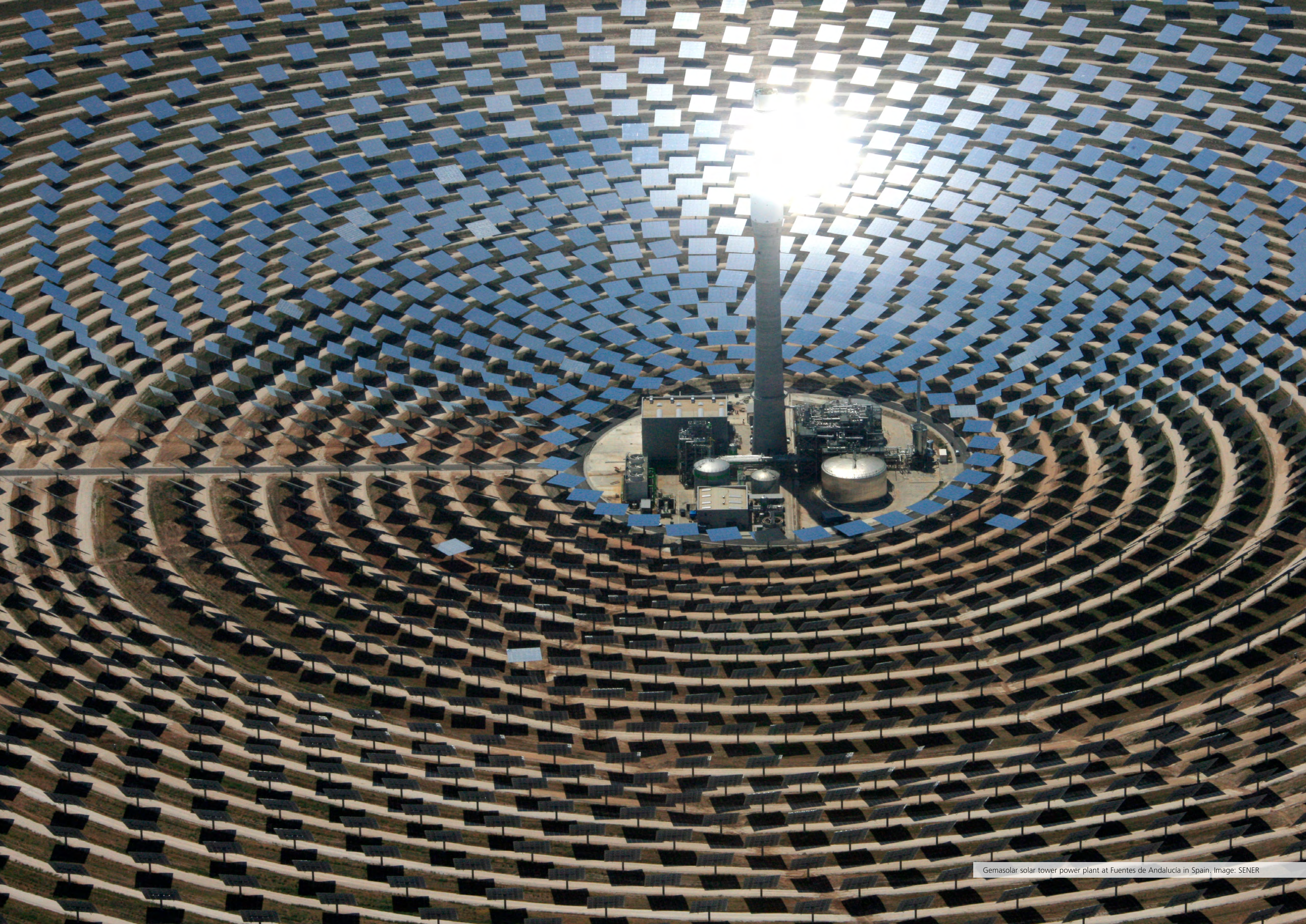


Gemasolar solar tower power plant at Fuentes de Andalucía in Spain. Image: SENER

Introduction

Background

Concentrating Solar Power (CSP) plants technology that is not yet widespread, and their relevance for the climate-neutral transformation of the global energy system is often underestimated. Growing proportions of fluctuating feed-in from renewable energy sources such as photovoltaics and wind into the power grid require, among other things, supplementation with controllable power plants in order to be able to provide the exact amount of electricity demanded at any given time. In energy systems in sunny countries that rely on renewable energy sources, solar thermal instead of fossil fuel power plants will be able to supply cost-effective base-load and peak-load electricity at low cost and stabilise the power grids.

With approximately six gigawatts of installed capacity worldwide in 2020, solar thermal power plants are still at the beginning of their market introduction, comparable to photovoltaics 15 years ago or wind energy 25 years ago. The potential to reduce costs through innovation, mass production and increasing competition in a growing market are therefore far from being exhausted. In addition to pure power generation, the technology can also be used to provide high-temperature process heat or to produce synthetic fuels and thus contribute to the decarbonisation of the industrial and transport sectors.

With its focus on export and great expertise in plant and mechanical engineering, German industry is well placed to become a leader in this technology field. However, small and medium-sized enterprises in particular often lack the financial strength to assert themselves against international competition in large-scale power plant projects.

This short study provides decision-makers in government and industry, as well as the interested public, with essential facts about the technology, effects and potential of solar thermal power plants. It is intended to be rapidly informative and act as an introduction to the subject.

Approach and methodology

The structure of the present study is based on frequently asked questions about different aspects of CSP technology. The focus is on solar thermal power plants for generating electricity. Other potential areas of application are only summarised – with references to separate studies. To answer the questions, both DLR's own work and external sources were evaluated. The short answers at the beginning summarise the most important statements. Readers are given a comprehensive overview of the questions and answers here. The individual aspects are dealt with in greater depth in the detailed answers.

Summary and recommendations for action

Due to their ability to generate electricity according to demand, solar thermal power plants are becoming increasingly important for a future, climate-neutral energy system. However, further measures are required to accelerate the spread of the technology:

- Development and demonstration of innovations to reduce costs, in particular by increasing efficiency, improving quality assurance and introducing digitally supported operational optimisation.
- Removal of innovation-inhibiting market barriers through the implementation of reference systems.
- Supporting medium-sized enterprises in securing project risks and building up production capacities.
- Entry into other areas of application such as heat supply and fuel generation by supporting demonstration projects.

The rapid expansion of the capacities of solar thermal power plants and the grid services available as a result will enable growing proportions of photovoltaic (PV) and wind energy in the future electricity mix.

Andasol 3 solar thermal power plant in the province of Granada, Spain. Image: Marquesado Solar

In brief:

Key facts about solar thermal power plants

1. How does a solar thermal power plant work?

Solar thermal power plants work like a conventional steam power plant in which the fuel is replaced by concentrated solar radiation. They use various systems of tracking mirrors to focus the sunlight. An integrated heat storage system enables demand-based electricity production regardless of fluctuations in the level of solar radiation that might occur over the course of the day. If necessary, a back-up heating system using fossil or regenerative fuels can also bridge longer periods of low solar radiation.

2. How can solar thermal power plants contribute to security of supply?

The largest increase in electricity generation from renewable energy sources today comes from wind power and photovoltaic systems. However, their feed into the power grid fluctuates with the available wind and solar radiation. There are currently no solutions for the economically viable storage of large amounts of electricity in order to compensate for these fluctuations. Solar thermal power plants store heat instead of electricity, a process that is currently approximately 80 to 90 percent cheaper. This enables solar power to be generated even when the Sun is not shining. They are even doubly protected against longer periods of darkness – if the thermal storage system is depleted, the steam process of the power plant can also be powered with other renewable or fossil fuels instead of solar heat.

3. What role do solar thermal power plants play in an energy system based on renewable energy sources?

The increasing expansion of photovoltaics in an energy system with predominantly renewable energy sources creates a systematic supply gap during the transition from daytime to night-time. In sunny countries, solar thermal power plants are suitable to fill this gap, as they can flexibly produce electricity at any time using their heat storage systems and by acting as hybrid power plants. Solar thermal power plants can replace fossil fuel power plants in their role as base load and peak load generators. For direct, decentralised power supply to industrial areas, smaller CSP systems are economically interesting if the industrial customers buy not only electricity but also process heat.

4. Are solar thermal power plants competitive?

In good locations, electricity from solar thermal power plants is already competitive with electricity generated using fossil fuels. PV and wind power are offered at lower costs but are only available when the sun is shining or the wind is blowing. With their integrated thermal storage systems, solar thermal power plants are the less expensive option for a reliable power supply in times of insufficient feed-in from energy sources reliant on sunlight and wind, which fluctuate over the course of the day. As the technology becomes more widespread, costs will decrease significantly.

5. How does the construction and operation of solar thermal power plants affect the environment?

Solar thermal power plants are characterised by very low environmental impacts. In particular, the greenhouse gas emissions over the entire life cycle are comparatively low. The land requirement roughly corresponds to that of large photovoltaic systems. In the power plant process of newer power plants, the use of dry cooling significantly reduces water consumption. The effects on the flora and fauna are minor and only very small amounts of pollutants need to be safely disposed of. In addition, solar thermal power plants have a long service life of up to 40 years.

6. What is needed for the operation of a solar thermal power plant in addition to solar radiation?

In addition to direct solar radiation, a CSP power plant requires a large area for the installation of the solar mirrors. Stone, rock and gravel deserts with little vegetation, as well as grasslands, scrubland and savannahs, for which there are practically no other economic uses and which are almost unlimited in the regions of the Sun Belt, are suitable for this. A low gradient, an existing grid infrastructure, the availability of water and a low risk of dangerous natural events are advantageous. Other decisive location factors are a low investment risk and favourable financing conditions for investors.

7. What skills are required to build and operate solar thermal power plants?

A solar power plant is a similar large-scale project to a conventional steam power plant. However, the planning and construction of the solar part with the mirror system and heat receiver and its connection to the steam cycle require specialist expertise. Only a few large companies in the world have this qualification and are able to take on the responsibility of being the prime contractor. They use inputs from construction companies, component and subsystem suppliers as well as engineering service providers. Due to the complex technology, the operation of the systems also requires specialist knowledge, operating experience and training.

8. What relevance does solar thermal power plant technology have for Germany?

To achieve its long-term climate protection goals, Germany will be dependent on energy imports. Potential electricity exporters are sunny countries where solar thermal power plants can provide controllable solar electricity. They could also produce green hydrogen and synthetic fuels. If the number of solar thermal power plant projects increases worldwide, this will create export opportunities for German companies and research institutions with a broad knowledge base about solar thermal power plant technologies. This secures and creates employment in Germany. Research and development activities in this area also act as a catalyst for start-ups. Concentrating solar systems can also be used directly in Germany – for example, to supply heat using renewable energy sources for district heating networks.

9. Where are the markets and what are the overall conditions?

Investments in solar thermal power plants are preferably made in locations with many hours of sunshine. Stable economic and political conditions are further positive factors for a possible location. Project development, planning and construction of the plants require not only technical expertise, but also stable protection for the necessary investments.

10. What are the socio-economic consequences of using this technology?

A special aspect of solar thermal power plants with regard to the socio-economic effects is their geographical location. Since they are mostly located away from metropolitan areas, they offer development prospects, especially in regions with a weak economic structure. In addition to direct and indirect jobs, this also creates induced employment effects.

11. Which factors support an accelerated proliferation of this technology?

For an accelerated proliferation, solar thermal power plants need long-term market stability and favourable financing conditions, as well as political support for the market launch. Increasing power plant construction and the associated cost reductions will also improve competitiveness. Increased research and development to improve individual components and systems will also help to reduce costs. The creation of internationally recognised quality standards for components and processes would also have a positive effect on the risk assessments conducted by banks and thus on the financing conditions.

12. How can this technology contribute to sector coupling?

Concentrating solar technologies have great potential to contribute to the decarbonisation of energy consuming sectors such as industry and transport. In the short term – even under Germany's climatic conditions – they can be used to supply heat for industrial processes up to approximately 400 °C and to supply district heating. High-temperature applications up to and in excess of 1000 °C for the production of hydrogen and other raw materials require good locations in Earth's Sun Belt and are still at a comparatively early stage of development.

13. How can technical innovations further reduce costs?

It is expected that the electricity production costs of baseload CSP systems can be halved to around five US cents per kilowatt-hour by 2030 with the help of technical innovations. More efficient power plant cycles and new types of heat transfer media will contribute to this. In addition, the investment costs for solar collectors can be reduced considerably through savings in series production and assembly logistics as well as through the improvement of optical quality and readjustment.

14. What contribution does DLR make to research and development work?

DLR has played a key role in the development of concentrating solar systems for solar thermal power plants for over 40 years. Since the beginning of the 2000s, it has supported the commercial market launch, particularly in Spain, through location analyses, collector development, feasibility studies, quality assurance measures and the training of personnel. Today, the high output of solar thermal power plants in most solar fields worldwide is based on technologies that were developed and marketed by DLR. In DLR energy research, more than 200 scientists from seven institutes are working in the research area of concentrating solar technologies. Together with industrial partners, they develop and test new technologies that further reduce the costs of solar-thermal energy.

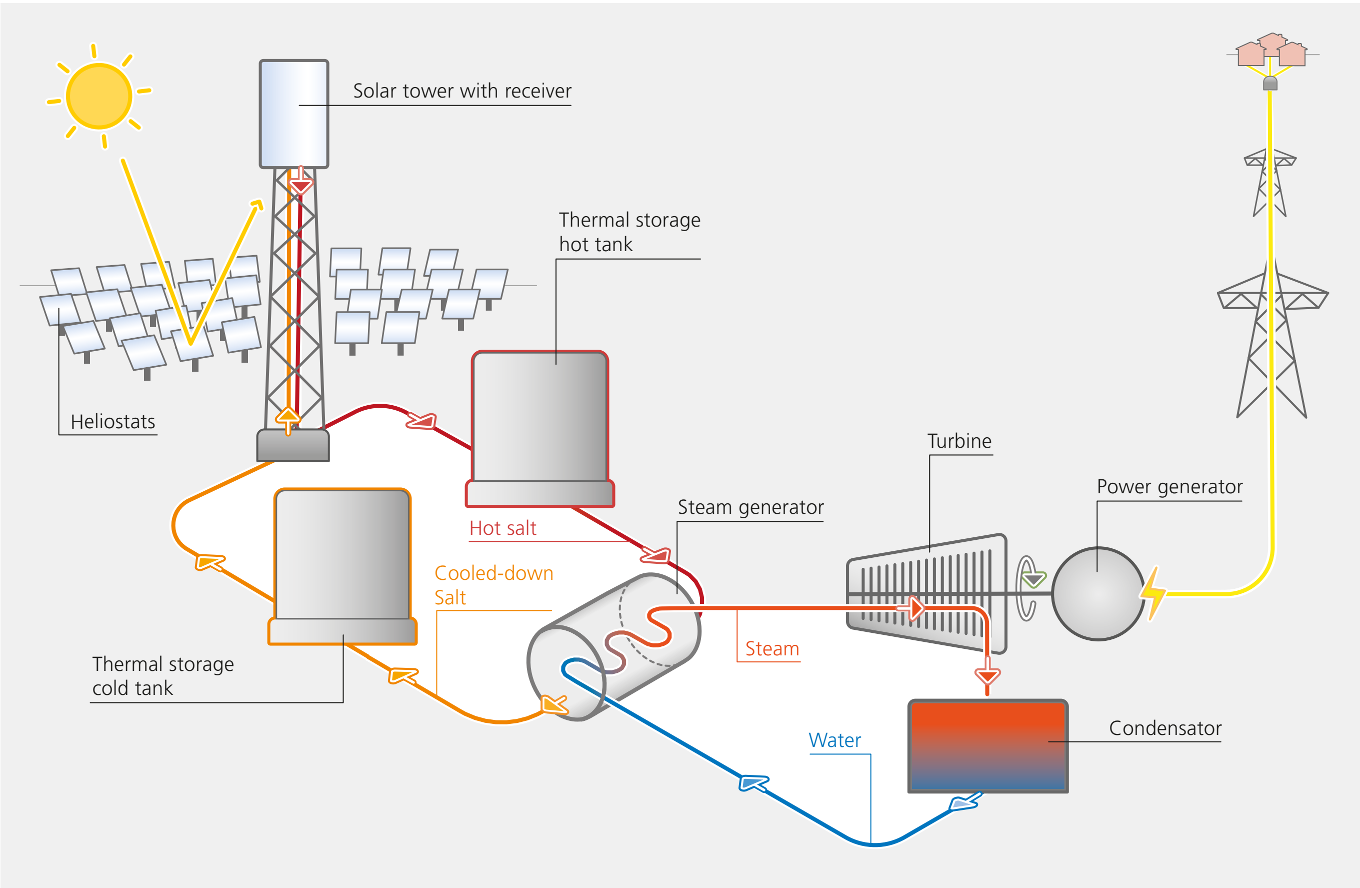
Answers to frequently asked questions about solar thermal power plants

1. How does a solar thermal power plant work?

Solar thermal power plants are also referred to as 'Concentrating Solar Power' (CSP) plants.

A solar thermal power plant uses mirrors to concentrate **direct sunlight** and convert this into **heat**. This is used to produce steam to operate a turbine, which in turn drives a generator that converts the kinetic energy into **electricity. Integrated heat storage systems** make it possible for the power plant to generate electricity exactly when it is needed, regardless of fluctuations in the intensity of the solar radiation over the course of the day. Longer periods of low irradiation can be bridged using fossil or regenerative fuels. Since steam turbines can only be operated economically above a certain minimum size, today's solar thermal power plants have rated outputs in the range of 50 to 200 megawatts. The main difference to a conventional steam power plant is the solar field, which supplies the heat for the steam generator.

In order to achieve the high temperatures required for steam generation, the solar radiation must be strongly concentrated. Only direct sunlight can be used for this. Mirrors that track the path of the Sun concentrate it onto a focal point or a focal line. The higher the concentration, the higher the temperatures that can be achieved. In accordance with the laws of thermodynamics, higher temperatures increase the efficiency of the power plant process. The higher the efficiency, the smaller the collector area the power plant needs to generate the desired electrical output. The technological challenge with the solar field is to achieve the required optical precision and simultaneous robustness against environmental influences such as wind and temperature fluctuations at the lowest possible cost. In practice, three different basic principles are used for the concentration of solar radiation: solar tower, parabolic trough and linear Fresnel systems



How a solar thermal power plant works, shown here for a solar tower power plant. Image: DLR

In a **solar tower power plant,** biaxially tracking mirrors, referred to as heliostats, direct the solar radiation onto a central receiver mounted on a tower. A heat transfer medium, usually molten salt or alternatively water / steam or air, absorbs the energy there and transports it to the thermal storage system and to the power plant circuit. The mirror surfaces of the individual heliostats can be up to 200 square metres in size. In commercial power plants, several thousand of them are aligned in a semicircle or in a circle around the solar tower. Their strong concentration of radiation can generate temperatures in excess of 1000 °C at the receiver. In practice, the systems are operated at between 300 °C to 700 °C, depending on the heat transfer medium being used.

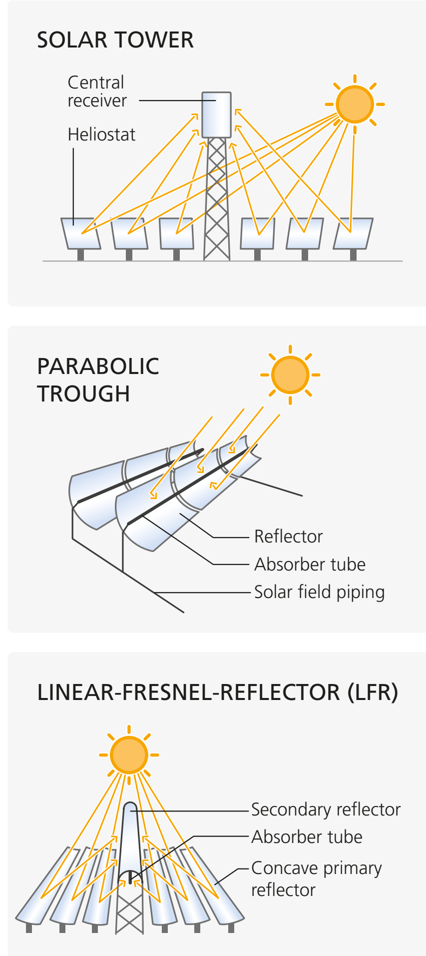
Parabolic trough power plants are the most common commercially implemented variant so far. Parabolically shaped mirror troughs track the sun uniaxially and focus the light on an absorber tube running along the focal line. The absorber tube contains a special thermal oil that absorbs the heat.

An optically selective coating on the tube absorbs the visible light and simultaneously inhibits the radiation of heat. The absorber tube is surrounded by a slightly larger glass tube, and similar to a thermos flask, there is a vacuum between the two tubes. This further reduces heat losses. The collectors are up to seven metres wide, up to 200 metres long and track the sun using a hydraulically powered drive unit. The thermal oils in commercial use today allow operating temperatures of up to 400 °C.

Fresnel collectors work in a similar way to parabolic troughs. The concentrator is divided into elongated, horizontally arranged and individually tracked facets. The absorber pipe is installed in a fixed position. Due to the low wind loads, this type of construction can be manufactured particularly cost-effectively and is also suitable for installation on flat roofs. To compensate for the lower optical efficiency due to the collector geometry, around 20 percent lower collector costs are required than with parabolic troughs (Morin 2012).

An important component of solar thermal power plants is the **thermal storage system** (see question 3). Two-tank systems with molten salt as the storage medium are most frequently used commercially. In tower power plants, the salt is pumped from the 'cold' tank (at around 300 °C) directly to the solar receiver, where it is heated to over 500 °C and fed to the 'hot' tank. A second circuit takes hot salt as needed and feeds it to the steam generator, from where it is pumped back into the 'cold' tank. In parabolic trough power plants with thermal oil as the heat transfer medium, the salt storage tank is loaded and unloaded indirectly via heat exchangers.

The indirect way of converting solar radiation first into thermal energy and only then into electrical power appears cumbersome compared to PV solar cells, which convert sunlight into electricity immediately. In fact, that is precisely the **value of solar thermal power plants for a future energy system without fossil fuels.** Heat can be stored more easily and more economically than electricity, and with the solar energy stored as heat, solar thermal power plants can produce solar electricity cost-effectively even after sunset.



Solar thermal concentrator technologies. Credit: DLR

2. How can solar thermal power plants contribute to security of supply?

Heat can be stored in large tanks of molten salt around 80 to 90 percent more cost-effectively than storing electricity in batteries.

The greatest growth in electricity generation from renewable energy sources today comes from wind power and photovoltaic systems. In addition to the considerations about the further expansion of renewable capacities, the discussion on **demand-based supply** and **network stability** is in the foreground. Wind and photovoltaics are dependent on electricity storage in order to be able to arrange the delivery of power flexibly over extended time periods. However, the investment costs of modern battery storage systems are currently still comparatively high at 300 euros per kilowatt-hour and their service life is limited to less than 10 years. In addition, there is still a lack of battery storage systems at a gigawatt-hour scale (Cole 2020). Therefore, the comprehensive balancing of electricity supply and demand with this technology is not yet fully economically feasible.

Thermal storage systems decouple the generation of electricity from the 'harvesting' of solar energy.
Credit: CSP Services

When large energy storage capacities are required, heat can be stored around 80 to 90 percent more cost-effectively than electricity (Steinmann 2021; Schöniger 2021). Solar thermal power plants therefore rely on the storage of the intermediate product heat and not the end product electricity. Electricity is generated by means of a steam turbine cycle, which is operated according to demand and is supplied from the thermal storage system. The storage system thus decouples the solar 'harvest' from the demand-oriented generation of electricity (Stadler 2019).

Today, molten salt tanks are the primary thermal storage method. Containers with diameters of up to 40 metres and heights of 15 metres are filled with a mixture of potassium nitrate and sodium nitrate as the thermal storage medium (Bauer 2021). The solar energy heats the salt, which melts at 250 °C, to temperatures of up to 560 °C. As soon as electricity needs to be generated, the storage tank supplies a steam generator with thermal energy. The steam generated then drives a conventional steam turbine process.

Storage and power plant section of the Andasol 3 parabolic trough power plant. Credit: Marquesado Solar

The steam turbines used in such solar power plants can be operated very flexibly and can optimally follow demand. Typical systems today have storage capacities of six to 15 full-load hours. This enables operation around the clock or specifically at times of peak demand. **Thermal storage** allows the shifting of amounts of energy over a day or a few days. Since power generation can be flexibly adapted to demand, solar thermal power plants are referred to as **controllable power plants.**

Solar thermal power plants have an additional advantage. If there is little solar radiation for several days due to the weather, they can be operated in hybrid mode. This means that the system can be expanded to include a combustion system for fossil or renewable energy sources such as biomass, which can provide heat for generating electricity and for filling the thermal storage system independently of the solar circuit. Since the thermal storage system, turbine and re-cooling system are already in place, the additional costs are comparatively low. Even in periods with reduced sunlight and empty storage, a solar power plant can generate electricity independently at any time, which the grid can use flexibly. Producers of renewable energies such as PV or wind systems are shifting this task, which is important for the energy system, to other power plants in the grid. The combination of energy storage for the daily shift of energy quantities and hybridisation for secure performance is one of the most important properties of solar thermal power plants.

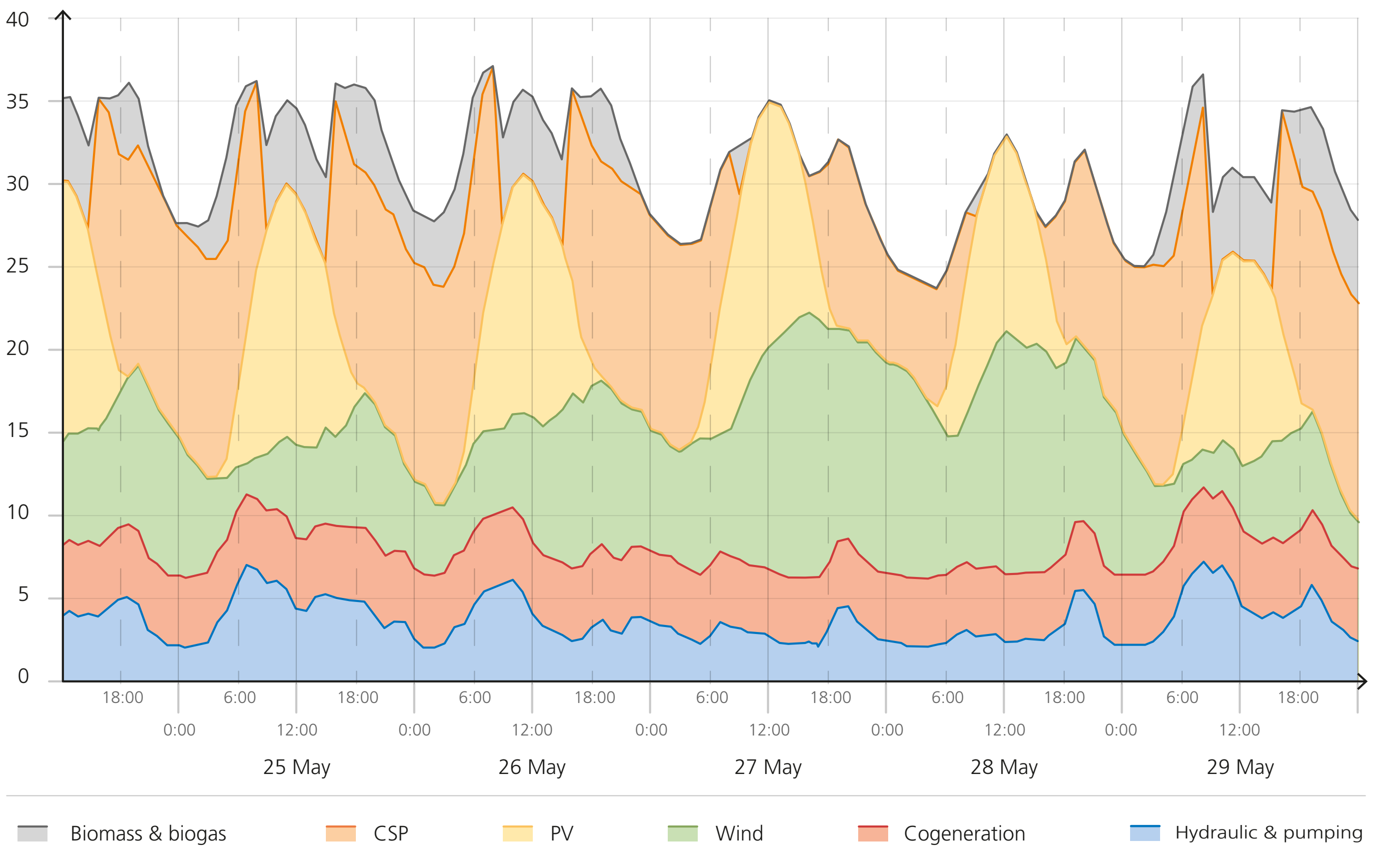
As is the case with all steam power plants, solar thermal power plants are also able to help stabilise the grid. The rotating mass of the turbine and generator has a stabilising effect on the frequency of the power grid. In addition, the turbine can absorb very rapid changes in load and thus react to short-term requirements from the grid operator. A solar thermal power plant can thus actively participate in the control reserve market if required.

3. What role do solar thermal power plants play in an energy system based on renewable energy sources?

In sunny countries, solar thermal power plants can become an essential component of an energy system that mainly uses renewable resources. In such a system, with the further expansion of PV systems, a systematic power supply gap arises at off-peak times and at night, and a surplus during the midday peak. Solar thermal power plants collect thermal energy throughout the day and store it in high-temperature heat storage systems. They complement the generation of electricity from PV and wind systems by being used as **flexible solar power** plants producing electricity primarily during off-peak times, at night and when there is insufficient renewable power from PV and wind systems available during the day.

Solar thermal power plants can thus take on the role that is still predominantly assumed today by conventional, fossil fuel power plants, which will no longer be able to be operated in the future for climate protection reasons. Only through the combination of the renewable technologies PV and CSP are large shares of solar power in the energy system of sunny countries possible, which are necessary for a cost-effective and low-CO_2 energy system (Denholm 2011). The fact that the technology is suitable for this is shown by the existence of more than 100 solar thermal power plants with a **total installed capacity of 6.2 gigawatts.**

POWER GENERATION
GW



Energy market scenario in Spain for selected days in May 2030. Source: Bonilla 2020

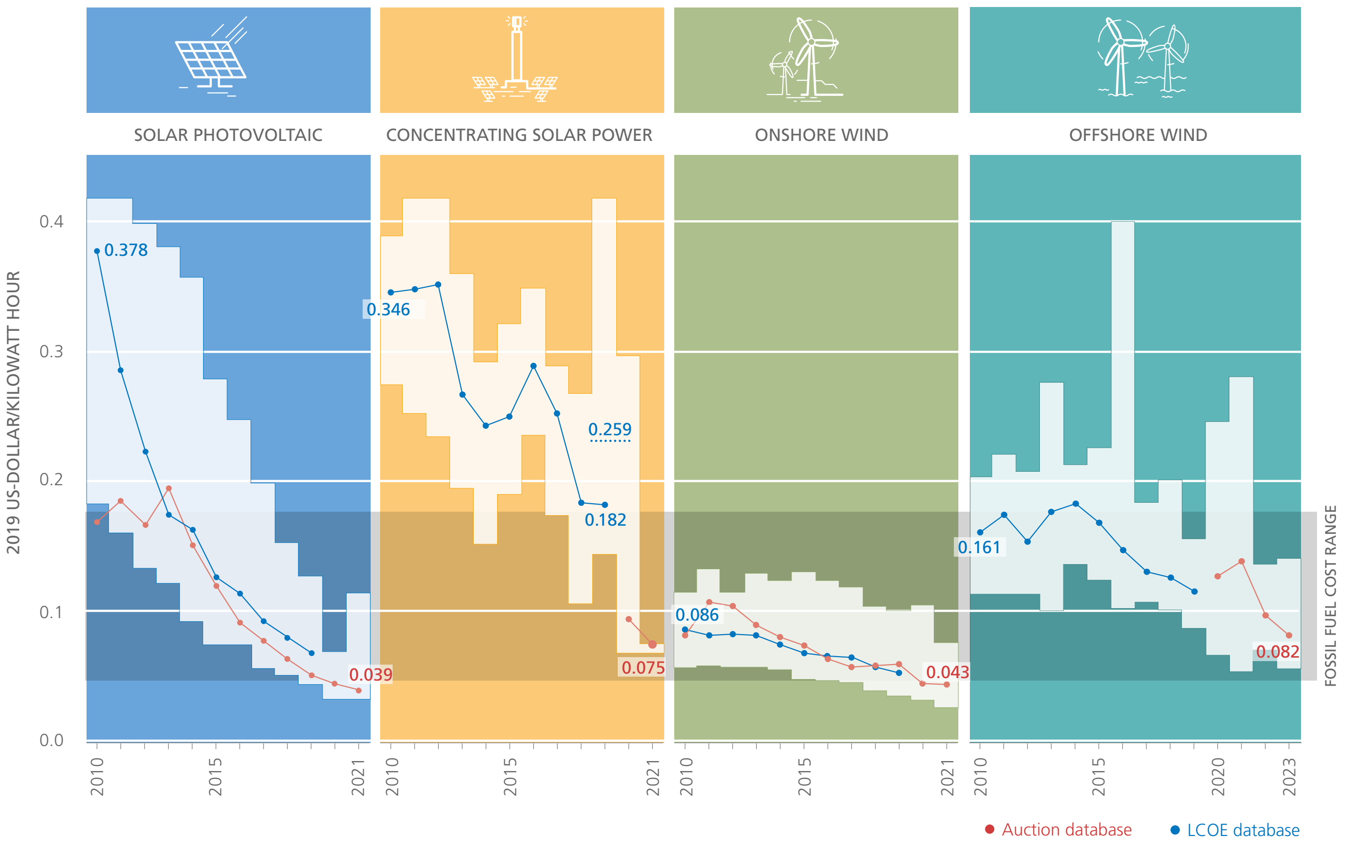
The country with the highest installed capacity is Spain with 50 power plants and a capacity of 2.3 gigawatts. At peak times, up to 10 percent of the total electricity demand is covered by CSP power plants (CSPFocus 2020). Worldwide, 21 gigawatt hours of thermal storage capacity are already installed in CSP power plants, which corresponds to approximately three gigawatts of electrical output with an average storage capacity of seven hours (REN21 2020). This power can be made available to the power grid as required. Today, solar power plants are already planned as an integrated solution to combine PV and CSP power plants at one location, which use thermal energy storage to ensure the requirements for security of supply in a cost-effective manner.

Approximately 100 solar thermal power plants were in operation across the world at the end of 2019, with a total capacity of 6.2 gigawatts.

In various scenarios for a future global energy system, the International Energy Agency (IEA) shows to what extent, with the expected growth in PV electricity in the energy system, the share of CSP electricity in global electricity production will also increase (IEA 2020: World Energy Outlook 2020). In 2018, there were two kilowatt-hours of CSP electricity for every 100 kilowatt-hours of PV electricity generated. In order to be able to increase the share of renewable energy in the overall electricity mix to 44 percent worldwide in 2040, three kilowatt-hours of CSP electricity will be required for every 100 kilowatt-hours of PV electricity. With an even higher share of renewable energies of 67 percent, there would be nine kilowatt-hours of CSP electricity for every 100 kilowatt-hours of PV electricity. To achieve this, the output of CSP power plants installed today would have to be increased thirty-fold – to about 180 gigawatts. A study (Teske 2016) confirms this fundamental relationship and predicts a sharp increase in the expansion of CSP in the period from 2030 to 2040. In order to be able to classify the ratio of PV to CSP electricity generation, the expansion of CSP power plants being concentrated in the 'Sun Belt' must be taken into account, while PV systems can be used worldwide. Investigations for the North Africa / Middle East region therefore come to a much more balanced ratio of CSP and PV capacities. They show that the combination of these technologies in this region is able to provide over 80 percent of a country's electricity generation (Steinbacher 2020). The cost of such a renewable energy system is comparable to the cost of gas- and coal-based electricity generation. If external costs are also taken into account, for example in the form of CO_2 pricing, they are considerably less expensive than fossil-fuel expansion paths at these locations.

As a rule, solar thermal power plants can only be operated economically as large-scale systems with nominal outputs of 50 to 200 megawatts. For the direct supply of industrial areas, smaller systems at locations with good solar radiation can be economically interesting if the industrial customers not only purchase electricity, but also **process heat** (see also question 12). In particular, where electricity generation from fossil fuels is expensive due to an isolated geographical location, such systems can already compete with fossil alternatives. One example of this is large mine complexes in Chile, where the particularly attractive conditions exist due to the high irradiation values.

4. Are solar thermal power plants competitive?



Cost development of energy generation using renewable sources since 2010. The grey shaded area shows the range of costs for fossil power generation. (IRENA 2020: Renewable Power Generation Costs)

Electricity from solar thermal power plants has seen significant cost reductions over the past 10 years and can now reach the cost level of conventional electricity generation. A report by the International Renewable Energy Agency (IRENA) shows the average worldwide development of the costs and prices of renewable energy sources and also takes a look into the future (IRENA 2020: Renewable Power Generation Costs). In the underlying 'Auction and PPA database', IRENA records the actual **auction prices** and **purchase prices** achieved for electricity generated using renewable energy sources. The 'Levelized Cost of Energy (LCOE)' database contains **calculated electricity production costs,** which are based on standardised assumptions about interest rates, lifetime and depreciation. In some cases, the LCOE values differ considerably from the auction prices, partly because the actual profitability calculations of the companies are not known and are therefore not included in the calculation. The calculated electricity production costs also do not take into account that solar thermal power plants, unlike PV and wind systems, provide dispatchable renewable electricity due to their integrated thermal storage and thus offer added value.

When evaluating the electricity production costs of the different technology options, it should be considered that solar thermal power plants are not yet widespread in the market. For this reason, the **cost reduction possibilities through mass production and competition** among many market participants have not yet come to fruition. The considerable decline in PV electricity costs in the last 10 years is mainly due to the large number of systems and modules installed. For example, the worldwide installed capacity rose from approximately 41 gigawatts to 580 gigawatts between 2010 and 2019 (IRENA 2020: Renewable Power Generation Costs).

Since over the course of a year the sun is only above the horizon for an average of 12 hours per day at sunny locations, during which PV systems can generate inexpensive solar power, storage systems or other solutions are required to ensure the **security of power** supply during the remaining 12 hours of the day. In addition, PV power generation fluctuates strongly within a day, even with a cloudless sky, and usually has a strong generation peak at noon. Storage systems can compensate for the daily fluctuations and cloud cover. It would be possible to equip PV or wind power plants with battery storage systems and thus store part of the fluctuating electricity and feed it in as required. The costs for the storage systems would then lead to higher electricity costs. In 2019, the electricity generation costs for PV electricity with a lithium-ion battery system having a four-hour discharge time were approximately 0.2 US dollars for one kilowatt-hour of electricity (IRENA 2019 and IRENA 2020: Renewable Power Generation Costs). For electricity from solar thermal power plants, IRENA calculated average electricity generation costs of 0.182 US dollars per kilowatt-hour for the same year. The average auction and power purchase prices for new solar power plants that will go into operation in 2020 and 2021 are between 0.073 US dollars and 0.094 US dollars per kilowatt-hour – that is, 48 to 59 percent below the calculated costs for 2019. Although the prices for 2020 and 2021 are not directly comparable with the costs for 2019, they clearly show that the competitiveness of CSP power plants is continuing to increase.

The cost comparison between PV and CSP electricity is heavily dependent on the combination of the key figures 'nominal output' (maximum possible generation output) and 'capacity' (maximum possible storage duration), which are important for storage-based systems. When comparing a CSP system and a PV system with the same nominal output but different storage capacities, the cost advantage of CSP compared to PV increases with increasing storage size. The reason for this is that battery-based electricity storage systems in common use today contain the two functions of energy storage and power supply in one unit. In solar thermal power plants, these functions are separated. The storage systems absorb the energy, and the power generation system provides the output. To increase the capacity, it is only necessary to enlarge the storage tanks.

In **combination with PV systems** (see question 3) solar thermal power plants enable the continuous supply of inexpensive solar-derived electricity and help to stabilise the power grid. This advantage is not reflected in a direct comparison of the electricity generation costs.

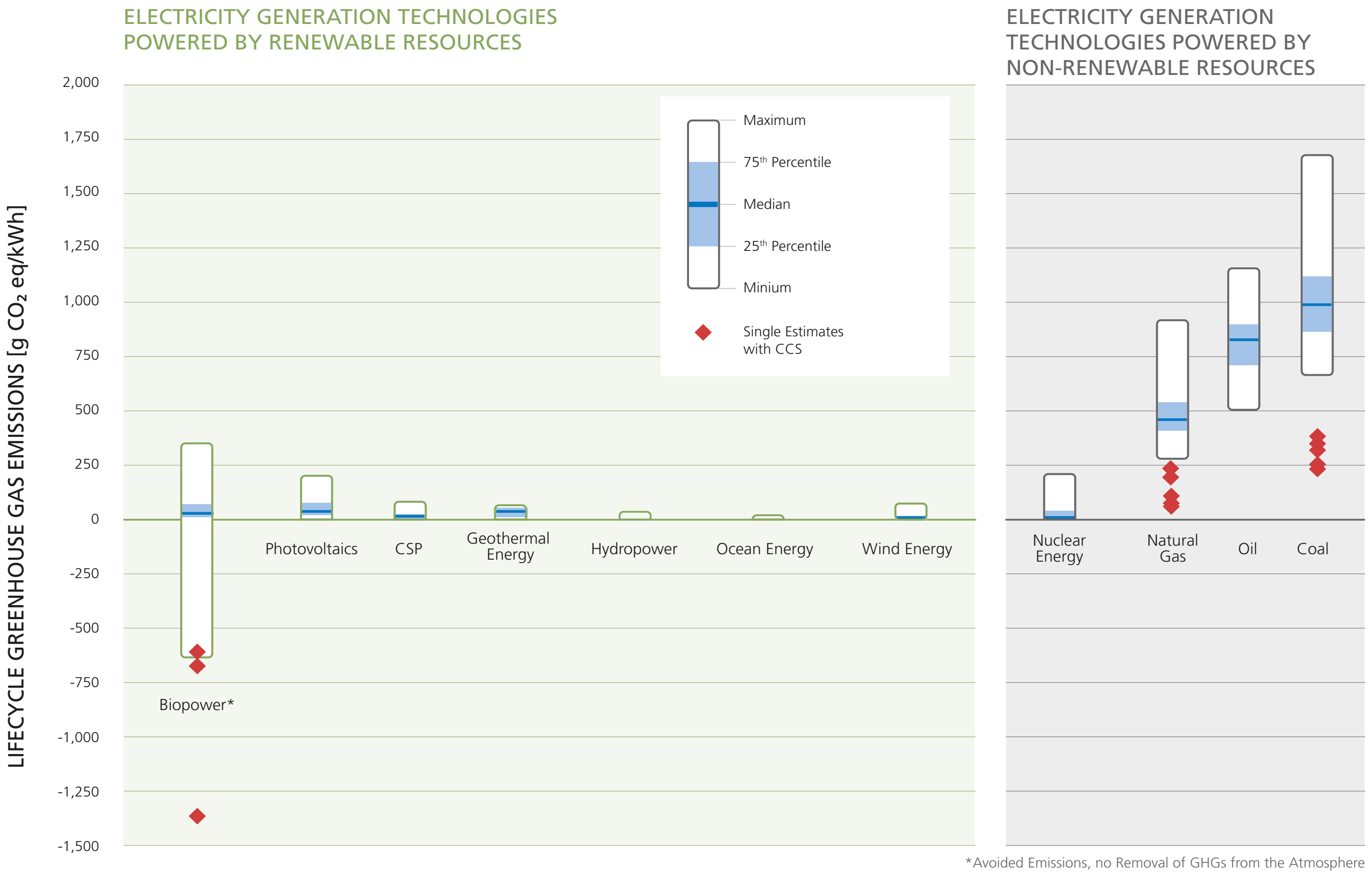
Assuming the availability of the necessary direct solar radiation, solar thermal power plants with integrated storage, working as part of a future greenhouse-gas-neutral energy system, are an important addition to the less expensive yet fluctuating PV and wind systems (IRENA 2020: Renewable Power Generation Costs), which remain more cost-effective during the day or in favourable wind conditions.

Prices for electricity from solar thermal power plants with thermal energy storage systems have now fallen to as low as 0.073 US dollars per kilowatt-hour.

5. How does the construction and operation of solar thermal power plants affect the environment?

Solar thermal power plants produce comparatively low **greenhouse gas emissions** throughout their entire lifecycle, also in comparison with other renewable electricity generation technologies. Most importantly, their emissions are significantly lower than those of conventional power generation technologies. The graphic shows the specific greenhouse gas emissions for various technologies over their entire lifecycle. Typical values for indirect emissions from solar tower power plants are in the range from 10 to 13 grams of CO_2 equivalents per generated kilowatt-hour of electricity (CO_2 equivalents represent the global warming potential of gas mixtures in relation to CO_2); for parabolic trough power plants emissions are in the range of 18 to 24 grams of CO_2 equivalents (Telsnig 2015).

The CO_2 equivalents shown relate to direct and indirect emissions. Indirect emissions are those that are generated in the manufacture of the construction materials glass, steel and concrete, during construction work and during solar power system operation. The power plant generates direct emissions when it burns fossil fuels such as natural gas or diesel to operate the steam generator. In particular, the early commercial solar thermal power plants, which were built without energy storage systems, increased their availability in this way. The resulting emissions increase total emissions to up to 200 grams of CO_2 equivalents per generated kilowatt-hour of electricity. Almost all new power plants have an integrated thermal storage system. They manage to produce the low emission values mentioned above with almost no combustion of additional fuel.



Comparison of the total greenhouse gas emissions of various power generation technologies (IPCC 2012)

Solar thermal power plants are primarily built in desert-like areas that are not suitable for agricultural use due to lack of water. Land consumption is therefore not an obstacle. The specific **land requirement** for a solar thermal power plant is around 1.3 hectares per gigawatt-hour of electricity per year (Ong 2013).

Environmental impact assessments are usually carried out for large construction projects. This results in measures for the **protection of plants and animals** in accordance with the applicable national regulations. The impact of the power plant on the flora can be assessed as minor, since only few plants grow in typical locations and only a small part of the power plant area is sealed. For birds and insects there is a risk of them not recognising the mirrors as an obstacle and of injuring themselves, or of dying when flying through the focal point created by the heliostats. A study on a solar thermal power plant in South Africa published in 2020 showed that the risk is far lower than previously assumed (van Heerden 2020). Appropriate control of the mirrors can further reduce the risk to birds. Parabolic troughs pose less of a threat to birds than tower power plants because they generate much lower concentrations and have short focal lengths.

The environmental impact of CSP power plants is significantly lower than that of fossil-fuel power plants.

Water consumption is an important factor at the locations of solar thermal power plants. Like all steam power plants, solar power plants also need water to produce electricity. They use water to cool the steam cycle, in the steam cycle itself and to clean the mirrors. The water requirements also depend on the location. For example, dust and moisture in the air influence the degree of soiling deposited on the solar mirrors. Many current and almost all new solar thermal power plants use dry cooling with ambient air, which can significantly reduce water consumption. CSP power plants with dry cooling have an average water requirement of 0.3 litres per kilowatt-hour of electricity (Turchi 2010), equivalent to approximately 120 litres per square metre of collector surface or 30 litres per square metre of power plant surface area per year. This is significantly less than is used for alternative land use at comparable locations. For example, grain cultivation in Morocco requires around 1600 litres per square metre of cultivated area per year.

Only small amounts of **environmentally hazardous waste** are produced during the operation of solar thermal power plants. These are mostly synthetic organic heat transfer media used in parabolic troughs, a mixture of biphenyl and diphenyl ether. In rare cases, they can ignite, contaminate soil and cause other environmental problems and must therefore be treated as hazardous waste. Today, power plant operators are obliged to dispose of them in accordance with the applicable guidelines (EASAC 2011). One goal of current research activities is to replace toxic heat transfer media with more environmentally friendly silicone oils or molten salts.

While parabolic trough systems produce almost no visual impairment of their surroundings, the reflections from the heliostats and strong brightness of the concentrated solar radiation reflected onto the receiver of solar tower systems can be perceived as disturbing. The distance separating solar thermal power plants from residential areas is usually so great that the reflections and concentrated light beams are not visible there. However, drivers passing by or visitors to the facility could be disturbed by the bright light. The hazard values are, however, well below those caused by the sun itself.

Overall, the environmental impact of CSP power plants is significantly lower than that of fossil fuel power plants (Bošnjaković 2019).

6. What is needed for the operation of a solar thermal power plant in addition to solar radiation?

The **location requirements** for solar thermal power plants are comparatively low. Stony, rocky and gravel deserts with little vegetation are suitable, as are grasslands, scrublands and savannahs, for which there are practically no other economic uses, and which are available is almost unlimited quantities for this application in the Sun Belt. **Land costs are therefore low in these regions**. But in the vicinity of more densely populated areas, often the only land that is available also has alternative uses, which drives up the costs. In this case, the land costs also depend on the ownership structure and the existence of a free real estate market.

A CSP power plant needs a large **area for the installation of the solar mirrors.** The mirror field of the 50 megawatt parabolic trough power plant Andasol 3, for example, extends over an area of 200 hectares, which corresponds to the size of 280 football pitches. For parabolic trough systems, the surface must be as flat as possible. Solar tower power plants, on the other hand, can also be built on surfaces with a steep gradient, as the mirrors have independent foundations and are not connected by a heat transfer circuit.

An **existing infrastructure** is another important location criterion, because a power plant needs access to transport routes, to high or medium voltage electricity networks and to water resources. If these are not available at the selected location, additional investments, permits and more time are required for the project. Newer solar power plants need water primarily for the steam cycle and for cleaning the mirrors. Most power plants cover their needs from the groundwater on site. If this is not possible, water has to be transported to the power plant, which creates additional costs.

Natural phenomena such as earthquakes and storms generally have an impact on the costs of energy systems. In the case of solar thermal plants, the design of the solar field and power plant buildings must be adapted to the special conditions, which leads to additional costs.

Other decisive location factors are a **low investment risk** and **favourable financing** conditions for investors. The most important instruments for reducing the investment risk are guaranteed feed-in tariffs or premiums for electricity that is generated using renewable energy sources, quotas for the proportion of renewable energies, tax incentives and long-term power purchase agreements (PPAs).

Solar power plants NOOR I-III in Ouarzazate, Morocco. Credit: SENER

Feed-in tariff systems with **guaranteed payments** over a period of time have been found to be very effective. Spain has achieved the expansion of 2.3 gigawatts of CSP capacity through a state-guaranteed electricity feed-in tariff. In **quota systems,** governments oblige electricity suppliers to purchase a minimum share of electricity generated from renewable sources. In the USA, for example, energy suppliers in some states are obliged to provide a certain proportion of the electricity produced from renewable energy sources. For example, **special tax incentives and investment grants** were used in California during the 1980s to promote the construction of the first solar thermal power plants.

A **long-term power purchase agreement,** which covers all costs and at the same time contains a reasonable return, guarantees the return on the investment capital. In conjunction with an international guarantee, this allows investors to raise part of the capital they need on the financial market at favourable terms and thus reduce financing costs

7. What skills are required to build and operate solar thermal power plants?

CSP plants are **process plants,** which are planned and implemented as major projects according to a scheme that has previously proven itself in plant engineering. However, the planning and construction of the solar part with the mirror system and heat receiver and its connection to the steam cycle require specialist expertise. Today only a few large companies worldwide have this qualification and are able to assume responsibility of being the **prime contractor.** The value chain when creating a plant includes planning, procurement and turnkey construction of the entire plant, also referred to as an Engineering, Procurement and Construction (EPC) contract. In addition, the specific components and systems used must of course also be planned, manufactured and delivered (Hümmer 2020).

The planning phase with the three sub-steps of conceptual engineering, basic engineering and detail engineering is followed by the construction and commissioning phase, and then the operation and maintenance phase (Sattler 2000).

EPC companies specialise in coordinating the various customised deliveries and services and integrating them into the system. In doing so, they bring their experience and expertise to bear on the elements of the value chain, such as subsystems, machinery, components and connecting elements, cables and pipelines. Specialist knowledge is also required for the integration of the required services, because these range from engineering documentation through procurement, production and commissioning to maintenance and quality control (PricewaterhouseCoopers 2017).

Airborne quality control of a parabolic trough. Photograph taken at the Plataforma Solar de Almeriía (PSA). The Spanish research centre CIEMAT is the owner and operator of the PSA.

Construction projects for solar thermal power plants require a high level of **specialised knowledge** in every part of the value chain (Mehos 2020). However, it is possible to use companies from the region for some construction work as well as during the operation and maintenance phase. This can create **local added value** in the countries concerned (Dii 2013).

In addition, **specific expertise** is required to plan, construct and operate the **solar field of a system** (Mehos 2020). The **quality of the optical systems** has a significant influence on electricity production and thus on the profitability of a power plant. For this reason, specialist companies use dedicated measurement technologies for quality assurance and construction supervision (Eickhoff 2010).

The operation of the plant is also complex and places high demands on the personnel. For this reason, new employees are trained by experienced staff. The primary goals of the **training** are to reduce operating errors and to ensure that the power plant staff learn to recognise possible system malfunctions at an early stage.

The value creation of CSP systems results from the combination of numerous components and subsystems, which range from the very complex and technology-specific (for example, absorber pipes) to comparatively simple and versatile components (for example, cables) (Dii 2013). Compared to photovoltaics, a large part of the added value and also the technological risk arises during the adaptation of these components and their integration into a functioning overall system.

During operation, it is important to keep the systems in perfect working order. This ensures the maximum economic efficiency of the power plant. Ideally, a predictive maintenance strategy based on regular condition monitoring is applied to avoid damage-related downtime (Papaelias 2016). If heat losses, leaks, contamination, positioning errors or defective components remain undetected, the output and thus the yield of the power plant decrease. Power plant operators need efficient technical solutions for this, such as digital automated monitoring systems.

Today, only a few large companies worldwide have sufficient expertise to be able to offer turnkey solar thermal power plants as prime contractors.

PROJECTS

- project development
- detailed planning & control
- procurement
- construction and assembly works
- owner
- site, resource
- operation & maintenance

EPC (detailed planning & control, procurement, construction and assembly works)

COMPONENTS

- turbine, power block
- storage, heat exchanger
- electrics, sensors, measurement technology
- controls, automation
- piping, instrumentation, valves, insulation
- pumps, hydroaulic drives, heat exchanger
- heat transfer fluid
- receiver, mirrors, tube connectors
- collectors, heliostats, solar field

ENABLING

- consulting
- engineering & support
- manufacturing machines & automation
- test & measurement, quality control technology
- cleaning technology
- infrastructure, others

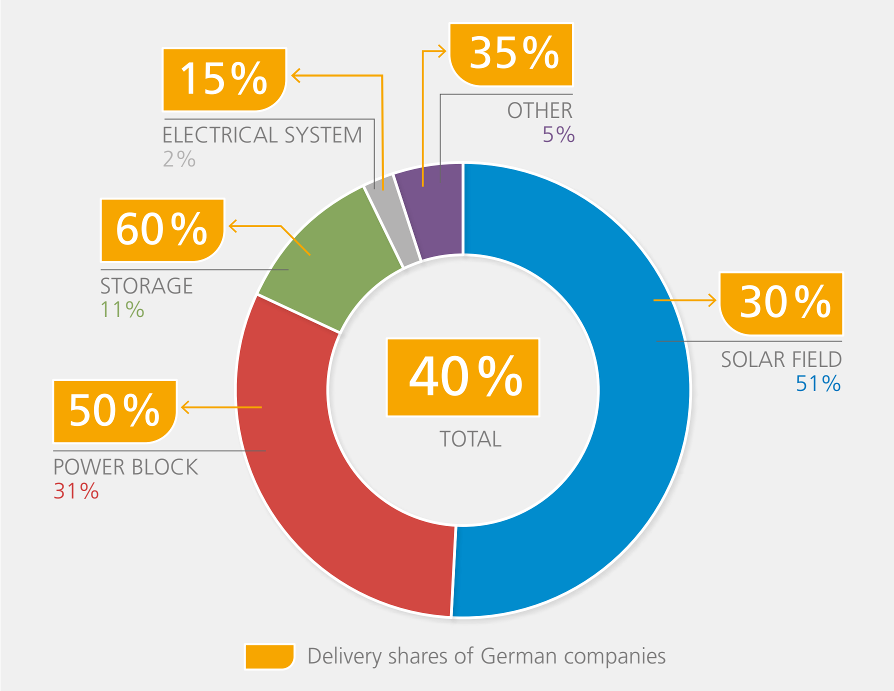
Elements of the value chain of a solar thermal power plant (DCSP 2018, own editing)

8. What relevance does solar thermal power plant technology have for Germany?

Although Germany is not a suitable location for the cost-effective operation of solar thermal power plants because of its meteorological conditions, the development of the necessary technology results in a number of advantages that it can make use of.

System-analytical studies of the energy transition show that a climate-neutral energy system in Germany cannot be achieved solely using domestic renewable energy sources (Öko-Institut 2015). As a result, Germany will in future be partly dependent on energy imports from particularly energy-rich regions of the world, such as Earth's Sun Belt. Energy imports are currently being discussed in particular for liquid and gaseous renewable energy sources like hydrogen or electricity-derived synthetic fuels (BMWi 2020). They can be transported and stored particularly cost-effectively, partly due to their high energy density. In addition, they can be used flexibly in industry, for power and heat generation and in the transport sector (DLR 2020, Part 2). **Generation of green hydrogen** using electricity from solar thermal power plants has a beneficial effect on the utilisation of the generation plants and thus also has a positive effect on the generation costs (see question 2; Trieb 2012).

Another aspect that illustrates the relevance of solar thermal power plants for Germany is the opportunities that the **expertise available in Germany** brings in relation to this technology. Solar thermal power plants largely consist of components that are already used in other applications, for example turbines, curved glass, flexible pipe connections, insulation, coatings, process technology and plant engineering, motors and pumps, measurement technologies and heat exchangers. German companies can use their skills and experience in these areas comparatively easily for the development of solar thermal technologies. In addition, many years of involvement in research on solar thermal power plants have resulted in new knowledge in Germany (IEA 2020: Energy Technology R&D Budgets). The opportunities that arise from this can be explained in particular on the basis of two aspects.



Delivery shares of German companies for the Moroccan power plant NOOR I. (DCSP 2018)

The **existing knowledge base** offers German companies the opportunity to participate in international solar power plant projects and thus secures or creates **employment** in **Germany** to a limited extent (O'Sullivan 2020). In this context, the existing industrial structures are an advantage here; however, the new business areas also act as a catalyst for start-ups and spin-offs that go hand in hand with research into and development of solar thermal power plants. A particularly striking example of an established company in this context is Siemens, whose steam turbine technology is regularly used in solar thermal projects (Siemens AG 2019). Overall, the services of German companies currently include aspects of project development and planning, the supply and integration of components, but also the commissioning of systems and maintenance. An example of this is the Noor I power plant in Morocco where German companies were involved in approximately 40 percent of the project's implementation by 2016 (see graphic).

One way to use the acquired expertise on solar thermal power plants in Germany is **technology transfer to new applications**. A current example is the use of thermal storage technologies, which have reached a high level of technical maturity through their use in solar thermal power plants. They are now also being prepared for use in **thermal storage power plants** in Germany (Steffen 2019; Trieb 2020). In addition, the storage systems developed for solar thermal power plants can be used in the field of **industrial process heat.** A transfer of expertise is also taking place in the area of **condition monitoring** of solar thermal power plants, which is required for the operation and maintenance of the systems. The methods developed for this and the knowledge gained during, for example, the condition monitoring of mirror fields from the air using drones, are now also being used for PV systems in Germany or are underway.

Concentrating collectors can also make a contribution to the provision of heat from renewable energies in Germany (see question 12).

9. Where are the markets and what are the overall conditions?

Almost all new projects have thermal storage to secure the supply outside of daylight hours

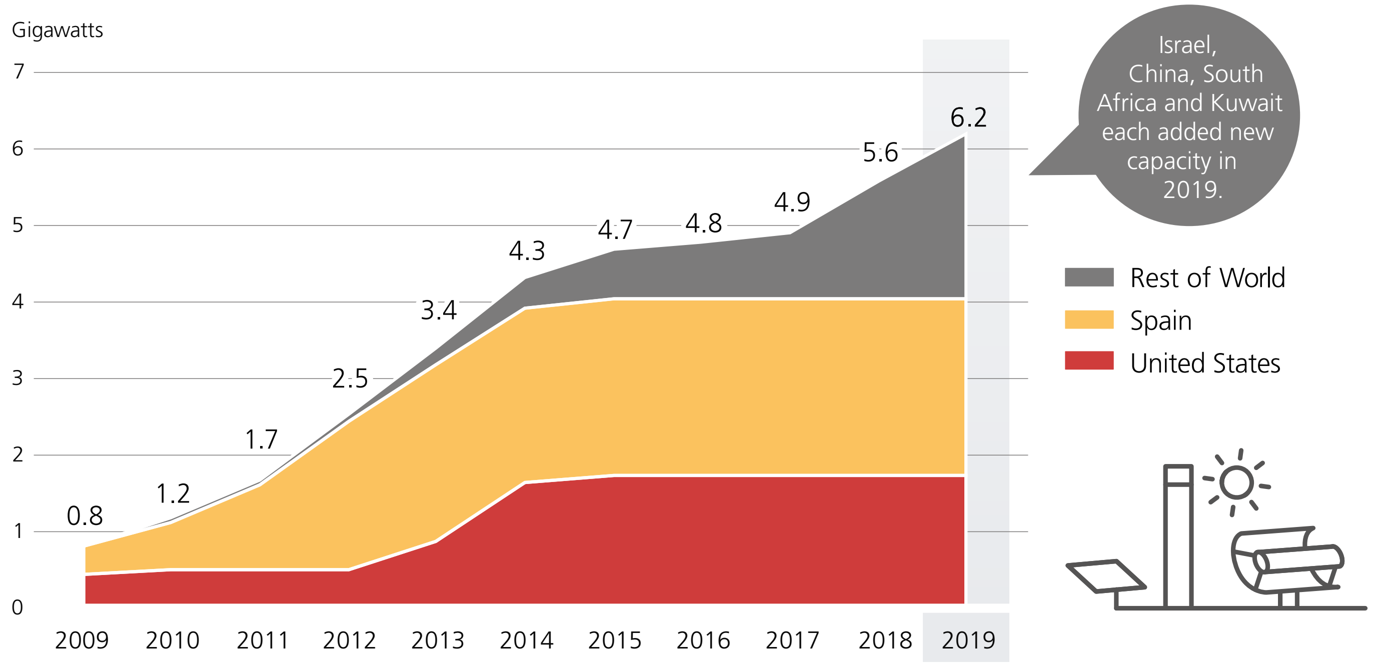
Large solar thermal power plants currently typically have an electrical output of 50 to 200 megawatts. The investment required for this is preferably made in locations where there are many hours of sunshine per year – in Earth's subtropical Sun Belt. In addition to the subtropical climate, other factors are important for the profitability of the power plants (see question 6). Because of the high initial investment (but low operating costs) compared to conventional power plants, it is important that the purchase of and tariff for the solar power produced is secured by contract or by law and that the political and economic conditions are stable. Project development, planning and construction of large-scale plants require technical expertise and, in particular, a strong economic background to be able to pre-finance these activities, which run over several years (see Question 7).

At the end of 2019, solar thermal power plants with a total capacity of 6.2 gigawatts were in operation, an increase of 600 megawatts over the previous year. Although no additional plants have been built in the pioneering markets of the **USA and Spain** since 2015 or 2013, respectively, with Spain having 2.3 gigawatts and the USA having 1.7 gigawatts, these countries clearly lead the field in terms of installed capacity. They are ahead of **Morocco** (516 megawatts), **South Africa** (500 megawatts) and **China** (420 megawatts). For the first time, as many tower as parabolic trough systems were installed, each accounting for 45 percent of the total increase, while Fresnel technology accounted for 10 percent (REN21 2020).

The largest share of the **growth in 2019** was realised by **Israel** with 242 megawatts, in equal parts through the 'Megalim' solar tower (without storage) and the 'Negev' parabolic trough power plant, which has integrated molten salt storage with 4.5 hours of storage capacity. These first commercial solar thermal power plants in Israel are also the largest power plants using renewable energies in the country. **China** commissioned 200 megawatts of capacity with four plants of 50 megawatts each, all with molten salt heat storage – a linear Fresnel power plant with 13 hours of storage capacity and three tower power plants with six, eight and 12 hours of storage. Further parabolic trough and tower power plants with a total of 250 megawatts of power and 2.4 gigawatt hours of thermal storage capacity are under construction. In **South Africa** the 100-megawatt parabolic trough power plant 'Kathu' went into operation, also with thermal storage (4.5 hours). In the state's Integrated Resource Plan, another solar tower with a capacity of 100 megawatts is planned by 2030. In Kuwait the 50-megawatt parabolic trough system 'Shagaya' is the first system in the planned Renewable Energy Park with a nominal output of three gigawatts. Here, in addition to PV and wind, a further 350 megawatts of solar thermal power plant capacity are planned. The smallest system completed in 2019 is the Fresnel power plant 'eLLO' with an output of nine megawatts and four hours of storage capacity, located in **France.**

Current **worldwide construction projects** include almost 900 megawatts of parabolic troughs and 300 megawatts of tower power plants as well as a 14-megawatt Fresnel system. More than 60 percent of this is accounted for by the **United Arab Emirates**, where three parabolic trough systems with capacities of 200 megawatts each and a tower power plant with a capacity of 100 megawatts are under construction as part of the Noor I project. In **Chile,** completion of the 110-megawatt tower power plant 'Cerro Dominador' is expected at the end of 2020. During 2021, in **Greece**, a Chinese consortium will start building the 52 megawatt tower power plant 'MINOS' on the island of Crete. Almost all new projects have thermal storage. These are increasingly being used in parallel with PV systems to secure the supply outside of daylight hours. This trend is also reflected in the Integrated National Energy and Climate Plan in Spain, according to which an additional five gigawatts of solar thermal power plant capacity with large thermal storage systems are to be realised by 2030 and the retrofitting of existing power plants with additional storage capacity is to be made easier (HeliosCSP 2019).

While companies from Spain and the USA led the CSP market until 2015, Chinese companies were involved in almost half of the projects in 2019. German providers with their expertise and high-quality engineering products are still successfully asserting themselves in this sector as exporting suppliers and as consultants (see question 8). The market participants are organised in the German industrial association DCSP and in the European association ESTELA.



Development of solar thermal power plant capacities from 2009 to 2019 (Ren21 2020)

10. What are the socio-economic consequences of using this technology?

The construction of a 50 MW parabolic trough power plant will create about 2000 direct and indirect jobs during the two-year construction phase.

From an economic standpoint, the use of solar thermal power plants is largely restricted to countries in what is referred to as the Earth's Sun Belt. Since many of these belong to the developing countries of the world (United Nations 2020), the question for them in particular is related to the consequences of the use of solar thermal power plants on their economic and social development. In general, the socio-economic consequences of the establishment of systems for generating electricity from renewable energies are less technology-specific. Most of the aspects discussed in this context relate to the entire energy transition across all technologies in the respective countries.

One of the most important socio-economic effects of the expansion of infrastructures is the resulting **employment impact.** A number of publications have examined the employment potential of solar thermal power plants for different countries (Gazzo 2011; Craig 2019; Milani 2020). They all show the possibility of attracting new companies and thus creating additional (direct and indirect) employment opportunities locally. For example, an analysis of the Spanish market from 2010 identified around 2000 direct and indirect employees for the construction of a 50 MW parabolic trough power plant, spread over a period of two years, as well as around 50 permanent jobs for the operations phase (Deloitte 2010).

However, realising this potential requires the development of a stable demand for solar thermal power plants in the respective countries and regions. Only in a few countries, such as Spain, did a continuous market emerge for a certain period of time. More than 40 power plants were installed there between 2008 and 2012, with employment rising to almost 29,000 people (Deloitte 2010). In many other countries, however, only individual projects have been implemented so far, so that there have not been any significant additional industrial arrivals. However, the requirements for **local added value,** which went hand in hand with the investments made so far, meant that existing local companies were able to provide services for power plant construction. In particular, trades and services from the construction industry as well as the work required to operate the systems contributed to local value creation (Gazzo 2011; Wuppertal Institute 2015). According to the presentation in question 7, these tend to be in sectors that require less specific expertise about solar thermal power plants. For many countries, however, it would be conceivable that areas of the value chain that require a higher level of specific knowledge will also establish themselves, especially if they do so as lead markets with stable demand (Gazzo 2011; WWF 2015).

A special aspect of solar thermal power plants with regard to the socio-economic effects is their geographical location. Since they are mostly located away from metropolitan areas, they offer **development prospects,** especially in regions with a weak economic structure. In addition to direct and indirect jobs, this also creates induced employment effects. These refer to the fact that, due to the higher income in the region, the consumption of everyday goods increases and thus new employment is also created (Milani 2020; Craig 2019).

Furthermore, the expansion of solar thermal power plants in regions with a weak economic structure can lead to the creation or improvement of **infrastructure**, such as transport routes or the energy and water supply. The regional population and economy also benefit from this. In addition, the location becomes more attractive for the relocation of other companies (Wuppertal Institute 2015).

Assembly of collectors for a parabolic trough power plant. Credit: sbp sonne

With regard to employment effects, however, reference should also be made to possible negative effects that generally relate to the expansion of renewable energies. They particularly affect countries that export fossil fuels. The expansion of energy from renewable sources has the potential to influence the employment situation in the previously predominantly fossil energy sector, the development of national energy costs, as well as the export share of fossil-derived energy and thus foreign exchange earnings. In principle, however, the export of energy from renewable sources represents a longer-term possibility compared to that of fossil resources (United Nations 2020, Dii 2013).

Other aspects that go beyond the consideration of employment are, for example, greater energy independence and cost control of the domestic energy supply, particularly for countries that were previously importers of fossil fuels (Dii 2013).

11. Which factors support an accelerated proliferation of this technology?

In the next 20 years, solar thermal power plant capacity is expected to expand globally by a factor of between 10 and 40, depending on the level of support assumed.

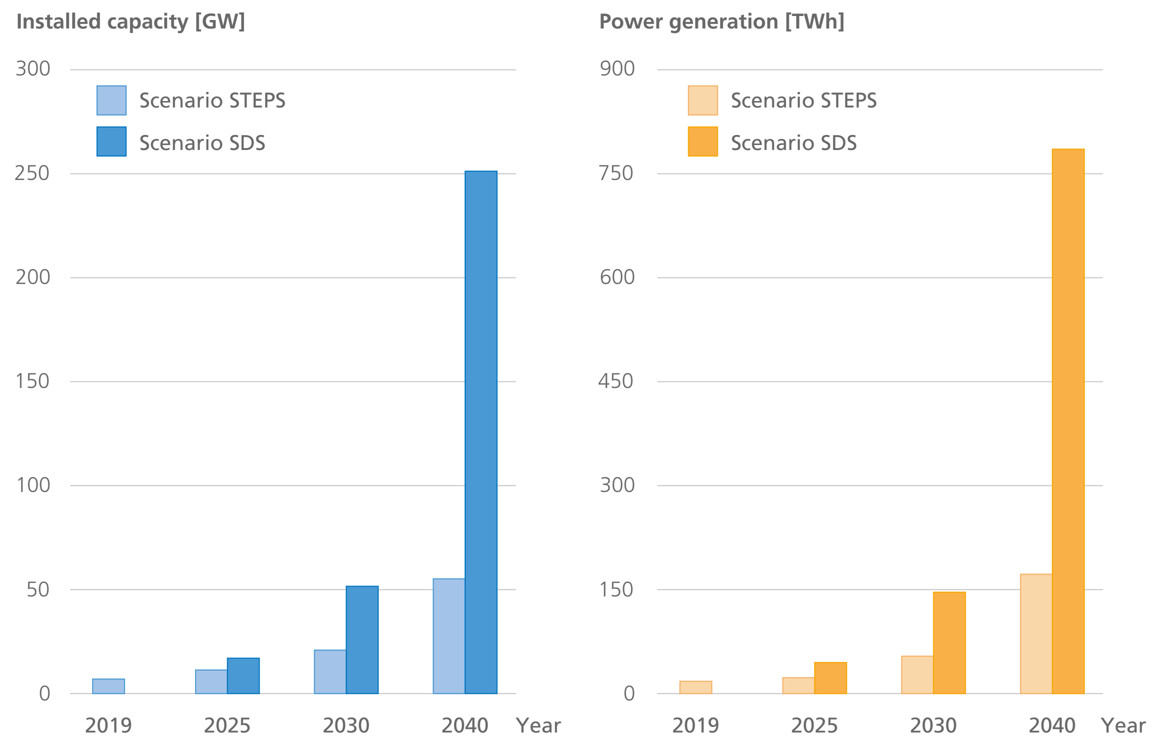
In sunny countries, a new solar thermal power plant project is usually one of the possible alternatives for generating electricity from renewable energy sources, which are still in competition with fossil-fuel power plants. In this competition, the cost of electricity generation plays a decisive role. Ultimately, however, whether solar thermal power plants become part of a national energy supply strategy depends on political will and the energy policy framework conditions (IEA 2010).

In all areas of technology, increasing production volumes combined with permanent improvements based on research and development lead to lower production costs. Until now, solar thermal power plants have only been able to benefit from such **'economies of scale'** to a limited extent. Their components are not in demand by a large number of decentralised users, as is the case with PV solar modules from homeowners. This is because at the moment only a limited number of new power plants are being built around the world each year. Economies of scale therefore develop more slowly here than in sectors with more dynamic demand development.

Since solar thermal power plants can feed their electricity into the power grid even after sunset, they are of particular value for an energy system based on renewable energy sources. Solar thermal power plants are of strategic importance in sunny countries to be able to phase out coal and gas power plants in the future. In order to promote them, political institutions should create suitable and predictable market conditions (IEA 2014). National governments can, for example, set targets for the expansion of selected technologies. Spain's National Energy Plan foresees the construction of solar thermal power plants with a total capacity of five gigawatts by 2030. In technology-open tenders for power generation systems, the decision on which technology is awarded the contract should not be based solely on the electricity production costs. The evaluation should also take into account the fact that solar thermal power plants can supply dispatchable solar power and thus compensate for the fluctuating output of PV and wind systems.

The accelerated expansion is also supported by long-term Power Purchase Agreements (PPAs) between power plant operators and consumers with a term of 20 to 30 years, attractive financing conditions and loan guarantees from public financing institutions (Lilliestam 2020). Such prerequisites would enable scenarios such as those considered in the current World Energy Outlook of the International Energy Agency (see graphic).

Another tool to reduce costs is the creation of internationally recognised **quality standards** for components and processes. They reduce uncertainty among investors and operators, as they guarantee consistently high quality from all suppliers. In addition, they enable standardised processes for the assembly and operation of the power plant, which shortens the construction time and enables a more efficient operation. This is also rewarded by insurance companies and banks in their risk assessments and in terms of financing conditions. The introduction of International Organization for Standardization (ISO) standards will require the development of new measurement techniques for quality assurance.



Possible expansion scenarios for CSP according to the International Energy Agency's World.
STEPS: Stated Policies Scenario) (status 2020);
SDS: Sustainable Development Scenario(necessary measures to achieve the UN sustainability goals, in particular limiting global warming to 1.5 °C if possible, in any case to below 2 °C).

An important prerequisite for the successful construction and operation of a power plant is a skilled workforce. National organisations for international development cooperation should therefore promote suitable programmes for training and further education of local specialists. This happened, for example, in the DLR enerMENA project for the training of skilled workers in the North African region, which was supported by the German Foreign Ministry.

In Europe, the promotion of **cross-border energy markets** can play an important role in opening up new sales markets for power, heat, hydrogen and electricity-based fuels from solar thermal power plants in southern European countries, while at the same time reducing energy supply costs and increasing security of supply (Trieb 2016; Boie 2020).

12. How can this technology contribute to sector coupling?

Concentrating Solar systems can contribute to the decarbonisation of the heat and fuel sectors.

Solar process heat generation at Kean Soft Drinks Ltd. in Limasso, Cyprus. Foto: Protarget AG

The ability to generate heat at different temperature levels, store it and release it again as required opens up areas of application for solar thermal power plant technology beyond electricity generation. These include the provision of heat for the industrial sector and the production of renewable hydrogen and synthetic fuels for the transport sector.

The industrial sector accounts for approximately one-third of the world's total energy consumption, around three quarters of which in the form of heat. Industrial heat energy demand exceeded total global electricity consumption by 18 percent (85 exajoules compared to 72 exajoules; own analysis from IEA 2020: Data and statistics).

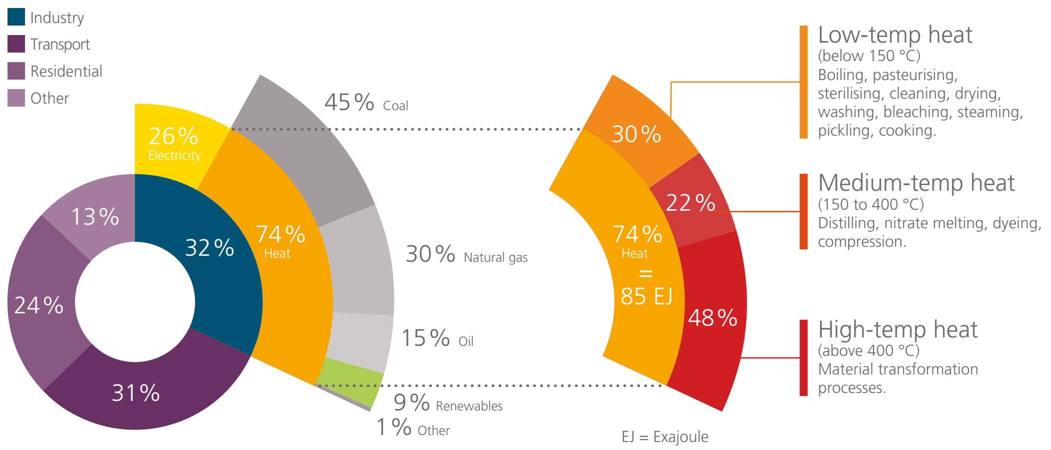
For the **temperature range up to 400 °C,** which accounts for over half of the world's industrial heat demand, application-ready parabolic trough and linear Fresnel collectors are available from various manufacturers. A parabolic trough system in Cyprus, for example, supplies steam for a fruit juice production plant via a heat transfer oil circuit. Information on further application examples can be found in the database initiated as part of IEA Task 49/IV on the Internet at ship-plants.info.

Two factors are still hindering the spread of the technology. Firstly, the diversity of industrial applications and relevant local conditions make standardised solutions for the integration of solar systems into the overall systems difficult to find. Secondly, due to the small number of systems built to date, there is a lack of experience and visibility and, as a result, a lack of confidence among users and investors. An IEA working group, in which German research institutions and industrial partners are playing a significant role, is addressing these challenges with the aim of making solar thermal energy a recognised and reliable component of industrial process heat supply (IEA 2020: Task 64).

The EU requirement for the member states to increase their share of renewable heat by 1.3 percentage points annually by 2030 (EU Renewable Energy Directive 2018) gives German technology providers the opportunity to implement commercial reference systems in the domestic market and to build up production capacities. German **district heating** systems delivered 161 terawatt hours in 2017 (Federal Statistical Office). Meeting the EU target in this sector would require the construction of five million square metres of collector area annually. For comparison, the market volume for solar thermal collectors in Germany in 2019 totalled around 0.5 million square metres (mainly flat-plate and evacuated-tube collectors for domestic hot water and central heating support) (BSW-Solar 2020). In this application, parabolic trough collectors achieve the same annual energy yields as flat-plate or evacuated-tube collectors – or even higher – in the local climate (VDI guideline 2020) and can represent an advantageous technology option in Germany, especially for larger systems (DCSP 2020).

Four particularly **energy-intensive industries** use high-temperature heat in the range above 400 °C – iron and steel, aluminium, chemicals and petrochemicals, and lime and cement (IRENA 2020: Reaching Zero with Renewables). Solar tower systems are capable of generating temperatures in excess of 1000 °C and can deliver the required heat to the respective process – either directly through concentrated radiation or via suitable heat transfer media. Technologies for applications in these industries are still at an early stage of development, on a laboratory or pilot plant scale.

Hydrogen will play a prominent role in the transformation of the energy sector. It can serve as a storage and transport medium, as fuel and as a carbon-free energy carrier, as it is the starting product for the production of a whole range of liquid fuels and basic materials, such



Global final energy consumption 2014 (Epp 2017)

as ammonia. However, hydrogen is only sustainable if it is split from the raw material water using renewable biomass or renewable energy sources to power the process. A comprehensive study describes the state of development and the need for research in the field of solar hydrogen generation from the perspective of DLR (DLR 2020). The focus is currently on the following processes: water electrolysis with renewable electricity from the sun and wind, the reforming of biogas and thermochemical water splitting.

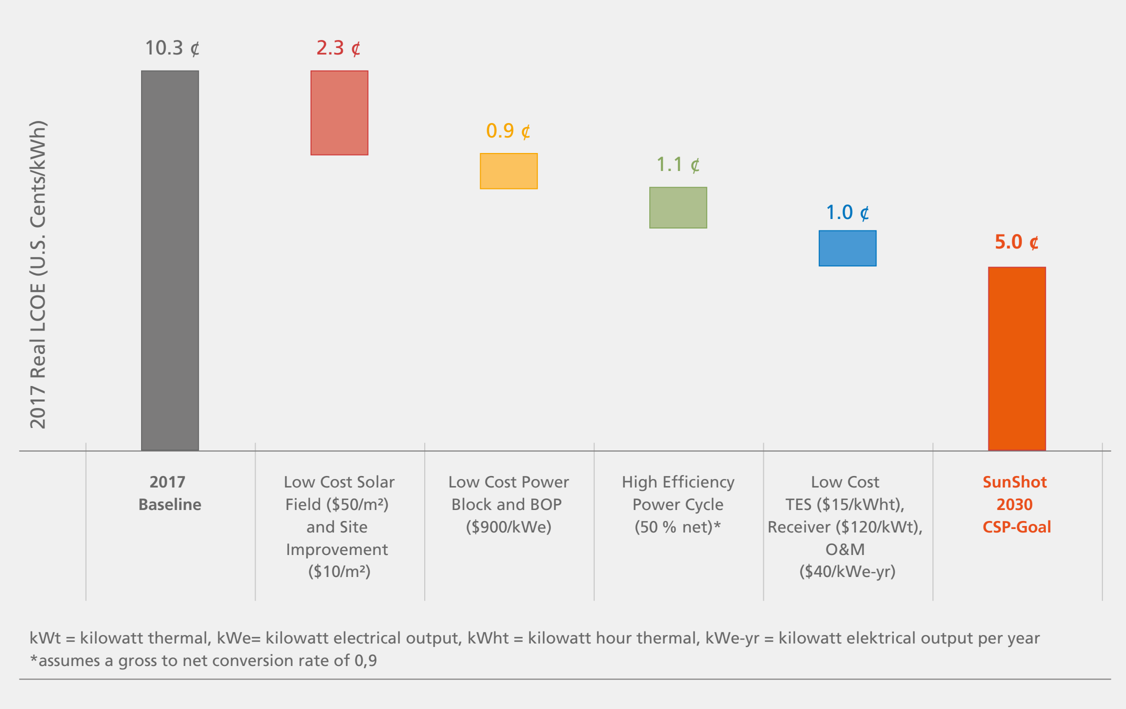
At DLR's solar simulator in Cologne researchers successfully tested the solar-powered calcination of raw cement powder as a step in cement production. Credit: DLR

The most developmentally advanced and, so far, only commercially available technology for the production of hydrogen from the raw material water is **electrolysis.** Large electrolysis capacities for hydrogen production from renewable energy are to be built up in the next few years. For the production of green hydrogen, CSP technology can provide not only electricity but also the heat from solar energy required in special high-temperature electrolysers. In this process, the electricity consumption of the electrolysis can be reduced and the hydrogen production costs thus lowered. Solar tower systems are particularly suitable as energy suppliers for thermochemical processes that require high-temperature heat at temperatures above 1000 °C. These processes have a potentially higher efficiency and use less land than the electrolysis process.

In the longer term, **solar thermochemical** metal oxide redox **cycle processes** in particular represent a promising possibility for producing hydrogen economically and on a large scale. Research work in national and international projects has significantly developed the processes and the necessary components and materials in recent years. The first pilot systems, such as the demonstration system for the EU project SUN-to-LIQUID in Móstoles, Spain, are now in operation.

13. How can technical innovations further reduce costs?

The electricity production costs for plants using renewable energy sources essentially depend on three factors. How much electricity does a plant of a certain size generate at a certain location? How expensive is it to construct? How much effort has to be invested in operation and maintenance per year in order to be able to operate it for more than 20 years? Technical innovations can influence all three areas and thus contribute to reducing costs. The US Department of Energy (DOE) calculated costs of 10 US cents per kilowatt-hour for electricity from solar thermal power plants in a good location for 2017 based on the technologies available at the time (Solar Energy Technologies Office 2017). This number is below the prices actually achieved by solar thermal power plants at that time, as they usually did not have access to the latest technologies due to the lead time in planning and mostly had different locations and financing conditions than those assumed by the DOE for the USA. As part of a roadmap, the DOE shows how these costs can be halved to around five US cents per kilowatt-hour of electricity by 2030 (see graphic). DLR determined similar cost reductions as part of a study commissioned by IRENA (Dersch 2019).



Example of a development path towards five US cents / kWh for base load-capable CSP electricity (Solar Energy Technologies Office 2017)

One adjustment mechanism for increasing annual electricity production is the efficiency of the system, that is, the efficiency of converting solar radiation into electrical energy. Since solar thermal power plants generate this via the conversion chain 'solar radiation-to-heat-to-electricity', improvements at all links in the chain have an impact. The most important starting point is the steam turbine (a heat engine), in which thermal energy is converted into mechanical energy. Since, according to thermodynamic principles, the efficiency increases at higher process temperatures, researchers and companies in the field of power plant development are looking for ways to improve the efficiency of this process.

The working temperature can be increased from 565 °C today to up to 700 °C in the future. To do this, the heat receiver, the heat transfer medium, the energy storage and the entire power plant circuit must be adapted to the higher temperature level. In particular, changing the heat transfer medium has a considerable influence on the design of the other components mentioned.

Studies predict an increase in the conversion efficiency of heat to electricity from around 42 percent today to 50 percent in 2030 (Solar Energy Technologies Office 2017, subsumed in the figure under the item 'Highly efficient power plant cycle'). Steam power plants with higher steam conditions (pressure, temperature) or innovative gas turbine systems that use CO_2 as the circulating medium instead of air (S-CO_2 turbines) are suitable for this. The latter are not yet available on a large scale. Promising heat transfer media that are suitable for the temperature range mentioned are salt mixtures, ceramic particles or liquid metals (Ho 2014). The challenge is to develop systems on the basis of these media that allow the thermal energy to be made available at the temperatures mentioned, to be stored and to be coupled into the power plant cycle.

Through technical innovation the cost of electricity production can be halved to five US cents / kWh over the next 10 years.

The increased process temperature also has a cost-reducing effect on the thermal energy storage system (see graphic, cost reduction storage), as more energy can be stored per unit of storage mass at a higher temperature.

The second important way to reduce electricity costs is to decrease the cost of the **solar field** of the system (the solar mirrors or concentrators). Targeted measures should reduce the costs from around 100 US dollars per square metre today to around 50 US dollars per square metre in 2030 (see figure, Low Cost Solar Field). Efficient production technology and logistics can reduce the production costs of the individual parts and accelerate the construction. Digitalisation and inexpensive optical sensors will enable intelligent, individual tracking and readjustment of the mirrors in the future. The required high optical quality of the systems will then no longer be dependent on costly, high-precision manufacturing and assembly. Further cost reductions can be expected as concentrator technology is only at the beginning of a learning curve that usually leads to a cost reduction of up to 20 percent when production capacities are doubled (Samadi 2018; Pitz-Paal 2017).

In the area of **thermal storage,** there is the potential to reduce capital costs in the double-digit percentage range through innovative storage concepts. One promising approach is to replace the two-tank storage systems with a single-tank storage system containing a filler. An inexpensive filler such as rock also stores heat and replaces a large part of the molten salt. This approach brings further advantages such as less expensive salt pumps and significantly lower heat losses (Klasing 2020). The already mentioned use of alternative power plant cycles allows a higher energy density in the system and thus a reduction in investment costs (see graphic, Low Cost Power Block and Balance of Plant).

Reducing the annual **operating and maintenance costs** from the current level of 60 to 40 US dollars per kilowatt-hour of electricity generated (see graphic, O&M - operation & maintenance) requires improvements in regulation and control. This involves the precise recording of all operating states with extensive operation automation. The detailed knowledge of the condition of the system makes it possible, for example, to carry out maintenance in advance and to save water by cleaning the mirrors only when necessary – not at fixed intervals as before.

14. How is DLR contributing to research and development work?

DLR has played a key role in the development of concentrating solar systems for solar thermal power plants for more than 40 years. As the coordinator of an international consortium, it was responsible for the construction of the first pilot power plant in Almeriía, Spain, at the end of the 1970s. For the first time in Europe, proof of the technical feasibility of solar thermal power generation was provided. From 2003 onwards, the commercial market launch, especially in Spain, was also supported by site analyses, collector development, feasibility studies, quality assurance measures and the training of personnel, thus making it easier for German companies to enter the market.

Today the high output in most solar fields of solar thermal power plants worldwide is based on technologies that were developed and marketed by DLR. For example, the development of advanced optical metrology has made it possible to analyse the optical accuracy of solar collectors both on site and in the laboratory with an accuracy and speed never before attained. This has led to a continuous improvement of these components and systems. Today the most extensive research and development work in this area in Germany is carried out at the DLR Institute of Solar Research.

From January 2021, the research topic of solar-generated fuels is also being further developed and expanded at the newly founded DLR Institute of Future Fuels. Research into this and the further development of thermal storage is being carried out by the DLR Institute of Engineering Thermodynamics. Five additional DLR institutes are working on other issues relating to concentrating solar technologies. In total, more than 200 researchers from seven DLR institutes are involved in research in the field of concentrating solar technologies.

As part of a long-term cooperation, researchers from the Institute of Solar Research are working at the largest European test facility for concentrating solar systems, the Plataforma Solar de Almería (PSA). The Spanish research centre CIEMAT is the owner and operator of the PSA.

Unique DLR test facilities, such as the Jülich experimental solar power tower and multi-focus tower , enable the use of concentrated solar radiation on a megawatt scale and under real operating conditions. In southern Spain, DLR researchers have access to the test facilities of the Plataforma Solar de Almería, which is operated by the Spanish research centre CIEMAT.

The objectives of our research are further improvements in the efficiency of the technology as well as product and process improvements in order to reduce the cost of generating electricity. The DLR sees itself as a bridge builder between research and industry. Together with industrial partners, we transfer innovations from the laboratory to large-scale applications.

Current research activities focus on the four areas highlighted below:

New heat transfer and storage media can withstand temperatures of 600 °C, higher than has previously been possible in solar thermal power plants. This increases the efficiency of converting solar radiation into heat and then into electricity. The power plant can then generate more electricity with the same collector area, so that the cost per kilowatt-hour decreases. DLR is developing and testing components and processes for the use of suitable new heat transfer and storage media together with various industrial partners. A company founded with support from DLR will further develop and market the technology developed at DLR (→ HelioHeat).

Optical measurement techniques, which are based on data acquisition using unmanned drones and the QFly system developed at DLR (Prahl 2017 and 2018), are intended to enable automated condition monitoring of large solar fields. It is much easier to inspect the mirror field from the air than from the ground. The use of sophisticated optical measurement techniques and sensors make it possible to localise defective components, contamination or the need for adjustment much more quickly and cost-effectively than before. Two DLR spin-offs are distributing and further developing the technology as licensees (→ CSP Services, Volateq).

DLR researchers are using the high-resolution data from solar power plants to enable **intelligent and autonomous operation** of solar power plants using machine-learning algorithms. In this way, power plants will be able to regulate their electricity production in line with the expected electricity demand, and predictive maintenance should further reduce the operating costs of solar power plants (Do Amaral Burghi 2020). Here, too, the development is taking place in close cooperation with a spin-off company (→ Heliokon).

Finally, methods that use **solar high-temperature heat for chemical processes** are to be developed to industrial maturity. Since this often requires significantly higher temperatures compared to solar thermal power generation, the focus is on the development and qualification of suitable materials, chemical reaction agents and reactor concepts (Falter 2018).

DLR institutes working in the research field of concentrating solar technologies:

- **Institute of Solar Research**
  › https://www.dlr.de/sf/en
- **Institute of Future Fuels**
  › https://www.dlr.de/ff/en
- **Institute of Engineering Thermodynamics**
  › https://www.dlr.de/tt/en
- **Institute of Materials Research**
  › https://www.dlr.de/wf/en
- **Institute of Atmospheric Physics**
  › https://www.dlr.de/pa/en
- **Institute of Networked Energy Systems**
  › https://www.dlr.de/ve/en
- **Institute of Low-Carbon Industrial Processes**
  › https://www.dlr.de/di/en

DLR spin-offs in the field of CSP

- **CSP Services**
  › https://www.cspservices.de/
- **HelioHeat**
  › http://helioheat.de/
- **Heliokon**
  › https://heliokon.com/
- **Volateq**
  › https://www.volateq.de/

The Jülich solar towers test facility for solar thermal power plants is operated by the DLR Institute of Solar Research.

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Parabolic trough at the Plataforma Solar de Almeriía (PSA). The PSA is owned and operated by the Spanish research centre CIEMAT.

Imprint

Publisher:
German Aerospace Center (DLR) Institute of Solar Research
www.dlr.de/sf/en/

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Participating institutes:
Institute of Engineering Thermodynamics
Institute of Future Fuels
Institute of Networked Energy Systems
Institute of Solar Research

Design:
bplusd agenturgruppe GmbH
The Ship, Vitalisstraße 67, 50827 Cologne
www.bplusd.de

Publication:
Cologne, May 2021

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Solar thermal power plants_GB_05/2021

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German Aerospace Center

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag