MASTER-THESIS

Comparison between various concepts of Solar Thermal Power Plants

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Dedicated to Univ.Prof. i.R. Dipl.-Ing. Dr.techn. Erich Rummich,

protagonist of solar technology

Zusammenfassung

Die vorliegende Studie beschäftigt sich mit der Möglichkeit, elektrische Energie oder Prozeßwärme über die Bündelung von Sonnenlicht bereitzustellen. Seit einigen Jahrzehnten gibt es Anlagen, die das Prinzip der konzentrierenden Solarstrahlung im großtechnischen Maßstab ausnützen. Diese Technologie erlebt derzeit eine Renaissance. An vielen Orten der Erde werden neue Großprojekte zur Nutzung konzentrierter Solarstrahlung geplant und auch schon errichtet. Steigende Energiepreise, Klimawandel und politische Umstände sprechen dafür, daß diese Technologie nach einigen Rückschlägen in den vergangenen Jahren nun endgültig den Durchbruch schaffen wird.

Die vorliegende Arbeit analysiert den Stand der Technik, fasst Produktionskosten für Strom aus konzentrierenden Solarsystemen zusammen und listet einschlägige Projekte auf. Außerdem werden bestehende technische Probleme und zugehörige Lösungsvorschläge sowie vorhandene Entwicklungspotentiale aufgezeigt.

Abstract

In this thesis the generation of electricity and production of process heat by concentrated sunlight is studied. The principle to concentrate sunbeams was already applied on a large scale several decades ago. In the meantime this technology had to face several difficulties and was not widely applied. Because of rising energy prices, climate change and political circumstances this technology currently is on the increase. Probably concentrating solar power will make the breakthrough now.

In the present study, state-of-the-art of concentrating solar power plants is explained. Furthermore, cost of electricity produced by solar power is given as well as an enumeration of solar power projects. Current technical problems are analyzed with respect to future development potential.

Keywords: *solar power, solar energy, solar trough, solar tower, Dish/Stirling, CSP, concentrating solar power;*

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2 Abbreviations

BMU – Bundesministerium für Umweltschutz, Naturschutz und Reaktorsicherheit (German Federal Ministry for Environment)
CAD - Computer Aided Design
CCD - Charge-Coupled Device
CCStaR - Collector Solar Concentrador Amb Reflector Estacionari (?)
CENIM – Centro Nacional Investigaciones Metalurgicas (National Center for Metallurgical Research, Spain)
CFD - Computational Fluid Dynamics
CLFR - Compact Linear Fresnel Reflector
COP - Coefficient Of Performance
CPC - Compound Parabolic Concentrator
CPV - Concentrating Photovoltaic
CPVT - Concentrating Photovoltaic/Thermal
CRS - Central Receiver System
CSP - Concentrating Solar Power
DC – Direct Current
DISS – Direct Solar Steam (Direct Solar System?)
DLR – Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DNI - Direct Normal Irradiation
ECOSTAR - European Concentrated Solar Thermal Roadmap
FEM - Finite Element Method
FHTW – Fachhochschule für Technik und Wirtschaft Berlin (University of Applied Sciences)
GBA - General Blockage Area
GEO - Geostationary Earth Orbit
GSP – Gross State Product
HCE - Heat Collection Element
HCPV - Heliostat Concentrator Photovoltaic
HITREC - High Temperature Receiver
HLV - Heavy Launch Vehicles
HVDC - High Voltage Direct Current (Transmission)
HYTEC - Hydrogen Thermo-chemical Cycles
IEA – International Energy Agency
IHCPV - Integrated High Concentration PV
IKTS - Institut Keramische Technologien und Sinterwerkstoffe (Fraunhofer Institute for Ceramic Technologies and Sintered Materials)
ISCCS – Integrated Solar Combined Cycle Systems
ISFOC - Instituto de Sistemas Fotovoltaicos de Concentración (Institute For Concentrating Photovoltaic Systems)
LEC - Levelized Electricity Costs *(total cost of electricity per energy unit including insurance, O&M, fuel and investment costs; [1] p.13 contains the exact formula.)*
LEO - Low Earth Orbit
LFR – Linear Fresnel Reflector
LHTES - Latent Heat Thermal Energy Storage

LSC - Luminescent Solar Concentrator
MICA - Multiyear Interactive Computer Almanac
MIUS - Modular Integrated Utility Systems
MTSA - Multi-Tower Solar Array
NREL - National Renewable Energy Laboratory (USA)
O&M - Operation and Maintenance
ORC - Organic Rankine Cycle
OTV - Orbital Transfer Vehicle
Pb - Lead
PCM - Phase Change Materials
PRS - Power Relay Satellites
PSA - Plataforma Solar de Almería
PV – Photovoltaic
PV/T – (combined) Photovoltaic – Thermal Solar Collector
REFOS - Receiver For Fossil-Hybrid Gas Turbine Systems
reSiC - re-crystallized Silicon Carbide
Rh – Rhodium
RPS - Renewable Portfolio Standard
RRM - Raster-Reflexionsmethode (Raster Reflection Method)
RRPGP - Renewable Remote Power Generation Programme
SCOT - Solar Concentration Off-Tower (Reflective Tower)
SEGS - Solar Energy (or Electric) Generating Systems
SFV - Solarenergie-Förderverein Deutschland e.V.
Sn – Tin
SOLASYS - ?
SOLGATE - Solar Hybrid Gas Turbine Electric Power System
STEPS - Expert System for Solar Thermal Power Stations
TEWA - Technologien zur Beherrschung des Wasserstoffproblems in Parabolrinnen-Receivern (Technology to master Hydrogen diffusion in parabolic trough receivers)
TOE – Tons of Oil Equivalent
WESPE - ?
YNES - Yearly Normalized Energy Surface
Zn – Zinc

3 Introduction

Rising energy costs and climate change caused by carbon dioxide (CO_2) emissions are the two main reasons that make technicians, scientists, politicians and many other people search for alternative solutions for the production of electric energy.
But there are some additional reasons why humanity should find new ways of energy supply than the conventional "fossil way":

- Fossil energy will some time run short.
- Fossil energy is often used as a medium of political power and political suppression.
- Renewable energy guarantees – if it is introduced in a decent way – employment, security and stability to both high- and low-qualified people.
- Renewable energy supply is a decentralized sort of energy supply more often than not. Decentralization on one hand does sometimes reduce economic efficiency but is not dependent on vulnerable transporting lines and political circumstances on the other hand.

At present time the world uses coal, natural gas and oil to produce electricity in front of all. Apart from hydro power no other renewable sort of energy has significant share in world-wide electricity production. The current state in the energy sector, which was presented 2007 by the Inter Academic Council, Amsterdam and the International Energy Agency, respectively, can be seen in Figure 1 and Figure 2 on the next page.
You can either take the total primary energy consumption or the final energy consumption to look at the share of alternative energy. No matter if we take the percentage composition of total final energy or of primary energy, it is obvious that fossil fuels are dominating the market. Non-conventional energy makes unfortunately just a very small part of total energy supply.

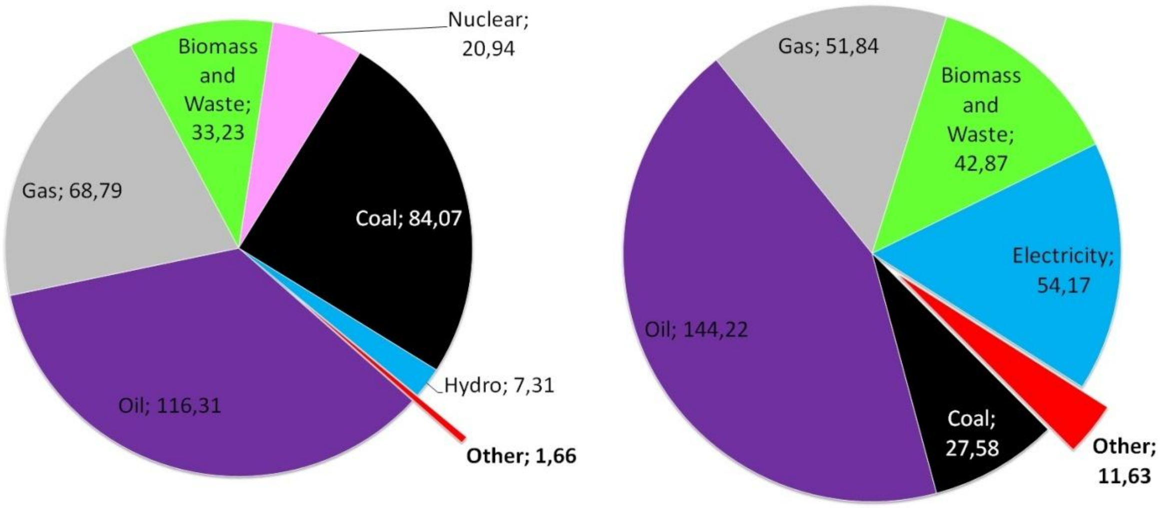


Figure 1: Shares of Total Primary Energy Supply (left) and Total Final Energy (right) in the year 2005. Values are given in Exa Joule (EJ). It is obvious that the worldwide energy market is still dominated by fossil fuels (oil, gas, coal). The category "biomass and waste" also includes a fossil part because most products are derivated from fossil fuels; data source: [2];

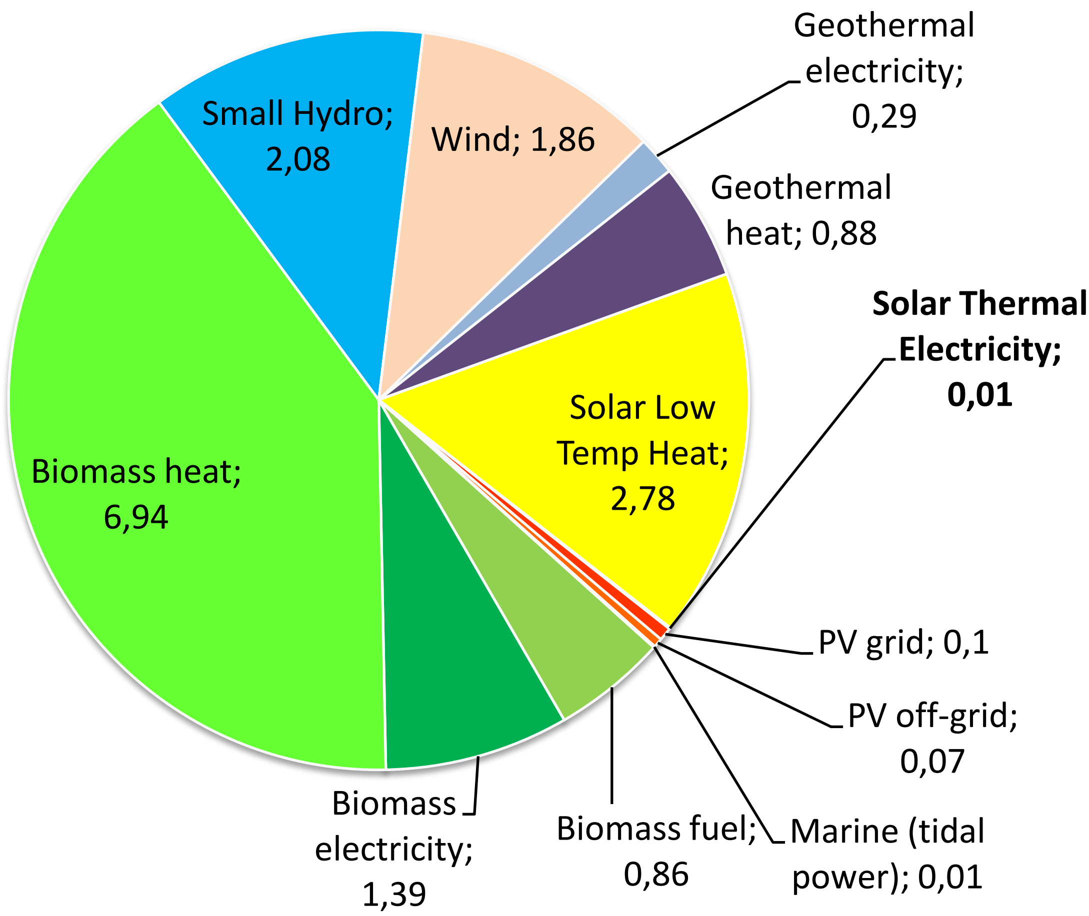


Figure 2: The share of Solar Thermal Electricity and Photovoltaic (PV) of worldwide 2005 energy production was rather low, even compared to other alternative energy sources. Large Hydro plants are excluded in this chart. Values are given in Exa Joule (EJ); data source: [3] p.94, International Energy Agency (IEA);

CSP – concentrating solar power

In mid-Europe many people are well-informed about photovoltaic cells but they underestimate the worldwide electric energy potential of CSP. This is caused by the fact that our region meets the requirements for electricity production by photovoltaic cells but not for solar concentrating power. Therefore the most productive solar concentrating power sites are in California and Spain, not in Central Europe at present time. All these facts can be seen in the following chapters of this work.

In [4] Klaiß, H. et al. name several reasons why solar concentrating power could play an important role in energy supply especially in developing countries in the near future:

- 320 billion US$ per year (1995) are invested in electricity supply systems
- In most of the developing countries power plants are still oil-fired. CSP technology would be a proper alternative because direct normal irradiation over the year, the most important factor for concentrating solar power, is very high in these regions.
- Inhabitants of developing countries generally have to pay more for one unit of electric energy than inhabitants of rich countries because of low efficiency of energy conversion. Even though they earn far less in average.

But there are many additional reasons why also Europe should show ambition to invest in solar concentrating power, in the economy sector as well as in the scientific area.

Many studies dealing with solar-concentrating power start with a general overview of main concentrating solar power (CSP)-types and also include the physical background and the potential of concentrating solar systems to substitute conventional energy. Because it is not the aim of this work to repeat what many other authors have already published, just references to useful literature and a very brief overview is listed in the chapter below.

In several articles basic information about manufacture and about the design of a concentrating mirror – derivated from the theoretical background of geometry of parabolas, approximation of parabolas by circles etc. - are given. The principle construction of concentrating systems (example of a fibreglass reinforced parabolic trough collector) is described in [5].

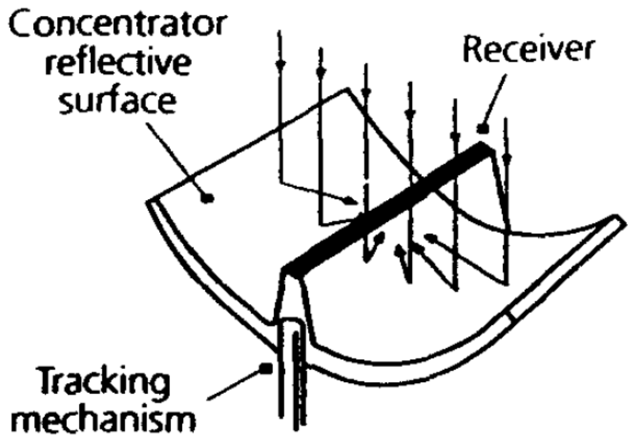
The three main principals to concentrate the sunlight for electricity producing purposes can be summarised as follows:

- **Parabolic dish / parabolic trough / solar tower:** They concentrate sunlight on a single point or a single line. This work deals with these three technologies mainly. They are described in the next chapter.
- **Optical lenses:** Optical elements with characteristics well known from physics are used to concentrate the sunlight. If arranged in an array, we talk about "compound lenses". Because of high prices and other conditions the use of lenses is not very widespread in CSP but Fresnel lenses (listed below) were derivated from them.
- **Fresnel systems:** They can be summarised as derivations from lenses or parabolic mirrors. The aim of constructing such Fresnel systems was to economise in front of all. In addition to economic advantages Fresnel technique has several further advantages, studied in this work.

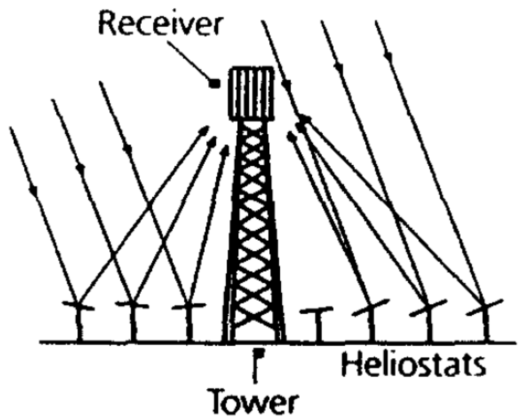
4 Basic solar power concepts

4.1 Common concentrating concepts: solar trough, solar dish and solar tower

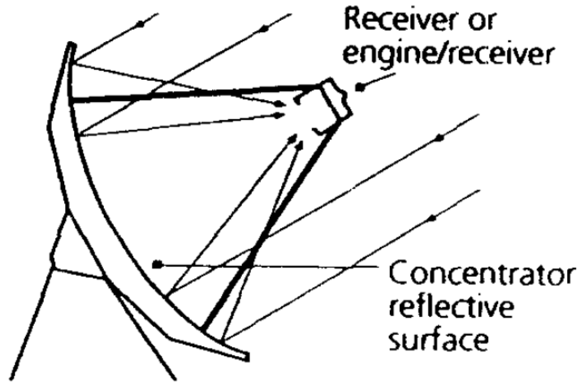
To give a short overview the main systems are shown in Figure 3.



a) Parabolic Trough



b) Solar Tower



c) Dish / Stirling

Figure 3: Three basic technologies of concentrating solar power systems: solar (parabolic) trough, solar tower and dish/Stirling; Source: [4] p. 167;

Each of these three basic systems, "Solar Trough", "Solar Tower" and "Solar Dish" have their specific advantages and disadvantages but all of them are based on the same basic principle: They concentrate the direct irradiation that hits their reflective surface and focus it on a smaller surface, which is called receiver. The rate of these two values is called "concentration ratio", often abbreviated as "C". Instead of "concentration ratio" many authors also use the expression "suns", e.g. a concentrating system that has a concentration ratio of C=100 can also be named a "100-suns-system". This means that energy flux on a square metre on the receiver is 100 times as high as direct solar energy flux on an ambient surface.

For a rough orientation one can estimate the concentration ratio at 30-80 for parabolic troughs, 200-1.000 for solar towers[1] and 2.000 up to 4.000 for solar dish systems[2]. [4] p.167, [6] p.5-46., [7] p.5-27.

General introductions, construction principles and further detailed information can be found in the following sources, that also include the theoretical background of solar concentration: [8], [4] p. 167 [9], [10], [11] pp. 68ff, [12], [13], [14], [15], [16], [17], [18], [19], [20], [21] and [22] pp 2-1ff; A detailed description of Compound Parabolic Concentrators (CPC), V-troughs[3] and parabolic troughs is illustrated in [23]. [24] discusses storage systems.

4.2 Requirements for CSP-sites

- CSP systems will always be erected in regions which have **low land prices**. Concentrating solar power in regions with high population density is mostly placed on flat roofs of industrial buildings where process-heat is needed.

  But also if the demanded ground is very cheap (like in most deserts in the world) one should try to reduce the use of space for solar concentrating systems from some other reasons which have effect on costs of such a plant. "Avoidance of large reflector spacing and high towers is an important cost issue when one considers the cost of ground preparation, array substructure, tower structure, steam line thermal losses, and steam line cost for installation next to an existing fossil fuel generating plant where the objective is the retrofit of a low pollution steam source," as Mills, D. R. and Morrison, G. L. state in [25].

1 Up to 5.000 ([105] p.4) or even 10.000 ([58] p.243), especially if secondary concentration is used.
2 According to [188] p.8 even rates of 11.000 can be reached.
3 A trough, the profile of which is shaped like a V instead of a parable.

- **High direct normal irradiation**

  A rough overview of sites where concentrating solar power plants could be placed and a comparison of potential of thermal electricity production is given in [4] p.179ff. More detailed information can be found in [26], pp.35ff.: Trieb, F. describes this so-called STEPS (Expert System for Solar Thermal Power Stations) project run by the German DLR. It dealt with the detection of direct normal irradiation (DNI) over a wide area. In contrast to in-situ studies that give very detailed information this is a much cheaper access for analysing the solar potential of a whole region. In [26] pp.35ff Morocco's potential for CSP was analysed. The results from such an analysis based on satellite-data are roughly equivalent to a system based on earth-bound measuring stations which have a distance of 50 km to each other. Of course cost level of the satellite-method is much lower. Czisch, G. ([34], [20], [35]) gives very detailed world-maps that illustrate the differences of world-regions: Some parts of the world have good irradiation conditions for solar concentrating power while the use of photovoltaic systems is suggested by physical circumstances in other parts of the world. There are some facts that are very surprising shown in the pictures: Direct horizontal insolation and even total global horizontal insolation (kWh/m²/a) are significantly higher for almost every Antarctic territory than on the equatorial region of the world. (Figure 4 and Figure 5) Consequently the gains of electric energy from photovoltaic as well as gains of thermal energy from parabolic troughs are also higher in Antarctic than in many countries on the equator. (Figure 6 and Figure 7) This seems to be unbelievable at first sight but considering e.g. cloudy weather conditions on equatorial regions it becomes more plausible. Fortunately energy demand is not very high in equatorial region yet.

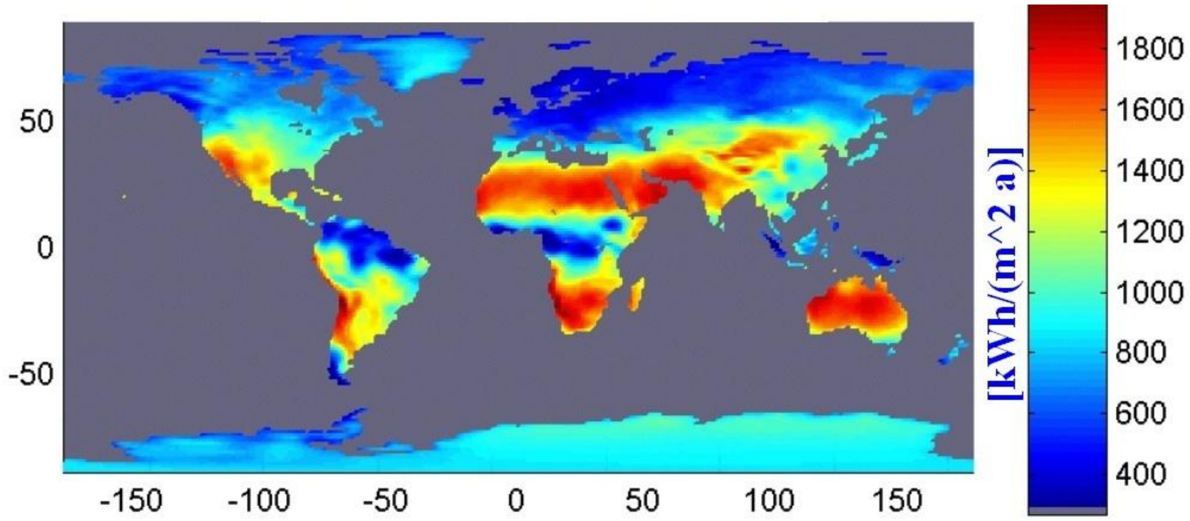


Figure 4: Direct Horizontal Irradiation; source: [34];

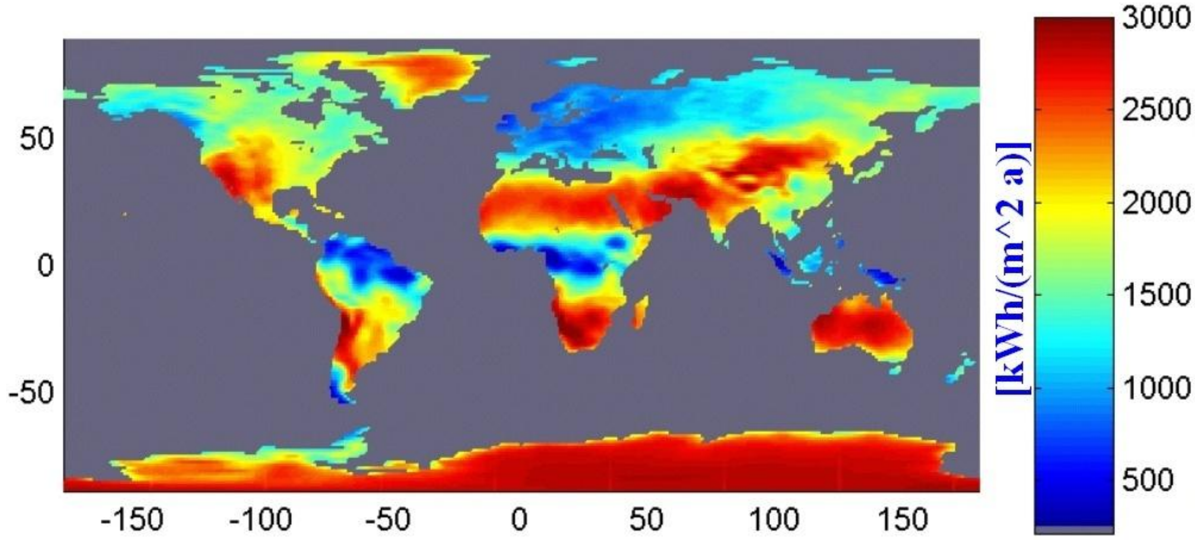


Figure 5: Direct Normal Irradiation; source: [34];

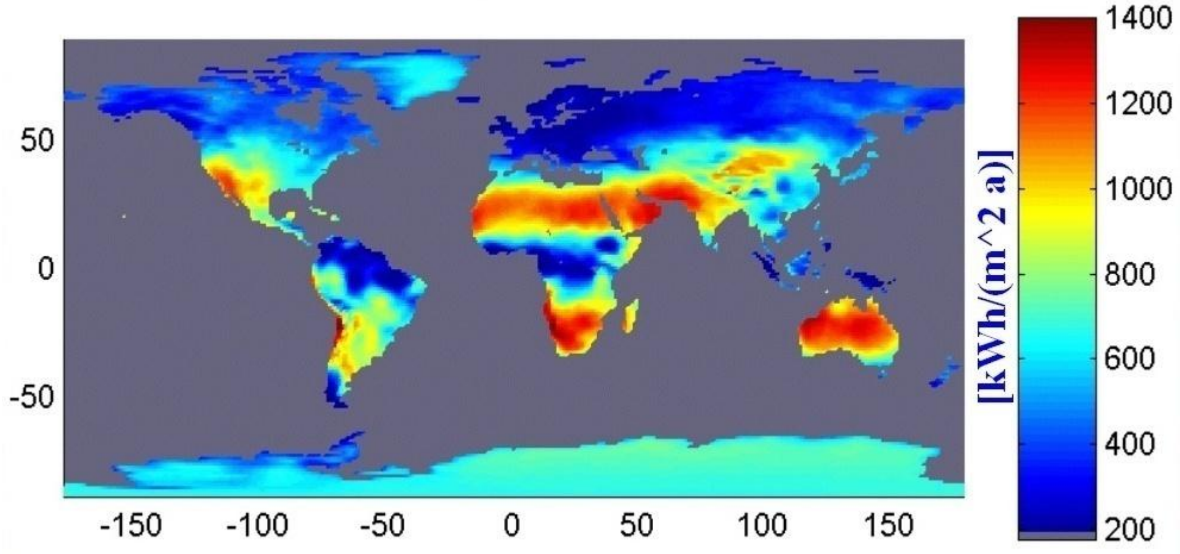


Figure 6: Thermal energy from solar troughs; source: [34];

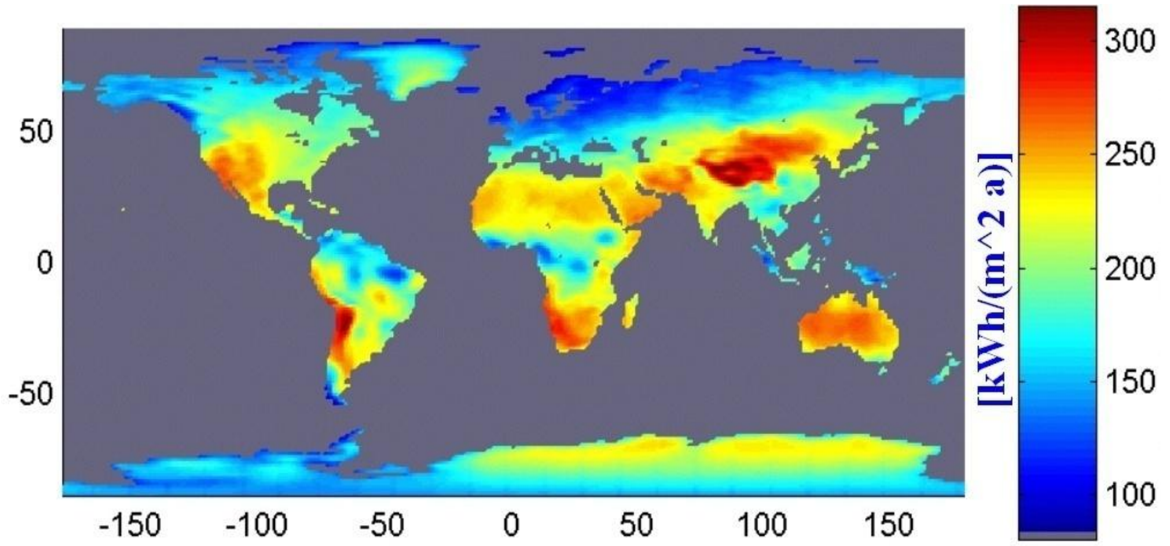


Figure 7: electric energy from photovoltaic (PV); source: [34];

Another issue if we regard the role of CSP in future energy supply is transportation. Widespread introduction of CSP will be impossible without high-voltage-far-range-transporting systems on one hand but on the other hand regions that have good conditions for CSP are not too far away from Europe, USA and Japan, the regions with highest electricity demand. This correlation is illustrated in [26] p.40. and can also be seen in Figure 6.

- High wind speeds can lead to deformation of mirrors or even destruction of parts of CSP plants.

- Ambience temperature: The higher the ambience temperature the lower the thermal losses are.
- Technical know-how in the region.
- Electricity costs and public subsidies.

4.3 Solar chimney

Solar chimney power plants are no concentrating systems but related to them because they also represent a way to produce electricity in an alternative way. So even though solar chimneys are not part of this work a reference to further information shall be given because solar chimneys are also an attractive way to produce electricity by using the sun in big-size plants. [26] pp. 85ff., [36] pp. 1417 ff.

4.4 Solar pond

As well as solar-chimney-systems solar ponds are no concentrating systems. They use solar energy by heating lower areas of a pond. Basic principle of a solar pond is that a temperature gradient occurs when the ground of the pond absorbs solar irradiation. This heat is used in a low temperature Stirling engine or an Organic Rankine Cycle (ORC). Further information can be found in [37], [9].

5 Description and comparison of common concepts

Many authors have already tried to draw comparisons between available CSP systems.

[38] gives a detailed comparison of parabolic trough and Fresnel technology. It also includes social, environmental and economical effects of both systems. Several reference sites were simulated and validated. Both physical and monetary efforts and gains are given in several tables. Generally spoken the main advantage of parabolic trough is its high efficiency (electric energy to DNI-energy on collector) while construction of the Fresnel system is much cheaper. This results in lower total electricity costs of Fresnel systems (ct/kWh)

The combination of high-melting-point phase change materials (PCM) with Fresnel solar systems is discussed in [39].

Further comparisons of Fresnel and trough systems as well as descriptions can be found in: [26] pp. 14ff, [40] pp. 20ff, [1] pp 47-49, 88-90 etc.. So an enormous number of very good basic information can be found. For this reason an accurate general introduction was excluded in this work.

The most comprehensive comparison of the three main systems (Solar trough, Solar Tower, Dish-Stirling, but also concentrated photovoltaic) can be found in [41] pp. 89ff. About Dish/Stirling systems the study says: "In this report we have presented both a 'distributed' as well as a 100-MW dish Stirling solar power plant, because dish Stirling is modular[4]. Currently, individual units have a capacity of only 25 kW. These units are designed to be eventually fully automated, contain only small amounts of hazardous coolant, and require no cooling water to operate.[5] Further, they make very low noise and have a relatively low profile. For these

[4] The modular construction system means that it is either possible to only build one Dish/Stirling unit (e.g. of 25 kW), several units or many units that reach several MWs of total power. In contrast to this one should not fall below a minimum level of plant size in the case of solar tower or solar trough systems from technical and economic reasons. – author's comment.

[5] "Because of the high operating temperature and high efficiency of the Stirling motor, air cooling can be used with little compromise on overall solar-to-electric conversion efficiency. The only water requirements for PV and dish Stirling are for occasional washing of mirrors and glass surfaces. This accounts for less than five gallons of water per megawatt-hour of power produced. This total water consumption is one-100th of the water requirements of conventional power." [41] pp.95.

reasons, dish Stirling can be installed close to residential areas. Their modularity and easy interconnection make dish Stirling systems attractive for small or midsized customers. Even though dish Stirling is more expensive than parabolic trough or power towers today, the amount of capital required to install the first *(25-kW, author's comment)* unit is low—around $100,000. This makes dish Stirling systems similar to wind turbines, and their early entry into the market may come from small installations of one or a few dozen dishes," the authors say about dish/Stirling systems. According to Concentrating Photovoltaic (CPV), they add: "Most of what we have said about dish Stirling systems also holds for CPV systems. Anticipated CPV unit size is 22-28 kW, similar to dish Stirling, making CPV a direct competitor with dish Stirling. CPV would even be more suitable for distributed installations because of its low O&M *(O&M - Operation and Maintenance, author's comment)* needs." "Parabolic trough plants and power towers, in contrast, are large industrial facilities. Economies of scale suggest that unit size should be about 100 MW (electrical). For a parabolic trough, the heat transfer fluid used in the heat-collecting elements of the solar field is currently a highly volatile organic compound and is hazardous. Because fires in parabolic trough plants are serious threats (and have occurred), these facilities must be built away from residential or industrial areas, with associated investments in transmission lines. Also, land below the solar collectors needs to be kept free of all vegetation in order to avoid grass or brush fires that would have the potential to destroy the solar plant. This weed control is currently done using herbicides, which may concern local environmental agencies as well as customers who are shopping for green power. Wind loading is also a greater problem for parabolic trough than for dish Stirling units."

The advantages and disadvantages of power towers are also summarized and further comparisons are given: "Power towers avoid the hazardous heat transfer fluid by using molten salt.[6] The salt is non-toxic and, in fact, is used as a plant fertilizer. Soil sterilization is not required because the focal point of the mirrors is at the top of the power towers - far off the ground - and no volatile heat transfer fluids are present. Of all CSP technologies, power towers are the most visible due to the tall receiver tower, and they occupy more land per megawatt-hour produced than any other CSP technology. Parabolic trough plants and power towers also require large amounts of cooling water (…). Only natural gas–fired combined

[6] Kearney D. et al. discuss this topic in article [189] named "Engineering aspects of a molten salt heat transfer fluid in a trough solar field".

cycle plants can achieve lower water requirements, and they only consume about one-half to one-third of the cooling water required by a steam plant. Solar resources are greatest in desert areas, but here water is a scarce and precious commodity. Therefore, the fact that cooling water is required for parabolic troughs and power towers is a big drawback for these technologies. (…) Parabolic trough plants and power towers can incorporate heat storage and fossil fuel hybridization, which allows them to displace existing capacity from the market. (…) Their ability to dispatch power also allows them to earn a higher average price for power. The monthly energy production of parabolic trough plants is more seasonal than for other CSP technologies. Parabolic troughs show a much greater drop in output toward the winter than dish Stirling, CPV, and power towers. (…) The efficiency of dish Stirling power plants is the highest of all solar technologies, and as little as four acres of land are required per megawatt of power. This means that a dish Stirling system can produce 60% more solar electric energy on the same plot of land than, for example, a parabolic trough plant. It is our view that an emerging solar power market will shake out the mix of solar power generating technologies."

In the end, the authors conclude: "Dish Stirling, CPV, parabolic trough and power tower are such fundamentally different technologies that all could have a place in the market, at least initially. The optimal supply solution will be influenced by many factors, including economics, aesthetics, environmental concerns, availability of cooling water, practicality, safety and funding. Nevertheless, CPV and dish Stirling will be in direct competition, as will power towers and parabolic troughs."

Further information about Parabolic dish (Solar dish / Stirling) systems in: [26] pp.23ff. and [6] pp 5-45ff.

5.1 Receiver and absorber types

One of the most sensible parts of CSP plants are its receivers. The receiver’s influence on total system efficiency is very strong. So it is important to improve these parts permanently. Because of high thermal stress, also life time of receivers is an important issue.

In recent years several developments have been done. Especially the use of solar towers offers many opportunities of receiver design. This can be seen from the classification of relevant receiver details shown in Figure 8.

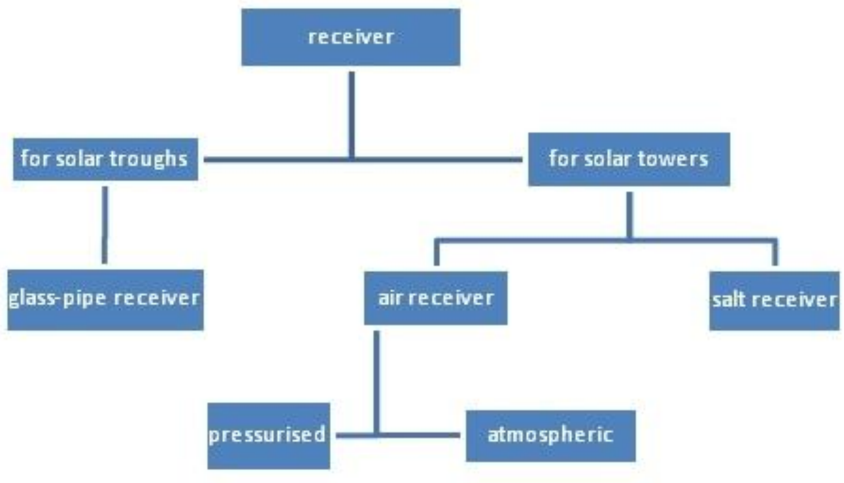


Figure 8: Most relevant receiver types used in CSP plants.

In [26] several advantages and disadvantages of receivers are described. Pitz-Paal, R. characterizes the different systems as follows:

5.1.1 Receivers for solar trough systems

Receivers for solar troughs principally consist of evacuated glass pipes that contain linear absorbers. They look like pipes of some solar thermal collectors that are sometimes assembled on roofs or galleries on private homes.

Pfänder, M. et al. in [27] investigated temperature distribution on solar trough absorber. Local differences in flux distribution can lead to damages of absorber materials as it is also the case for receivers in solar towers that are described in the next chapter. In article [27] named "Infrared temperature measurement on solar trough absorber tubes" the authors describe solar-blind measurement of surface temperatures that can be used instead of temperature sensors which need direct contact to the object. Flux distribution on linear receivers is also the topic of [28].

5.1.2 Receivers for solar tower systems

In comparison to receivers for solar trough systems more information can be found about receivers for solar tower systems.

5.1.2.1 Salt-receiver

Because salt is a very good medium for energy storage (also see chapter 8.1) it is obvious that one should also use salt as heat transfer medium. So heat exchangers can be avoided. Apart from this the system does not need high pressure. On the other hand salt can also solidify in pipes when the plant is out of operation (e.g. during the night) which can be a challenge to construction. Salt is also more aggressive to metal pipes.
A salt receiver principally works as follows: Salt is heated directly in an absorber on the solar tower and than either stored or channelled to a heat exchanger to produce steam or to heat gas. Further information can be found in [29], "Study on design of molten salt solar receivers for beam-down solar concentrator" published by Hsuike, H. et al., or in [1] p.12.

5.1.2.2 Air-receiver

At such a receiver a porous material or another suitable surface or structure is heated by concentrated solar irradiation. The temperature of air is boosted while it is running through the porous receiver. It is possible either to run the receiver in an open cycle (atmospheric air receiver) by channelling air from the surrounding through the receiver and using the heat in a steam cycle after that or to run the system by compressed air (re-boosted air receiver) which is expanded in a gas turbine. In this case the receiver or at least the air must be isolated behind a sheet of glass or inside a tube. [26] pp. 23ff
The use of tube-bundle-receivers did not lead to success for generating hot air. Therefore so-called "volumetric receivers" were established.

Atmospheric air receivers (Open volumetric receivers)

Fend, T. et al. in [30] describe volumetric air receiver's construction and how they work: "Porous solids like extruded monoliths with parallel channels and thin walls made from various oxide and non-oxide ceramics, ceramic foams and metal structures have been tested in the past with the objective of applying them as open volumetric receivers in concentrated solar radiation. In this application, ambient air flows through the solid, which is heated by concentrated solar radiation. A heat exchanger then transfers the energy to a conventional steam turbine process. In all cases, to obtain high efficiencies, high absorptivity in the visible and near infrared range has to be combined with a high porosity to create large surfaces for convective heat transfer from the solid absorber to the fluid. (...) To achieve both high efficiencies and reliable operation, an optimised combination of geometrical as well as thermal conductivity and heat transfer parameters has to be selected." The output temperatures range between 700 and 800°C and the absorbed heat flux between 200 and 800 kW/m².

The aim of construction is very simple: Reducing the outside surface of the receiver by shifting the "inner surface" at the same time. Therefore a light beam hitting the surface of the receiver is "caught" inside the system and can hardly leave the absorber any more. Re-radiation of the receiver is much lower than the re-radiation of a flat absorber of equivalent size. The material that absorbs the irradiation consists of plaitings of metal wire, ceramic foams, felt or ceramic honeycombs etc.. These systems are discussed in detail in [42]. Two newly created absorber materials – a double-layer silicon carbide foam and a screen-printed porous silicon carbide material ("typed material") – are described and tested. A comparison shows that the double-layer foam-system (looking like a sponge) has higher efficiency than the typed material (which looks like the catalytic converter of a car).

Materials used in solar receivers are exposed to high solar irradiation that affects "both their pore structure and their mechanical characteristics". This was investigated by Agrafiotis, Ch.C., et al. in [43]. Several effects like "Surface oxidation of reSiC *(re-crystallized silicon carbide – author's comment)* materials to SiO_2" occurred.

So the basis structure of a volumetric receiver is always the same. Some of them look like the basic structure of a catalytic converter of a car, several types (e.g. ceramic foam manufactured by the IKTS) exactly look like a sponge made by ceramic material. Pictures as well as several graphics showing the functional principle can be found in: [30] pp. 827ff, [44] p.39. and [26] pp. 25f.

Examples for common systems: SOLAIR 200 (Plataforma Solar de Almería (PSA) / Spain) or "High Temperature Receiver" (HITREC), which is an open volumetric air receiver [45], as shown in Figure 9.

Figure 9: Open volumetric air receiver (HITREC); source: [45];

Fend, T., et al. in [30] also describe how they evaluated HITREC's efficiency using the DLRs "Solar Furnace" (p.825). Efficiency is stated at about 75 to 92% depending on working temperature (or power on aperture) and the used absorbing material (metallic catalyst carriers, fibre mesh and fibre mesh combined with SiC catalyst carrier have been tested).

Additionally some problems occuring in open-volumetric receivers are described here: "However, it can be shown that especially high performance absorbers tend to be sensitive to inhomogeneous flux distributions, which may cause local overheating of the material. In various tests with specific kinds of materials, flow instabilities[7] occurred, which partly leads to hot spots and a sudden destruction of the receiver." [30] p.823.

An example for an atmospheric air receiver is the so-called PHOEBUS system. "The international PHOEBUS Consortium was formed by companies from Germany, Switzerland,

[7] author's comment: Instabilities in (air) mass flow are described in [30], [190], [47];

Spain and the USA and the feasibility study completed in March 1990 (…) Unfortunately the project could not complete the necessary grants and financial support and did not come to eventual construction," as stated in the ECOSTAR[8]-Road Map Document [1] p.65.

Pressure-boosted air receiver (pictures: [26] p.26ff)

- Tube-receiver
  They consist of several tubes which are assembled in a hollow space shape. Inside the tube air is heated while solar beams hit the surface of the receiver. Air temperature rises from 290°C to 500°C for example.
- Siliciumcarbid-pressure-boosted receiver
  For higher temperatures silicon carbide pressure-boosted air receivers are introduced. Temperatures up to 1000°C have already been reached.
- SOLGATE pressurised air receiver
  Absorber is placed in a pressure-resistant vessel. The side of the vessel directed to the heliostats is closed by a quartz window. A secondary concentrator is placed in front of that window. Advantage of such a volumetric receiver is that the temperature of the output-air is very high while the pressure drop on the receiver is low. Output air temperature has already reached 845°C on test sites and shall be shifted up to 1100°C soon. An Example for a pressurised air receiver is the REFOS -type receiver (receiver for fossil-hybrid gas turbine systems), described in [31] p.22., [32] and [33] p.1239. Further information about SOLGATE project can be found in [1] pp. 72ff and [46] pp. 1226ff.

5.1.3 Receivers for solar dish-systems

The application of receivers for solar dish systems is discussed in [47]. An additional receiver type for dish Stirling systems is described in [16] p.29. To avoid the need of an additional combustion chamber for gas used in a Hybrid system, a so-called-Hybrid receiver was created: It consists of a chamber with the receiver inside. Concentrated solar radiation can come through a window in the front side of the chamber. From the back side the receiver

[8] ECOSTAR - European Concentrated Solar Thermal Roadmap

can be heated up by natural gas. For de-central dish/Stirling systems it is an advantage to have electricity round the clock and hybrid receivers are in use in these systems therefore. See also [4] p.175.

Comparisons between several receiver types, working fluids etc. are also summarised in [1] pp. 131ff.

5.2 Automatic control of heliostat's, trough's and dish's sun-tracking

Control of heliostats has been a challenge for tower technology. The general problem is that hundreds of mirrors are directed on the central receiver when the system is in operation. Because of that it is not easy to find out which mirror is shining on which part of the receiver. Several efforts have been made since that to improve quality of mirror-positioning.

In their article "An artificial vision-based control system for automatic heliostat positioning offset correction in a central receiver solar power plant" [48] Berenguel, M., et al. describe the "development of a simplified and automatic heliostat positioning offset correction control system using artificial vision techniques and common CCD[9] devices." This is necessary because open-loop controllers are just based on astronomical laws and do not include errors resulting from "tolerances, wrong mirror facets alignment (optical errors), errors due to the approximations made when calculating the solar position, etc.". The system described in the article uses CCD cameras: "The obtained images are used to estimate the distance between the sunbeam centroid projected by the heliostats and a target placed on the tower, this distance thus is used for low accuracy offset correction purposes. Basic threshold-based image processing techniques are used for automatic correction." [48] p.563.

Currently sun-tracking systems do not need sensors more often. This trend is also described in [49] p.4:

"The tracking system developed for the ET100 and ET150 on the Plataforma Solar is based on 'virtual' tracking. The traditional sun-tracking unit with sensors that detect the position of

[9] CCD - Charge-Coupled Device

the sun has been replaced by a system based on calculation of the sun position using a mathematical algorithm (…). The latest version of the solar coordinates calculation algorithm was checked against the Multiyear Interactive Computer Almanac (MICA), a software product of the United States Naval Observatory. Errors in longitude and/or latitude of the site below 10 km do not provoke a significant positioning error, if the parabolic trough collectors are correctly aligned.

Also in [48] pp. 563f. this information can be found: "The current trend in solar concentrator tracking systems is to use open-loop controllers that compute the direction of the solar vector based on location and time. (...) When controlling the temperature and flux distribution in the volumetric receiver, the algorithms calculate the amount of the shift using an equation appropriate for each heliostat depending on its current temperature dependent focal length and orientation dependent aberrations in addition to beam errors and sun size. As a first approximation, a heliostat aiming point strategy providing a desired energy flux correlated with the air mass flow through the receiver can be selected to solve the control problem. Nevertheless, there are error sources that increase the complexity of the control system (…): time, ephemeris equations (sun model), site location (latitude and longitude), heliostat position in the field, time-varying astigmatism and cosine effects, processor accuracy, atmospheric refraction, control interval and structural, mechanical and installation tolerances." Further information of flux-measurement is mentioned in [50] and [51].

Controlling and moving several mirrors together

Even the idea of ganging heliostats has been analysed. While the ECOSTAR-Roadmap estimates considerable cost reduction of ganged heliostat concepts ([1] p.133) there are also many disadvantages. In [25] p.279 Mills, D.R. and Morrison, G.L. analyse the situation for ganged parabolic troughs which is to some extend comparable:

"Although a ganged field might lead to lower capital cost, non-ganged configuration has practical advantages, since focusing can be finely tuned, and all mirrors can be aligned vertically in hailstorms, or horizontally in high winds. Independently tracked mirror lines can also be aligned or inverted for the cleaning. During absorber maintenance, arbitrary sections of the mirror array can be realigned to other absorbers, maintaining output, and individual rows can be aligned vertically to provide walk-through paths. A single control system could control many hundred drive motors of this slow-moving tracking system. The issue of ganging mirrors must therefore rest as a minor issue that needs to be resolved during detailed equipment and operation design. In the remainder of this study it is assumed that the unganged system is used."

On the other hand control systems make just a small share of total cost, even if we just regard a single heliostat without tower and turbine/generator (power block) system: "The major part of the costs are regarding to control and tracking (14% and 30%), the reflector (36%) and the structure (20%), as the technical components of the concentrators." ([1] p.86)

As an example for cost share [1] p.78. analysed the SOLGATE – solar tower plant. The authors state that investment of solar field is only responsible for 22%. Compared to investment for power block (39%) or receiver and tower (11 + 8 %) this is a relatively small part of total costs.

6 Alternative Concepts, combined systems, further developments

6.1 Hybrid solar – gas power production

6.1.1 Integrated Solar Combined Cycle Systems vs. Solar Energy Generating Systems

Several solar concentrating systems are considered to shift the efficiency of existing gas turbines by pre-heating in a particular part of a combined cycle. In [7] p. 5-25 an Integrated Solar Combined Cycle System (ISCCS) is defined as "a new design concept that integrates a parabolic trough plant with a gas turbine combined-cycle plant."
[33] p. 1232 is also dealing with hybrid systems. The authors say that the ISCCS - solar-fossil hybrid technology had only "short-term perspective" because "the achievable annual solar share is restricted (4% without, 9% with thermal storage)" in this case.
A comparison between several combined and hybrid systems can also be found in [26] p.50. Quaschnig, V. et al. state in their conclusion that Solar Electricity Generation Systems (SEGS) including storages should be preferred to ISCCS. ISCCS integrates a parabolic-trough plant into a combined gas and steam turbine. Solar energy can only substitute a part of steam production in this case. In contrast to this, the situation for SEGS is different: In this case up to 100% of solar energy can be available theoretically, especially if the system contains storage. SEGS is working on a steam-turbine basis. To reach a hybrid system a conventional, gas-fired steam generator can be added. **To summarise, one could say that an ISCCS is a conventional power cycle with a solar system added while SEGS is a solar power system with temporary support by gas combustion.**
So one should prefer pure solar operation or at least limit the use of gas, as it is the case in California’s CSP sites that are described in chapter 9: "CSP sites – planned, erected and put in / out of operation". But every application of solar technology that saves fossil energy has positive effects on the environment.

Unfortunately it is not easy to find proper data about energy savings in such plants. According to [18] p.2 the maximum amount of thermal energy from gas in California's SES plants must not exceed 25% by law, for example. Characteristic data of CSP plants can generally be found in a wide range: [26] p. 15 submits 190.000 m² for collector field aperture while [9] p. 270 prefers to suggest 165.376 m². Table 1 shows relevant key data of California's SEGS plants.

	year of starting up	net electic power producion [GWh/a]	gas consumption [10^6 m³/a]	efficiency (only regarding gas)	net solar-to-electricity efficiency
SEGS 1	1985	30,1	4,8	63%	9%
SEGS 2	1986	80,5	9,5	85%	11%
SEGS 3	1987	91,3	9,6	95%	10%
SEGS 4	1987	91,3	9,6	95%	10%
SEGS 5	1988	99,2	10,5	94%	10%
SEGS 6	1989	90,9	8,1	112%	12%
SEGS 7	1989	92,6	8,1	114%	12%
SEGS 8	1990	252,8	24,8	102%	14%
SEGS 9	1991	256,1	25,2	102%	14%

Table 1: Characteristics of California's SEGS plants; data source: [26] p.15; Further details about CSP plants can be found in chapter 9; "Efficiency (only regarding gas)" in this table is defined by dividing the "net electric power production" by fossil energy input ("gas consumption"); we assume that 1 m³ of gas contains 10 kWh of energy;

General and economical considerations about Hybrid systems can be found in many articles, e.g. in [52], [53], [1] pp 72ff, [54], [55] pp 5-11ff and [22] pp 2-5 ff.

6.1.2 Support of power plant via chemical reactions

Another approach is described in [4] pp.173f. In contrast to the classical CSP-system in this case heat from concentrated sunlight is used for running a chemical reaction instead of physical preheating. The authors describe this idea to "upgrade the natural gas by a methane reforming process" as follows: "Natural gas is mixed with steam at 200°C and 20 bars and heated up to 665°C in a super-heater before entering the windowed volumetric receiver-reactor. The reforming takes place in the Rh[10]-coated Al_2O_3 ceramic foam absorber. The syngas leaving the reactor at 959°C transfers its sensible heat in the steam generator and can be stored at ambient temperature before it is fed into the burner."
According to article [4] the "fuel consumption is reduced by nearly 17%" if the combined cycle with the so-called "external solar reforming" is used.
In [56] Noglik, A. et al. describe the European project "Hydrogen Thermo-chemical Cycles" (HYTEC) that started 2004. The aim of this project is to produce cheap hydrogen from solar thermal heat from concentrated solar systems. Heat for this process is available at a temperature level of 1200°C. Main topic of the project was to crack sulphuric acid at 1200°C in the solar furnace of the German DLR in Cologne-Porz (Köln-Porz). The authors found out that even though the chemical reaction worked best at a temperature level of 1200°C, total efficiency of the process was higher at 1050°C because losses caused by re-radiation from the receiver increase rapidly when the temperature of the receiver increases. The authors state that receivers built in "Cavity-Design" would be a proper solution to that problem.
In [57] Uhling, R. et al. present a software tool that allows calculating several types of tube-receivers. The developers of this software tool promise that it makes just a small effort to do such a calculation.
An overview of possible thermochemical processes that can be supported by heat from solar concentration systems is given in [58]. Further information about solar reforming can be found in [59] or [60].

[10] Rh - Rhodium

6.1.3 CO_2 capturing supported by energy from the sun

In [61] Pak, P.S. et al. present an additional application of solar concentrating systems. The authors state that a system combining a gas turbine and trough-type solar system including CO_2-capturing can reach higher efficiency than conventional gas-turbine power plants. From a technical point of view this might be right. But as mentioned in the introduction, fossil fuels should be replaced by renewable energy. CO_2-capturing could lead to continuation of the traditional energy-mix and will create new problems. Next generations will have to deal with CO_2-waste in addition to nuclear waste.

Further basic information about advantages and disadvantages of Hybrid systems also including CO_2 avoidance costs are given in [62].

6.2 Specific concepts derivated from basic CSP's

6.2.1 Fresnel systems

Fresnel systems are frequently described in literature of solar concentration systems ([63] p. 100, [13] p. 15, [38] etc.; pictures: [16] p. 13, [44] p.38). The idea is very simple but impressing: To avoid expensive parabolic shapes (solar troughs as well as parabolic dishes), these shapes are simply approximated by many small plane mirrors. A sketch of a Fresnel system can be seen in Figure 10.

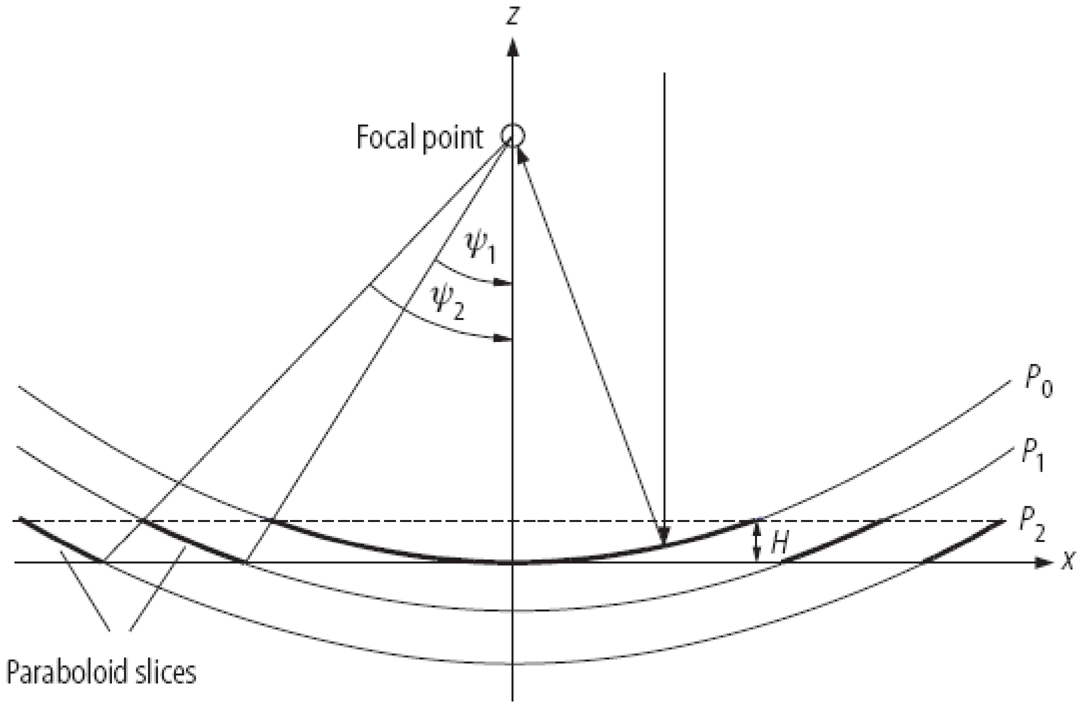


Figure 10: A Fresnel reflector approximates a parabolic shape by several Parabolic slices or even plane mirrors; source: [9] p.278;

In [38] a detailed comparison between Fresnel- and parabolic troughs is given. The authors of this article acknowledge that some assumptions had to be made for Fresnel systems because Fresnel technique has not been validated for such a long time as solar trough technique. The authors state advantages and disadvantages for both systems. (As already mentioned in chapter 5, Fresnel has the advantage of higher cost-efficiency while parabolic troughs reach higher solar to electricity efficiency.) For the future the authors predict economic improvements for both technologies.

Because of the wide distribution of "conventional Fresnel systems" just some remarkable new concepts shall be stated in this work:

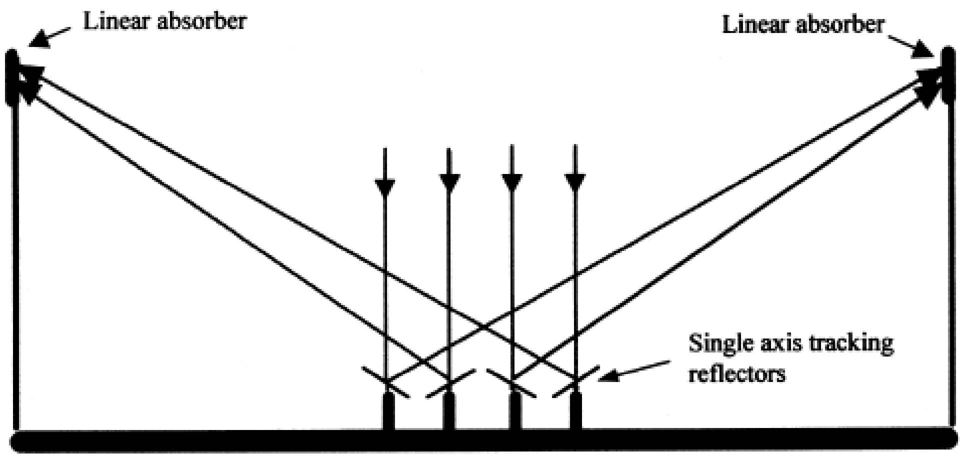


Figure 11: Arrangement of mirrors in a Fresnel or solar tower system to avoid shadowing and blocking. Source: [25] p.265;

A very specific idea of arranging mirrors and absorbers for a linear Fresnel concentrator is given by Mills, D.R. and Morrison, G.L. in [25]. The so-called "Compact Linear Fresnel Reflector" (CLFR) which differs from conventional Fresnel systems and which is illustrated in Figure 11 is described as follows:

"(…) CLFR technology is, in effect, a second type of solution for the Fresnel reflector field problem which has been overlooked until now. The classical linear Fresnel *(LFR – Linear Fresnel Reflector – author's comment)* system has only one linear absorber on a single linear tower, and therefore there is no choice about the direction of orientation of a given reflector. However, if one assumes that the size of the field will be large, as it must be in technology supplying electricity in the multi-MW class, it is reasonable to assume that there will be many linear absorbers in the system. If they are close enough, then individual reflectors will have the option of directing reflected solar radiation to at least two absorbers. This additional variable in the reflector orientation provides the means for much more densely packed arrays, because patterns of alternating reflector inclination can be set up such that closely packed reflectors can be positioned without shading and blocking. (…) This arrangement minimises beam blocking between adjacent reflectors and allows higher reflector densities and lower absorber tower heights to be used." [25] p.264f., The principle can, anyhow, be used for 2-dimensional as well as 3-dimensional concentrating applications. In the first case this leads to many parallel linear absorbers (CLFR - Compact Linear Fresnel Reflector), in the second case (MTSA - Multi-Tower Solar Array) to several towers. A picture can also be found in [40] p.25, additional geometrical and other basic considerations in [64] and [65].

6.2.2 Concentrating Photovoltaic (CPV) and combined PV – thermal (PV/T) systems

The idea to combine photovoltaic with solar thermal systems is rather old. Even though this concept has found no widespread application from several reasons until now: On one hand there is no need to combine the two systems just to save space: At the current situation space on house roofs is not yet a limiting factor – and for this reason it is not reasonable to make efforts to combine the two systems. (In contrast to this one could even say that both photovoltaic- and solar-thermal-collectors on a roof of a private house help the owner economising double sum of roof tiles than a combined system that needs only half of space on a roof.) Apart from this it is well-known that efficiency of the photovoltaic-cell goes down if temperature of thermal collector rises. So we face a typical conflict of goals.

Another approach would be to chill photovoltaic elements and to dispose of thermal energy in a swimming pool or something else [66], [67]. For a rough calculation one can estimate that gains of electric energy will rise up to 5% per 10°C lowering of temperature. The reason why this technology has not found wide implementation may be caused by disproportional investment costs or even by proportional high energy need for fluid convection. Apart from this many people do not have access to a heat sink at low temperature in summer.

If we are dealing with concentrated sunlight the idea of cooled photovoltaic becomes more realistic: On one hand we reach temperatures that are much higher than in flat-plate photovoltaic-cells and cooling becomes more attractive and more easily. Additionally the needed cells are much smaller because the sunlight is already concentrated and for this reason cooling is also cheaper for the same output of electric power.

Concentrating sunbeams for photovoltaic electricity production

Fresnel and other concentrating systems can be used to achieve higher irradiation (e.g. several hundred suns, e.g. 500 suns according to [10] p.3) on expensive, high-efficient photovoltaic-cells.

Because photovoltaic cells are relative expensive it is reasonable to irradiate them by concentrated light and cool them at the same time. The combination of photovoltaic and concentrating systems is therefore very widespread in technical literature. Used abbreviations for it are CPV (Concentrating Photovoltaic) or CPVT (Concentrating PV/Thermal) or IHCPV (Integrated High Concentration PV).

On the other hand concentration of solar irradiance on PV elements also bears a great challenge for construction: No matter if the sun is concentrated on a line or on a single point, it is important that solar flux on the PV element is very homogenous: "Because low illumination on one cell affects all cells in series, the electrical performance is very sensitive to radiation flux non-uniformities longitudinal to the trough. The lowest dip in the flux profile typically results from the combination of slope error in the mirrors, gaps between mirrors and regions of shading due to the receiver supports. Non-uniform illumination and temperature across a cell has the effect of softening the fill factor and reducing open circuit voltage," Coventry, J.S. states in [68].

In a very recent article published 2008, the construction of a new 3-MW-CPV site in the Spanish province of Castilla-La Mancha is described [69]. The results of the responsible Institute ISFOC (Instituto de Sistemas Fotovoltaicos de Concentración, Institute for concentrating Photovoltaic systems) looks promising up to now, according to the article.

There are many studies that discussed this issue: [26] pp. 61ff., [70]. Other articles dealing with concentrating PV-systems are: [71] 2-2, A-2f., A-11f., [72], [41] pp 41f, 81f., [72], [73], [74], [75], [76], [77] and [78];

6.2.3 Integration into industrial buildings, shopping centres etc.

Romero, M., et al. propose that development of CSP systems should not alone try to shift power size but should also regard "integration into communities and energy islands for local power supply". [79] p. 249. As an example for the so-called MIUS "Modular Integrated Utility System" (MIUS) they quote a shopping centre that could be set by a small 1,36-MW solar tower plant with 345 single heliostat mirrors. According to the article the "solar system can cope with 56% electricity demand during shopping hours and 49,5% of the heat demand contributing to an energy saving of 687 toe *(toe – Tons of Oil Equivalent, author's comment)*."

6.2.4 Application of concentrating mirrors for generation of process-heat

Another approach to CSP is the direct use of thermal heat. In [26] p. 15 we find the information that almost 10.000 m² of parabolic troughs have been assembled from 1977 to 1982 for this purpose by Acurex company. In 1983 another process-heat facility consisting of 5580 m² parabolic troughs in Chandler / California for producing thermal energy for a copper-processing factory started operation.
Perhaps it is possible that concentrating solar power will make a big step to market maturity by benefiting from developments in the conventional solar process heat sector. Most of the needed components are nearly identical and economies of scale could support this effect. Apart from this the value of solar process-heat production is very high. If it is possible to substitute electric energy by producing process-heat in de-central plants where the heat is needed it has the same effect as to substitute conventionally-produced electricity by solar electricity – and it can be estimated that local heat-production will be the cheaper way more often than not.
The study "The potential of solar industrial process heat applications" ([80]) published by Kalogirou deals with this topic. Several projects dealing with process-heat (from concentrating solar systems in front of all, most of them in Europe) are described in [81]. Additional overviews, most of them dealing with direct hydrogen-production, are given in [82], [83], [84], [85].

Solar concentration for material treatment

In several solar concentrating (test-) sites (using heliostats or parabolic mirrors as well as simple lenses or Fresnel lenses) solar energy is used for surface materials treatments. Sierra, C. and Vazquez, A. describe the use of Fresnel lenses in [86]: "Solar energy concentrated by a Fresnel Lens has been used in the National Center for Metallurgical Research (CENIM) for several surface modifications in metallic materials: thermal treatment of steels, stainless steel and cast iron, gaseous nitriding of Titanium alloys and coating processes by self-propagating high temperature reactions. The processes are short because high temperatures are quickly achieved." Further information about hardening treatment on a 40CrMo4 steel at

PSA and a comparison to the use of lasers[11] that "is becoming increasingly popular" can be found in [87].

Solar cooling

Another technology that will hopefully get more penetration of the market and that will at the same time bring a massive rise in solar thermal application in domestic home water and heating systems is the so called "solar-chilling-process". These are adsorber- or absorber-systems that can be run by thermal energy (e.g. from a flat-plate solar collector) instead of expensive electricity for a conventional compressor. From Carnot's law it is clear that efficiency of such a system rises if higher process temperatures (which are limited to round about 90°C for flat-plate collectors) could be provided for the cycle. For this reason it is clear that the use of concentrated solar irradiation will improve power of solar cooling systems.

The same statement can be found in [88] p.7. Kandilli, C. and Ulgen, K. write that scientists have pointed "that (…) the introduction of solar fibre-optic mini-dish systems (…) could deliver high-temperature heat at high solar to thermal conversion efficiencies. It was analyzed that a further boost in net COP[12] to around 1.4 can be achieved by modifying the conventional scheme to a thermodynamic cascade that takes maximal advantage of high-temperature input heat by solar mini-dish systems."

Because this topic is not in the centre of this work just several sources for further information are listed here: [89] p.86f., [73] and [90]. As mentioned before it is as valuable to avoid a specific amount of electricity consumption as to build electricity plant for the same amount of energy. Especially in case of chillers it is obvious that it is - generally spoken - cheaper to replace the very widespread conventional chillers that run by electricity by solar-cooling machines. Coincidence of solar energy supply and the need for cooling is a serious argument for solar chillers, whether run by concentrated or normal sunlight.

[11] Also the approach to run lasers by concentrated solar energy (directly, without the indirect way via electricity generation) has been made. Lando, M. et al. describe the advantages compared to conventional lasers in [191] p.127 as follows: "Direct solid state laser pumping with solar light is inherently more efficient, much simpler, and more reliable."

[12] COP - Coefficient Of Performance

6.2.5 Optical fibre application

An unconvential approach to solar concentrating systems is the idea to use optical fibres to concentrate sunlight. The principle is relatively simple and can be seen in Figure 12. The basic idea which is always behind the use of optical fibres is to make the place of harvesting of solar radiation more or less independent of the spot where sunlight is needed. Apart from this fibres are used to shift concentration ratios as shown in Figure 12, too.

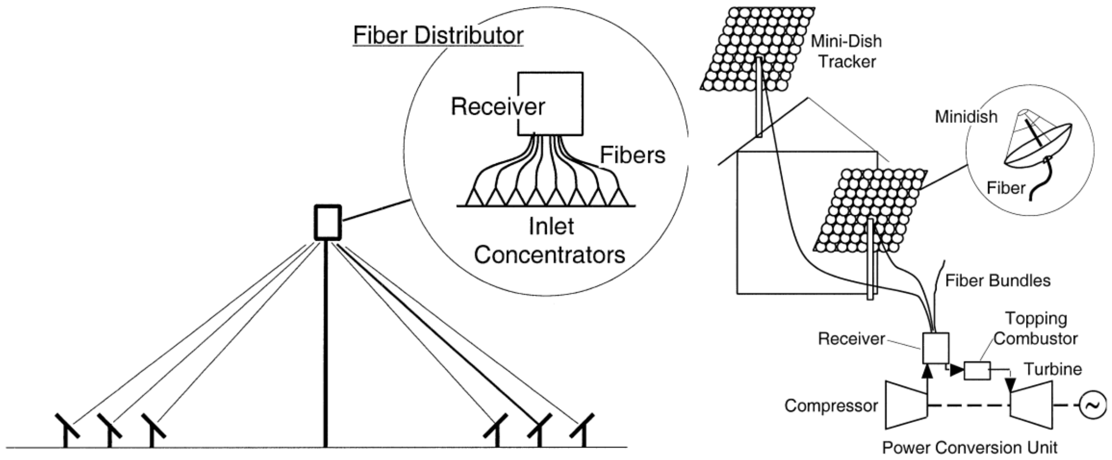


Figure 12: The use of optical fibres shifts CSP's flexibility and concentration ratios; source: [91];

In principal it is not necessary to concentrate solar irradiation before channeling it through an optical fibre but because optical fibres are very expensive (estimated cost of $ 0,20 /m for a silica-fibre of a diameter of 1mm, under assumption of extensive competition and mass production which is not yet the case. [92] p.18) this is the common way. [91] and [93] also deal with this issue.

Figure 13: Concentrated sunlight can be channelled whereever it is needed; source: [88];

Two photographs (Figure 13) showing a parabolic dish and an attached fibre glass bundle that can transport the light to every desired point are given in [88] p.12f besides many additional information about this technology.

Karni, J., Ory Zik, O. and Kribus, A. have summarised current developments in this area in [92]. The authors describe the main advantage of fibre-use: "By using optical fibers, however, we open the possibility of a truly distributed receiver. We can channel parts of the fiber bundle to different locations, and operate separate receivers that are independent and functionally parallel to each other. This new degree of freedom can be used for novel applications that are not accessible with a single receiver. For example, many of the turbines available today have a distributed, multi-chamber combustor: the compressed air is distributed to separate combustion chambers located around the circumference of the turbine. These turbines cannot be integrated with a standard solar plant, which requires all the compressed air to be available in a single external duct. Using a distributed receiver system, we can construct many small receivers, one for each combustion chamber, and channel a portion of the optical fibre to each receiver. The fibre distributor then provides access to gas turbines that were previously not compatible with solar energy applications." [92] p.16.

The authors state: "Optical fibers have been steadily improving and their cost has been declining as a result of the proliferation of their use in communication, and more recently in the lighting industry." [92] p.13. [91] headed "Optical fibres and solar power generation", published by the same authors, is dealing just with this issue, too.

In [94] Dutta Majumdar, M.R. and Das, D. analyze if it is possible to use the full spectrum of solar energy by utilising a so-called "Luminescent Solar Concentrator (LSC)" principle which also includes optical fibres. "Solar power generation" is also the topic of [88] p.6f.. Kandilli, C. and Ulgen, K., the authors of the article tell of an experiment: "(An) optical fibre tip was placed in the focus of a small paraboloidal mirror. (…) The power supply was estimated to be 26 W at the end of a 10 m-long fibre with 88% transmission efficiency."

Unfortunately the use of optical fibre has not become a state-of-the-art-technique yet even though the idea is very impressing. Probably the time for application of solar fibres will come if prices for solar fibres once decrease. Apart from developments in the communication sector it is to hope that direct transportation of light will become possible for rooms that do not have access to daylight so it will become more widespread in the future.

6.2.6 CSP with fixed mirrors and moving absorber

A very interesting way to concentrate solar insolation was to move the absorber around a system of fixed mirrors. Rummich, E. has e.g. published this idea in [63] p. 14. Several pictures and a detailed description of this idea can be found in [95] and the principal design is shown in Figure 15. Unfortunately references used in this source are mainly of the 1970s and new studies are very rare. The way of constructing a solar concentrating system was obviously not pursued in wide range. It was not possible to find more information about or against this idea. Therefore it is not possible to give further statements why this technology does not appear very often in the CSP-sector.

One relevant source about this concept can be found in the "Journal of Solar Energy Engineering" of the year 2000 [96]. Labri, A.B., author of the article, describes the development of a 3D-Fresnel collector that approximates a "hemispherical bowl" and a receiver that is always directed to the focus (which is moving) by a tracking mechanism. The Fresnel system should provide solar heat at a medium temperature of 200-300°C. A computer simulation was done and the geometric concentrations as well as the mean period of collection were calculated. In his conclusion the author states that this 3D-Fresnel-system using the fixed-mirror-principal could be less expensive than conventional CSP systems.

Installation and maintenance costs could be reduced because the fixed mirror profiles could be much lower and wind loads could be reduced therefore.

But not only theoretical studies exist: The fixed-mirror, tracking-absorber principal has been put in practice at the University de les Illes Balears in Mallorca as shown in Figure 14. "In June 2006 the company Tecnologia Solar Concentradora S.L. has been constituted with the purpose of developing the CCStaR concept on an industrial stage," as Weiss, W. states in [97] p.5 and [81]. *(CCStaR seems to be the abbreviation of "collector solar concentrador amb reflector estacionari" but a precise definition is missed in relevant sources.)*

Figure 14: CCStaR collector with moving absorber and fixed mirrors; source: [81];

Even though the technology has found no widespread diffusion the theoretical background of this very specific solution for concentrating the sunlight has been investigated during this work. For the two-dimensional case the geometrical arrangement of such a CSP system was constructed by using a CAD (computer aided design) software tool. In Figure 15 this surprising geometry is illustrated. From a first consideration it is not obvious that it is possible to arrange mirrors in a way that sunbeams are always concentrated on a bowl's surface while the sun is moving.

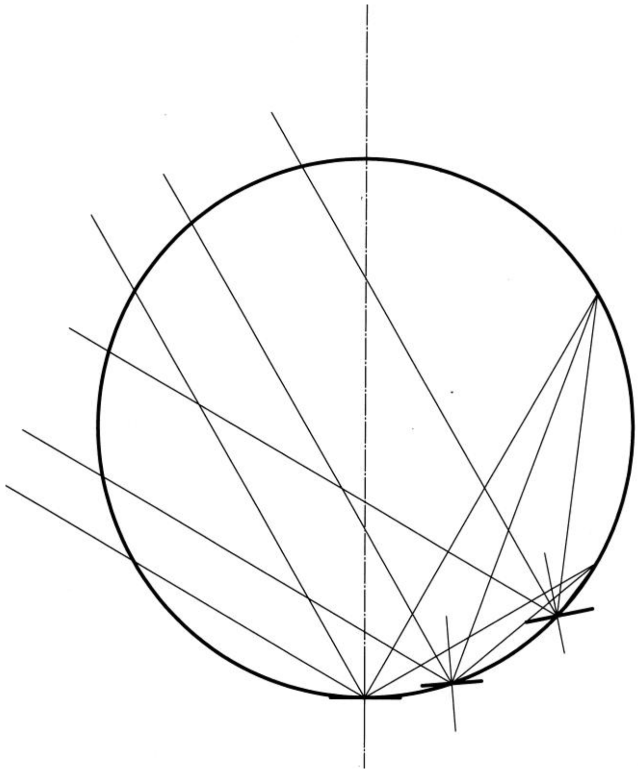


Figure 15: Principal of a moving-absorber-fixed-mirror concentration system;

6.2.7 Tower-Top vs. Tower-reflector-system

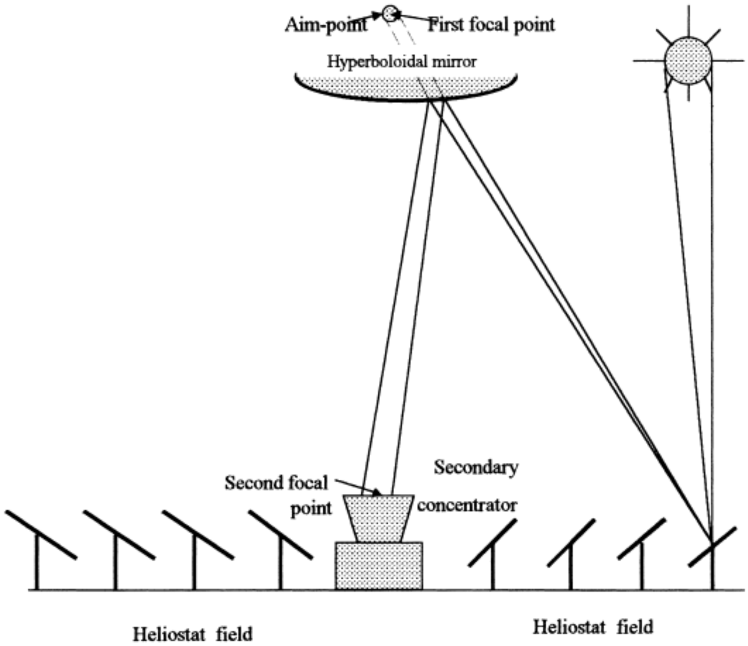


Figure 16: Tower reflector principal including secondary concentration; Source: [98] p.217;

A large amount of synonyms for the Tower-reflector system exist: Solar Concentration Off-Tower (SCOT) system, Reflective tower system or Beam-Down-system.
"Traditional solar central receiver plant design consists of large receivers installed on top of a tower." [99] p. 337 In contrast to this the Tower-reflector-system works as follows: "A hyperboloid reflector on top of the tower projects the concentrated radiation on a lower focal plane, where it is intercepted by an array of non-imaging concentrators and corresponding receivers." as mentioned in [92] p.18. But why should this effort be made? "The main advantages of this configuration are moving of the major hardware (receiver etc.) from the top of the tower to ground level, and reduction of optical aberrations due to the longer focal length of the Cassegrainian optics." [99] p. 337 *(Complementary Cassegrain Concentrator, whose surface is the concave branch of a hyperboloid [100] p.86)*
Kribus, A. Zaibel. R. and Segal, A. have done a simulation of a Tower-reflector-system. The findings are described in [99] and can be summarised as follows: "reflective elements should be installed only on the part of the Tower reflector’s hyperboloid surface that is actually illuminated by some heliostats."
"An additional loss that should be considered for a SCOT configuration is the atmospheric attenuation along the path from the tower receiver down to the CPC, which could be significant for tall towers."
"(...) a combination of SCOT with modern high-reflectivity surface technology (...) makes the SCOT optics an attractive option for large solar power plants."
The geometrical background of solar tower reflectors is described in article [101], which also deals with tower reflectors of elliptical shape. Segal, A. and Epstein, M. have found out that the elliptical shape has two main disadvantages compared to the hyperboloidal ("conventional") shape: The "elliptical reflector requires always a higher tower (...) and the size of the reflector is also larger in the case of the elliptical shape." [101] p. 240.

6.2.8 Secondary concentrator

[98] p.207 describes why secondary receivers are in use instead of conventional ones:
"Various processes (…) require process temperatures above 1100 K with receiver working temperatures of more than 1200 K. For these applications, solar energy must be concentrated to a high level because at these temperatures, the radiation becomes a major

mechanism for thermal losses from the receiver. The radiation losses are proportional to the aperture size of the receiver. Decreasing the size of the aperture requires higher concentrations; otherwise, the energy spillage around the receiver's aperture is increased. Improving the performance parameters of the primary concentrator is one of the important ways to increase the concentration level. However, often this is neither sufficient, nor economical, and a secondary receiver is required. The secondary concentrator intercepts most of the energy directed to it by the primary receiver and concentrates it further (…)."

It is obvious that the optical losses of a secondary receiver, resulting from absorption, rejection and spillage around the entrance aperture must not exceed the energy gained from introduction of the secondary receiver, as the authors add.

With regard to windowed receivers the authors state: "Newly developed windowed-type solar air receivers (…) can presently operate at approximately 1500 K."

A specific study dealing with secondary concentration was also done by Chen, Y.T. et al. and it is summarised in [102]. Because concentration ratio must be very high to get high temperatures the tracking system must work very precisely. For this reason a specific heliostat was constructed which works as follows: The heliostat consists of a big moving frame that is responsible for rough sun-tracking. Several single mirrors, each with a dimension of 40x40 cm are placed on this mirror. For fine-tuning these small mirrors are moved each second to compensate off-axis aberrations. ([102] pp 531ff.) To measure the temperature that was reached in the experiment several materials were melted in the focusing point. The system exceeded the topic of 3400°C, according to the authors.

Another idea is to use a secondary concentrator in combination with a linear concentrator to get point focusing instead of a focusing line. Murphree, Q.C. describes this idea in [100] p.85 as follows: "(…) a point focusing solar concentrator can be made from two reflective parabolic troughs, a primary and a secondary, by orienting their longitudinal axes in perpendicular directions and separating them by the difference of their focal lengths along the optical axis. (…) Still, geometrical constraints limit the concentration to about 2000 suns (…)," the authors admit.

Further sources that deal with secondary concentrator and Tower-reflector systems: [103], [59], [104], [101], [105] and [106].

6.2.9 Combined production of electricity and potable water (Combined solar power and desalination plants)

Because water is rare in most regions that fit for CSP sites and the heat at low temperature is waste for the turbine cycle of the CSP plant (or cooling for the power cycle is needed) it is decent idea to combine CSP and desalination. Additionally some water is needed for cleaning or steam-production and other purposes in the plant itself and if it is produced in-situ transportation efforts can be avoided. So there are several reasons to combine CSP and desalination systems.

Further information how such a combination can be realised are presented in [107]. Additionally Trieb, F. et al. in [108] describe the advantages of desalination / power-generation – plants. The authors state that "A 200-MW plant (...) under the economic and meteorological conditions of e.g. Dubai would deliver approximately 1,5 billion kWh/yr of electricity and 60 million m^3/yr of freshwater at approximately 4,3 €-ct/kWh and 1.30 €/m^3." This would be a very good price – even for Southern European conditions.

7 Optimisation and development of CSP systems

Conditions for Optimisation

There are several important parameters and construction details that cover potential improvements for solar concentrating system. Physical laws are the same for all solar concentrating systems, no matter if thermal energy is used for power generation or other applications and no matter if a CSP-site is based on parabolic, tower or another system. For that reason relevant factors are also the same for all these systems. They are simply summarized as stated below. There are several studies dealing with optimisation of solar concentrating systems.

The authors of the ECOSTAR-roadmap [1] p.89 have detected several main sectors in CSP power plants that allow shifting efficiencies and reducing costs. "The detected innovations covered in this investigation for the concentrators are combined for the LEC calculation and the change of it due to improvements. The mayor fields are:

- ganged heliostats,
- linear Fresnel systems,
- large area heliostats,
- thin glass mirrors / front surface mirrors[13],
- dust repellent mirrors,
- autonomous heliostats.

[13] Such an approach is also described by Fend, Th. et al. in the article “Applicability of highly reflective aluminium coil for solar concentrators” in [192]: “Because of their manufacturing flexibility and their low costs, mirrors based on anodized or coated sheet aluminium are a promising alternative as primary or secondary concentrators in a number of solar energy applications. They offer solar weighted reflectances of 88–91%, good mechanical properties and are easy to recycle. However, problems occur due to their limited corrosion resistance. (…) Materials involved are standard commercial anodized sheet aluminium with layers of different thicknesses and standard high specular aluminium with a metaloxide layer system plus an antioxidation polymer coating. Results show that optical degradation is strongly dependent on climatic conditions. Non-organic coatings involved are primarily attacked by humid climates with higher amounts of atmospheric pollution. Standard anodized materials withstand outdoor and accelerated weathering. However reflectance tends to become less specular, which limits their application in concentrating technologies,“ the authors of [192] state.

Jähning, D. et al. in [10] analysed important parameters of concentrating systems and tried to develop a trough collector that can be easily installed on flat roofs of industrial buildings. In the article [10] "Development and optimisation of a parabolic trough system" they summarised the relevant factors for construction of concentrating troughs. "In the present project, a small-scale and low-cost concentrating parabolic trough collector (was) developed. (…) The operating characteristics of the first prototype, manufactured by the company Knopf Design, Vienna (Austria), were measured at the test facility of AEE INTEC in Gleisdorf (Austria). The main goal of these tests was to determine the optical and thermal efficiency of the prototype. The optical efficiency of the first prototype (at just below 50%) was still too low to compete with conventional *(vacuum-tube-, author's note)* collectors. Measurements of the radiation intensity in the focal line of the collector led to the conclusion that one of the main reasons for the relatively low optical efficiency was the poor positioning of the receiver tube. This and other improvements were incorporated in the second prototype by Knopf Design and, consequently, tested at the test facility in Gleisdorf. The optical efficiency has been improved from about 50% to about 60%." [10] p.9.

The authors revealed the following reasons as having effects on efficiency of the system:

"1. A part of the radiation is absorbed by the mirror.

2. A part of the radiation is not reflected at the same angle as the incidence angle.

3. The parabolic shape of the trough is not ideal.

4. The receiver is not positioned exactly in the focal line."

Other relevant factors mentioned in the article are the "selective coating and the evacuation of the glass cover tube."

Consequently, the following measurements have been taken to improve performance of the parabolic trough:

"1. Low-iron safety glass was used instead of standard window glass.

2. More precise positioning of the receiver tube (mechanical optimization of the supports and the possibility to adjust the receiver position from the outside)

3. Receiver coating Poligrat instead of solar varnish (leads to a lower optical efficiency but to a lower slope of the efficiency due to the selective characteristics of the coating)

4. Evacuated glass cover tube (reduces the heat losses and prevents the decomposition of the selective coating)

5. Receiver diameter 12 mm instead of 8 mm (This increases the optical efficiency but also increases the heat losses). The inner receiver tube has an outer diameter of 6 mm. The cross section of the inner receiver tube is equal to the annulus between the two tubes. This reduces the pressure drop of the receiver tube." [10] p.16f

Further investigations on evacuated tubes for solar trough systems can be found in [109].

7.1 Orientation of mirrors

7.1.1 Orientation of Concentrating Solar Power:

Solar furnaces / tower systems:

Roughly spoken one would estimate that it was an advantage if the landscape in front of a tower receiver (where the single heliostat-mirrors are placed) would ascend steeply to make the mirrors not shadow each other and to have shorter distance between single mirrors and the receiver unit. Even though some authors state that "flat land" is a condition for the heliostats of a solar-tower system. (e.g. [110] p.38 says that ascend should be lower than 2,1%; On the other hand the solar furnace of Odeillo is placed on a ground which is absolutely not "flat land" [111]).

Heliostat-arrangement

In analogy to the question of solar trough’s axis orientation, arrangement of heliostat mirrors is an issue which is discussed since solar tower plants exist. Apart from the general question if heliostats shall mainly be placed in the northern area of the tower or if the tower should be surrounded by them technicians also have to decide about distances, sizes of mirrors etc.. It is not always easy to find the optimal solution because the problem is complex. The answer to these questions also depends not only on site’s condition or on geographical latitude but also on other developments in solar concentrating technology. For example, [32] describes that improvement in receiver technology in recent years (e.g. windowed pressure air receiver technology for secondary concentration in the receiver) influences the decision if North-oriented or other concepts for Heliostat arrangement are optimal.

Further basic considerations about designing and placing of heliostats are given by Schramek, Ph. and Mills, D.R. in [64]. They present heliostats that fit for multi tower solar arrays (MTSAs), which are also described in chapter 6.2.1. Because of their hexagonal shape these mirrors allow a ground coverage of up to 100%.

A detailed comparison of software tools that can be used for heliostat layout is published by Sánchez, M., Romero, M. in [112]. These systems, based on several mathematical models and simplifications, are very useful: "(...) it is possible to calculate the yearly energy available at any point in a site for a given tower height, the yearly normalized energy surface (YNES). Yearly efficiency maps can be generated based on the cosine factor, the spillage factor and the atmospheric attenuation coefficient of the site using real Direct Normal Irradiance (DNI) data, within a reasonable computing time. It is therefore easy to find the place where the yearly energy available is the highest for location of the first heliostat. It is also possible to calculate the effect of shadowing and blocking by this heliostat on the YNES, so YNES can be re-calculated and the best position for the next heliostat can be found. Although this iterative method is time-consuming, it is worthwhile if either the efficiency of the solar plant can be increased or the capital cost reduced." [112] p.861.

Solar trough

In [26] a relevant comparison is given for a site in Egypt (27,14 degrees north). It illustrates that parabolic troughs that have an east-west oriented axis do not receive as much energy from the sun as those having a north-south orientation. (Table 2) Shifting the axis on its

System	**Annual direct solar irradiation hitting on the aperture of the collector [kWh/(m²*a)]**
Fresnel-collector	1,936
Parabolic trough, east-west oriented	1,981
Parabolic trough, north-south oriented	2,464
Parabolic trough, north-south oriented, 5° shifted	2,523
Parabolic dish, 2-axis-tracking	2,760

Table 2: Influence of axis orientation and CSP type on solar gains; source: [26] p.19;

northern end can also boost the energetic earnings (5° angle of axis to the horizontal plane). This is very plausible information, well known from conventional domestic solar technique.

In respect to effects of deviation of the angle between the axis of the parabolic trough and the theoretical ideal axis for orientation to the sun, [10] p.30 says that the long axis shall be parallel to axis of the earth. Even so the article states that East-West oriented systems are far more widespread than North-South oriented troughs.

In contrast to this [71] p.A-1 says: "Rows are typically placed on a north-south axis, allowing the single-axis troughs to track the sun from east to west during the day."

This is also stated in [1] p.34: "The solar field is modular in nature and comprises many parallel rows of solar collectors, normally aligned on a north-south horizontal axis."

Further information can be found in [40] p.20: "the SEGS (...) installed in southern California (...) utilize(s) single-axis parabolic trough reflectors that track the Sun with a north–south axis of rotation. (...) A north–south tracking axis orientation gives a high summer bias to annual electricity output, which is useful in California."

The Spanish DISS-site consists of a North-South oriented tracking axis. [113] p.637.

On the other hand East-West-oriented systems would lower differences in energy-supply during winter and summer. "(...) parabolic-trough collector axes are oriented North–South to collect the largest amount of solar radiation per year, even though the differences in solar field thermal energy output in winter and summer are more significant than with East–West orientation," says [114] p.1272.

[25] p.281 shows diagrams which also compare Horizontal North-South, Horizontal East-West and Polar orientation of Fresnel linear concentrator systems. Both Horizontal systems are very similar (East-West orientation shows better balance during the year but in summer energy gains are higher for North-South oriented types) but Polar systems seem to be superior to them regarding total delivered energy and balances during the seasons of one year.

Also in the "appraisal report to the Ain Beni Mathar Solar Thermal Power Station Project" ([115] Annex 7, page 2) practical consequences of axis-orientations can be found: In the case of East-West oriented troughs "the sun-tracking movement is limited to such slow rotation that it does not require any automatic control" in contrast to "North-South, which requires a single rotation, but a faster speed that consequently needs to be automated.".

Problem: adjustment of heliostats, measurement

The German DLR developed several methods to measure and adjust heliostat-mirrors of solar tower sites. Up to now this was a problem to these solar power plants. According to the authors of [116] the methods described in this article have higher resolution and should be faster and much more simply to apply than existing methods like Laser-scanning or photogrammetry. For that reason, DLR invented the so called "Raster-Reflexionsmethode" (raster reflection method - RRM) that detects patterns that occur when defined lines are reflected on the mirrors. Other issues are the deformation of mirrors under gravitation force. (Gravitation force on heliostats is changing when heliostats move because the angle to the horizontal plane changes).

According to [116] several hundreds of heliostats will be measured during one night fully automatically. In this way the use of modern measurement systems will help to increase the energy output of solar power sites.

7.2 CSP-components

Heat transfer medium / steam- or gas turbine-process / etc:

At the beginning of solar thermal power electricity was produced by steam-turbines. Consequently most systems used steam for transferring energy from the receiver to the turbine. Disadvantages of steam are that it is not possible to store high amounts of energy at reasonable cost level and that it is not easy to control continuous steam production while solar irradiation is changing. For that reason several systems were established up to now. All of them have characteristic advantages and disadvantages. Pitz-Paal, R. discusses those problems in [26] pp.23ff.

8 Problems and particular solutions

Many efforts have been made to shift efficiency and reliability of solar concentrating power systems. At the same time it is the aim of many projects to reduce the price of CSP-technology. Even the German Ministry for the Environment, Nature Protection and Nuclear Safety has financed more than 30 projects dealing with this issue in a cost range of 100.000 to 1.000.000 € each which started in the years 2005-2007. ([117] pp14ff, [118]). According to this ministry approximately 30 Million € have been spent on research on solar thermal power from 2001 to 2006 [119] p.27. Several comparable initiatives were also started by Spanish and US-American institutions.
The most relevant problems that are described in specialist literature are listed and discussed in this chapter.

8.1 Energy Storage in CSP systems

8.1.1 Energy storage in concentrating solar power plants

Herrmann, U., Kelly, B. and Prince, H. summarise why storage systems are in use at CSP plants and they list the main advantages of storage systems in [120] p.893: "Thermal storage can considerably improve the attractiveness of solar thermal power plants. It allows to extend or to shift the operation of the plant from sunny periods with a high peak demand. Thus, the plant can operate much more flexibly and times of mismatch between energy supply by the sun and energy demand can be reduced." So compared to hybridisation of CSP plants (see chapter 6.1) adding a storage system is the more environmental-friendly way.
In chapter 9 data of storage systems are given for many sites. One to three hour storage is the most common value.

8.1.2 Storage medium: Salt vs. Steam vs. Solid matter

Before presenting several alternative concepts for energy storage, the most common storage media are summarised and compared by their specific advantages and disadvantages:

Salt [26] pp.23ff:

+ A mixture of sodium nitrate-salts and potassium nitrate-salts is a cheap medium for storage. Changing the ratio of the two salts allows suiting the melting point of the mixture. So it is easy to make the storage medium fit to both gas turbine and receiver.
+ good heat-transfer coefficient
+ storage in huge tanks at low pressure is possible
- high melting point between 120 to 140°C (290 to 550°C according to [121] p.28) leads to plugging of pipes when the system is out of operation. Therefore pipes must be heated by electricity when the system starts working again.
- Corrosive

In the study [120] the authors stated the advantages of a storage-system using molten salt instead of the very expensive heat transfer medium in parabolic trough systems. "(...) the technical and economical feasibility of a two-tank molten salt storage was assessed. No major technical barriers were found to realize this concept. (...) this concept can improve the economy (...). A storage of 12 h full load capacity reduces the LEC *(levelized electricity costs, author's comment)* about 10%. Hence, storage systems not only improve the flexibility of solar power plants but also help to reduce the specific electricity cost and thus can support market introduction of the parabolic trough technology."

Also, most phase-change-materials (PCMs) are salts. In the article "Screening of high melting point phase change materials (PCM) in solar thermal concentrating technology based on CLFR" published by Hoshi, A. et al. PCMs are compared: Metals (e.g zinc (Zn), tin (Sn) lead (Pb)), Sugar alcohols or Organic materials can be used as PCMs apart from salts.

The use of most PCMs implies new requirements for storage construction. "The low conductivity of salt mixtures, vessel corrosion and the avoidance of freezing stresses in the containment vessels of metal PCMs are serious design problems in medium and high temperature PCM systems. Thermal conductivity may be able to be overcome using direct heating of the PCM without a heat exchanger wall, or by micro encapsulation," the authors of [39] say. Additionally they draw the following conclusion with respect to PCMs in solar thermal power plants: "In selecting high melting point phase change materials (…) molten salts with melting point in the 500–1300 K appear promising. Generally, melting point and heat capacity tend to increase in the order of nitrates, chlorides, carbonates and fluorides, making very high temperature PCMs potentially attractive (…). (…) the thermal conductivity of the PCM becomes an important factor. Materials which exhibit appropriate high melting points can also exhibit large thermal conductivity. In particular, Na_2CO_3 has been identified as a useful low cost high conductivity storage option (…) Large CLFR plants using low pressure turbines could successfully incorporate LHTES[14] storage based on a PCM salt such as $NaNO_2$, which is low cost and has a suitable melting point. Zn may be a cost effective option for trough systems using higher boiler temperatures. Implementation of high temperature LHTES storage in solar thermal electricity systems based on CLFR and MTSA systems will require numerous design issues to be resolved associated with thermal conductivity, vessel corrosion, and vessel integrity under PCM freezing. However, such PCMs are potentially both technically and economically feasible and will be the subject of further investigations. ([39] pp 338f.]. According to [122] (2004) Herrmann, U. et al. give a cost range of US$ 30 to 40 per kWh for a two-tank molten salt storage. James E. Pacheco, J.E. et al. describe the two-tank storage system in [123] p.2 and states 31$ per kWh. [124] (2001) even describes a cascade of several latent heat storages.

Steam [26] pp.23ff:

- \+ direct use in steam turbine
- \+ very cheap
- \+ well known from conventional power sites
- \+ not toxic
- \+ operation at 400°C, 100 bar; [121] p.28
- \- not easy to control when light irradiance is changing
- \- storage expensive

[14] LHTES - Latent heat thermal energy storage

- storage without massive thermal losses impossible
- Steam as steam medium is just in a development phase

Air [26] pp.23ff:

+ easy to handle; well known from conventional systems; direct utilisation
+ cheap
+ no temperature-limits (neither for high nor for low temperature). For that reason higher efficiency can be provided in a gas turbine- or even in a combined cycle.
+ not toxic
- low heat-transfer coefficient

Solid matter:

+ cheap material
+ high lifetime
- charging / discharging process is rather difficult.

In [125] pp. 1284ff Laing, D., Steinmann, W.-D. et al. compare two different solid-matter storage media: a cast able ceramic and high-temperature concrete. In the article headed "Solid media thermal storage for parabolic trough power plants" the authors describe this project: "(...) the application of solid media sensible heat storage is an attractive option regarding investment and maintenance costs. In the project WESPE (...) solid media sensible heat storage materials have been researched. Two storage systems with a storage capacity of about 350 kWh each and maximum temperatures of 390 °C have been (...) erected at the Plataforma Solar de Almeria in Spain." In their conclusion the scientists state: "Both materials researched (...) are suitable for solid media sensible heat storage systems. Considering the results available to date, high temperature concrete seems to be the more favourable material due to lower costs, higher material strength and easier handling. Test results so far let us expect a high suitability of the realised systems for storage use."
Further information about solid-matter storage can be found in [126].

8.1.3 Chemical energy storage systems

Thermochemical conversation of solar energy: Luzzi, A. and Lovegrove, K. ([127] p.317f) state that the use of ammonia could solve the problem of energy storage in solar concentrating power plants easily. The principle is relatively simple: "Thermochemistry allows concentrated sunlight to be stored in the chemical bond by providing energy for an endothermic reaction, with subsequent storage and transport of the reactants at ambient temperature." "A 4-MWe solar-assisted natural gas power plant is under consideration for Tennant Creek in Northern Australia. This base-load power plant will employ a steam Rankine cycle power conversion unit and incorporate an array of 28 direct-steam-generating dishes with 400 m² aperture each. A preliminary investigation of replacing its water/steam heat transfer network with an ammonia-based heat transfer system indicates that 24-hour storage could be provided at an additional cost of only 12%. Furthermore, for alternative sites with no natural gas back-up available, it was found that a thermo chemical ammonia system could demonstrate 24-hour base-load solar power generation for the same per-dish capital cost as a solar-only steam system without storage," the authors say in [127] published in 1995. Further information can also be found in [128]. Unfortunately the project was "put on hold" meanwhile, according to the Australian Greenhouse Office [129] in 1999.
Tamme, R. describes the synthesis of hydrogen gas supported by high-temperature solar energy, assembled in the SOLASYS project [26] p.100 ff. Another approach is the so-called "high-temperature electrolysis" of hydrogen. In that case heat from solar concentrating systems can be used to save energy for electrolysis of water.
Further chemical reactions that can be used for storage are named in [58].

There are several additional systems that could be used for energy storage in CSP plants like air, thermal oil etc.. They are not widespread in use or do not have great potential for future. E.g. air has almost the same disadvantages as steam and thermal oil is too expensive.

Almost the same advantages and disadvantages of energy storage media can be listened for a comparison of **heat transfer media** that are in use or at least considered to come in use: (Steam, pressurised water, thermal oil, air, salt, etc.)

8.2 Hydrogen diffusion through glass-pipe

This problem can be described easily: Because of high temperatures and other conditions in absorber pipes hydrogen is emitted by thermal oil. Due to its small atomic diameter hydrogen does diffuse through the absorber pipe. This effect is well-known from other applications where hydrogen appears. Unfortunately the vacuum between the glass pipe and the absorber tube deteriorates while concentration of hydrogen rises. Thermal losses rapidly increase therefore. Price, H. et al. describe how this effect has been discovered: "Receivers that have lost vacuum are generally easy for crews to identify because the barium detector getter turns white when exposed to air. (…) Field inspections showed that some receivers that still appeared to have good vacuum actually had glass temperatures above those that had lost their vacuum. When a hole was drilled through the bellows of one of these receivers, air was observed to be sucked into the annulus. The glass temperature then cooled off to that of a receiver with air in the annulus. Based on this behaviour, the hot receivers appeared to be showing signs of a build-up of hydrogen in the vacuum annulus. The hydrogen is assumed to come from decomposition of the heat transfer fluid (HTF) which is permeating through the stainless steel tube into the vacuum annulus." A detailed description of heat loss testing of solar tubes is presented in [130] by Lewandowski, A. et al.. The design of a tube for solar trough systems is shown in Figure 17 in principal.

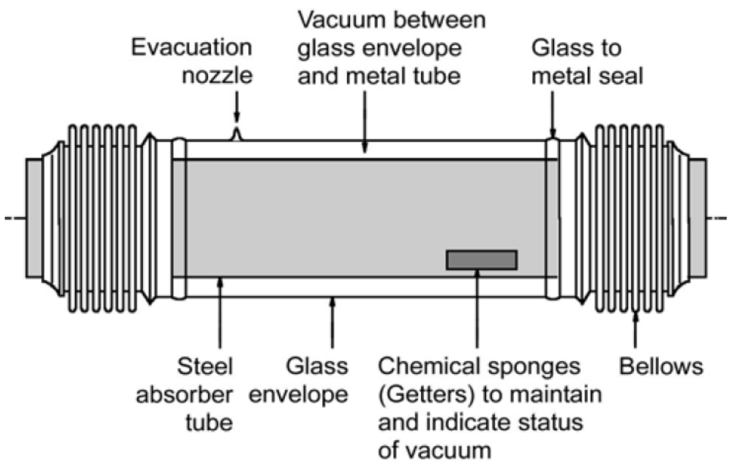


Figure 17: Design of a solar-trough absorber tube; source: [131] p.2, Flabeg Solar International;

The German DLR has started a project to investigate this issue. A 400.000 €- project called "Technologien zur Beherrschung des Wasserstoffproblems in Parabolrinnen-Receivern - TEWA" (Technology to master hydrogen diffusion in parabolic trough receivers) was financed by the German Ministry for the Environment, Nature Protection and Nuclear Safety [117] p.14, [132], [133].

The problem of hydrogen diffusion resulting from the use of thermal oils could be avoided if steam would be produced directly in the absorber pipe which was tried in the European DISS project. The European DISS-project is presented in detail in [113], [1] pp 41f, [134], [114], [135] pp.20ff., [136], [137] and [138]. These articles or the DISS-project in general can be summarised as follows: Instead of heating a heat transfer medium (synthetic oil etc.) in the absorber pipe water is preheated, evaporated and superheated immediately in the absorber pipes. Three basic DISS-types (or operation-modes), are described in [134] and other sources. In case of the "Once-through"-mode water is preheated, evaporated and superheated by passing one receiver after another without being redirected or mashed. The "injection system" is very similar but has the additional option to inject cold water during this process. Most authors favour the so-called "’recirculation’ concept in which liquid is circulated in an evaporating portion of the array at saturated steam conditions, and steam is taken off with a steam separator to a separate part of the array for superheating." [40] p.20

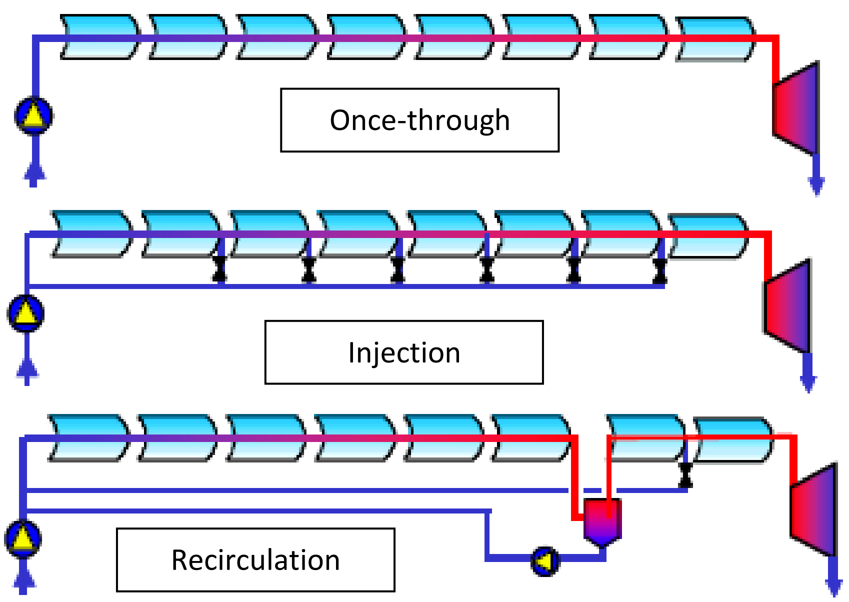


Figure 18: Once-through, Injection and Recirculation-mode in DISS-systems; source: [134] p.2;

8.3 General problem: Energy supply in North Africa vs. Energy demand in Europe

Many efforts have been made to find a reliable and cheap solution for energy transportation via large distances. In relevant books and articles the most widespread suggested solution for transferring electricity are the so-called HVDCs. HVDC means "high voltage direct current". It is an alternative to the conventional transmission of electricity by alternating currency. Transmission of alternating current is not possible for long distances without high losses. Apart from this erection of a HVDC system is – generally spoken - much cheaper than an AC-system, especially if undersea lines are included. Seboldt, W. describes the HVDC-concept with respect to a world-wide connection of energy producing sites and centres of energy consumption in [139] p.392. This concept is called "Global Energy Network" and it is illustrated in Figure 19. It would include transmission lines of a total length of 82.000 km that connect large thermal power plants of about 20.000 km² each "at favourable sites (high insolation, sparse population)" e.g. in China, Northern Africa and the US.
Further examples for articles about HVDCs are: [139] p.392 and [140] pp. 211ff. The basic idea of a "worldwide energy web" called Global Energy Network (GLEN) is illustrated in Figure 19.

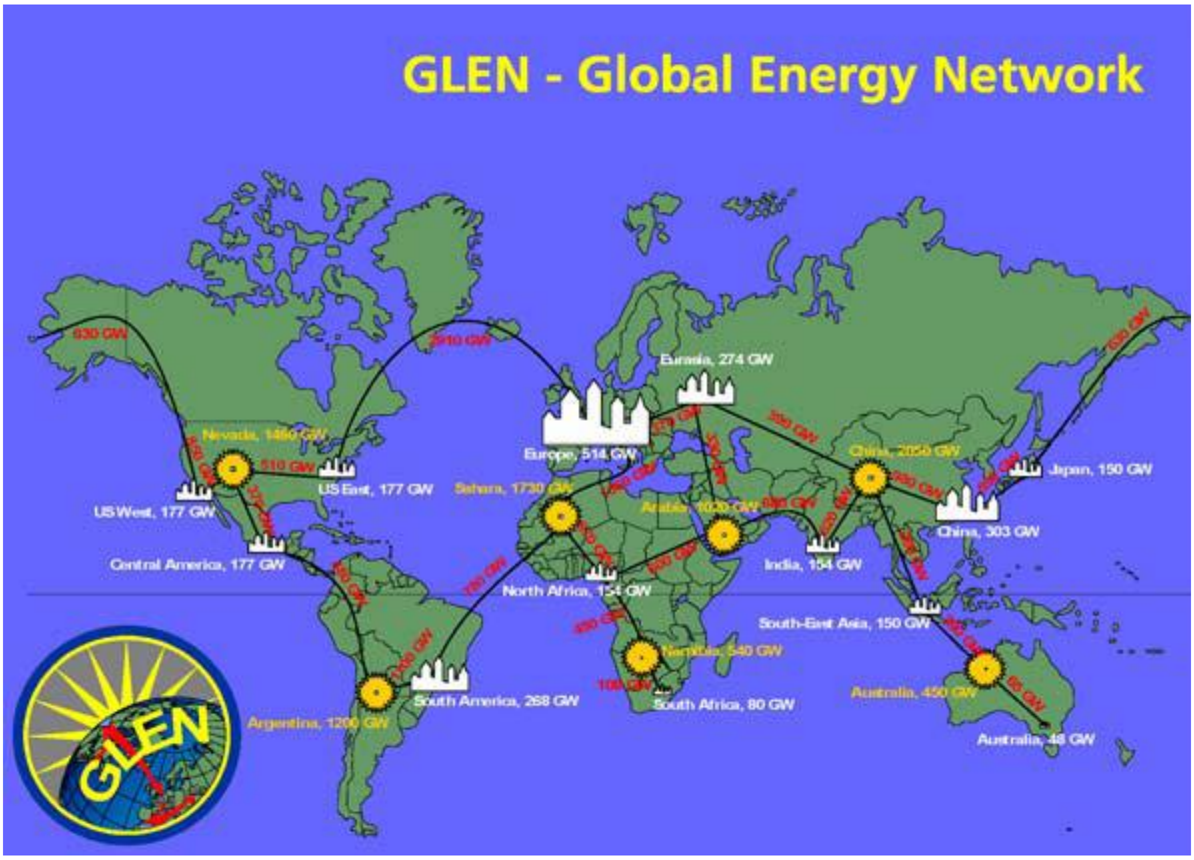


Figure 19: The "Global Energy Network" would connect several sites around the whole world; source: [139] p.392;

Another solution to produce energy in the south and use it in the North is suggested in [141]: Trevisani, L. et al. describe the idea of transporting liquid hydrogen (LH_2) "trough a cryogenic pipeline, acting at the same time as the cryogen of a MgB_2 superconducting DC line for the concurrent transport of electric energy and LH_2" [141] p.158. Apart from this double advantage the "stored hydrogen can be reconverted into electric energy in periods of renewable energy sources shortage." [141] p.158.

Another very strange solution for far-range transportation of electric energy from CSP-plants to power consumers is suggested by Seboldt, W. in [139]. The so-called Power relay satellites (PRS) concept "consists of (…) a transmitting antenna on ground, an orbital reflector satellite (…) and a ground receiving antenna." It works as follows: "On the power generating side on Earth, electricity is fed to microwave generators which are parts of a large phased-array antenna used to produce an electronically controlled beam which is focused towards the reflecting PRS. The PRS intercepts and redirects the power beam to a rectenna at the desired power-consuming location on Earth. This rectenna converts the microwave beam back into

DC electricity." Even though this principle of energy transportation seems to be far away from technical feasibility, the author cites cost-estimations for this sort of electricity transportation which expect that specific construction costs would range between 1000 and 2700 €/kW that would result in costs of 0,7 to 2,0 $-cts per kWh for an expected operating time of 30 years.

But even the idea of collecting solar power on the moon and transmitting it to Earth is presented in this paper. This would imply "lunar infrastructure, multiple satellites (…) to redirect the beam from the Moon to target sites on Earth" etc.. ([139] p.393) But in respect of this concept the author admits that "technology requirements are extremely high, and major technological and operational break-throughs are necessary to satisfy them."

Also the concept of producing electricity by a "Sail tower" of 15 km x 350 m size in the Space seems to be derivated from a science-fiction movie. (Figure 20) It consists of photovoltaic cells that produce 450 MW of electricity which result in an energy output on the ground of 275 MW after microwave transmission.

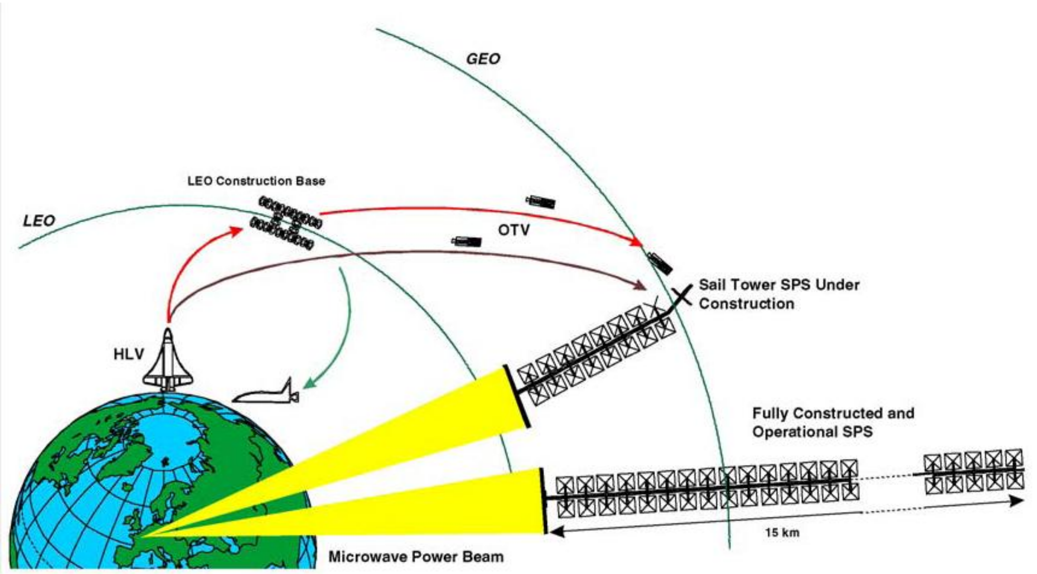


Figure 20: Scenario of electricity production in space and related energy transportation to Earth by microwaves; source: [139] p.398; GEO - Geostationary Earth Orbit; LEO - Low Earth Orbit; OTV - Orbital Transfer Vehicle; HLV - Heavy Launch Vehicles;

8.4 Mechanical resistance and deformation

Practical experiences at California's SEGS-plant are very positive: rate of breakage of solar mirrors was lower than 1% per year and after 10 years of operation they were working as well as at the beginning, even though they had and have to resist heavy storms in the desert. Availability was above 98% during 5 years. Geyer, M. assumes that the planned time of operation (25 years) will be exceeded easily [26] p. 16. Even though there is a potential of optimisation: solar troughs and heliostats can be reinforced, 'self-cleaning'-glass etc. can be used to guarantee even longer lifetime or reliable operation.
With respect to the Californian SEGS plants [7] p5-30 says: "Differing seasonal soiling rates require flexible procedures. For example, high soiling rates of 0.5%/day have been experienced during summer periods. After considerable experience, O&M procedures have settled on several methods, including deluge washing, and direct and pulsating high-pressure sprays. All methods use demineralized water for good effectiveness."

Deviation of real shape to ideal shape of parabolic mirror and influence of external forces
The authors of article [142], members of German DLR, describe the influence of position tolerance and size of absorber diameter to the efficiency of the Euro-Through-Collector. The aim of the project was to validate relevant software by comparing the used computer model and data from measurement. There are several parameters that determine if a beam hits the absorber after being reflected on the mirror surface: parameters of construction, positioning parameters of construction structure, tracking system, solar irradiation are stated as relevant factors. In [143] Pottler, K. et al. give additional information to this topic. They state that up-to-date measurement methods are important during production, (in front of all in assembling the steel structure) to avoid problems when the parabolic through is in work.
Apart from gravity forces and consequences of imperfections caused by production, wind pressure is an important matter which is discussed in [144]. On one hand wind forces can lead to a loss of energy output. On the other hand the structure must stand storm without damage. In the project described in [144] a small model of a heliostat was investigated in a

wind-tunnel beside CFD[15]-calculations. In addition to wind characteristics like velocity or direction of the wind there are some more important contributory effects. The project took interactions into account that result from the fact that mirrors shadow each other: To calculate these effects the so-called "General Blockage Area (GBA)" – factor was invented. It is used to infer on stress of each mirror from the wind characteristic hitting the whole heliostat field. Using data of forces that have effect on each heliostat it should become possible to calculate lifetime of the technical equipment in advance.

Further approaches to wind flow on parabolic concentrator systems can be found in [5], [145] and [146] p.121;

Results of a FEM (Finite Element Method) investigation on several designs are presented in [49] p.2.: "Detailed wind tunnel tests have been conducted for obtaining a reliable database for the expected wind loads at different locations in the collector field. Bending and torsion forces have been determined in these experiments. Horizontal forces and pitching moments have been evaluated for different wind speed and direction, different collector positions in the field and various elevations of the collector."

8.5 Flexible junction of medium pipe for moving absorber

Some in the above-mentioned problems are also stated in [7] pp 5-29ff. It reports about practical experiences for SEGS’s plant operation. The most relevant knowledge can be summarized as follows:

"A simple problem with a single component, such as an HCE[16], can affect many thousands of components in a large solar field. Thus it is essential that each of the SCA components is designed for the 30-year life of the plant (…). Luz used three generations of collector during the development of the nine SEGS plants. (…) Three components (…) have represented the largest problems experienced: HCEs, mirrors, and flexhoses."

The main problems with Heat Collection Elements (HCEs) were the following: "Loss of vacuum, breakage of the glass envelope, deterioration of the selective surface, and bowing of the stainless steel tube (which eventually can lead to glass breakage) have been the

[15] CFD - Computational fluid dynamics

[16] HCE - Heat Collection Element

primary HCE failures (…). Several of the existing SEGS plants have experienced unacceptably high HCE glass envelope breakage rates. The subsequent exposure to air accelerates degradation of the selective surface. Design improvements have been identified to improve durability and performance, and these have been introduced into replacement parts manufactured for the existing plants. In addition, better installation and operational procedures have significantly reduced HCE failures."

Mirrors mainly caused the following problems: "Separation of the mirror mounting pads from the mirrors was an early problem caused by differential thermal expansion between the mirror and the pad. This problem was resolved by using ceramic pads, a more pliable adhesive, and thermal shielding. (…) Mirror breakage due to high winds has been observed near the edges of the solar field where wind forces can be high."

A vulnerable part of solar troughs are the flexible hoses that make rotation of parabolic troughs possible: [7] describes this problem: "The flexhoses that connect the SCAs to the headers and SCAs to each other have experienced high failure rates at the early SEGS plants. Later plants used an improved design with a substantially increased life that significantly reduced failures. In addition, a new design that replaces the flexhoses with a hard piped assembly with ball joints is being used at the SEGS III-VII plants located at Kramer Junction. The new ball joint assembly has a number of advantages over flexhoses including lower cost, a significant reduction in pressure drop, and reduced heat losses. If ball joint assemblies can be proven to have a life comparable to the new longer-life flexhoses, then they will be included in all future trough designs."

So the "ball joint" is an alternative to conventional flexhoses. An additional solution would be to use parabolic mirrors turning around a fixed receiver tube. This concept called "Focal point rotation" is presented in [147]: "Focal point rotation must address the following: 300 mm of receiver expansion; vertical translation of the receiver; relative motion between piping and the concentrator; and large bearings that must withstand concentrated flux while allowing focusing of individual concentrators. The solution to the problem involves independently supporting the HCE’s and the concentrator. The concentrator support bearings have a large annulus to allow the passage of the HCE." A possibility to avoid these problems (distance between single mirror troughs to allow bearing) is "to fix the HCE’s to the concentrator using supports that allow axial movement only. The single joint at the end of each row accommodates rotational movement."

8.6 Dust on reflecting elements

Dust on mirrors reduces the efficiency of concentrating solar systems. Finding a site with low dust concentration in the air is therefore a relevant issue before starting construction first of all.

Using dust repellent mirrors would be another way to reduce average coat of dust on the mirror’s surfaces. Proper materials for this purpose are not available on the market yet and new materials should be developed because of that, according to [1] p.87. Its authors estimated the potential of dust repellent mirrors for reducing LEC in a range of 0,5 to 3,1% depending on the SCP type (Hybrid, atmospheric / pressurised air system) and on the conditions presumed.

[148] deals with techniques for measurement of dust influence on concentrator’s performance.

Fernández-Reche, J. studies several strategies of reflectance measurement in solar tower heliostats fields in [149]. This is an important issue if one wants to avoid cleaning activities which are not absolutely necessary or at least not profitable. This is a relevant cost factor for large heliostat fields and troughs. The author has revealed the following strategy: "It has now been demonstrated that the reflectance measurement is independent of the heliostat to be measured (as there are no significantly different groups of heliostats). So with one facet in each heliostat, at a given position on each facet, a random sample of the heliostat field can be measured." ([149] p. 782f.) According to the author’s statistical research at the PSA, it "is possible to provide the mean reflectance measurement for the heliostat field by measuring only 12 of the 116 facets which comprise the heliostat field." ([149] p. 785f.)

9 CSP sites – planned, erected and put in / out of operation

In the available sources an all-inclusive summary, including names and sites of all existing CSP-plants, performance data, date of start-up etc. is missed unfortunately. For this reason this work was done in this study as stated below. To guarantee good overview a table was used. Additional information can be found in the sources given at the end of the table stated below (Table 3).

The most comprehensive summary of pictures of several CSP-sites of many different kinds is given in [44].

According to [89] p.20 "there is currently 350 MW of CSP generation in the U.S., all of it in Southern California's Mojave desert." On the other hand, the article states that dish/engine-plants of together 800 MW will come on line in the next several years. Furthermore the price of CSP-energy is predicted to drop below 6 $-ct per kWh. Efforts are made to map a strategy to deploy 1-4 GW of CSP in the Southwest by 2015. Compared to round about 100 000 MW of Total Renewable Energy (first of all Hydroelectric) the same amount of nuclear Energy and 788 000 MW of total fossil energy (electric net summer capability) 350 MW of CSP are still a very small share of total energy supply in U.S. [89] Table 6.1. The amount of electricity net generation is given in [89] Table 7.1 as one billion kWh compared to 3883 billion total electricity generation.

Many CSP-projects can also be found on the SOLARPACES-website:
http://www.solarpaces.org

A comprehensive overview of conventional, flat-plat solar photovoltaic-plants (without concentration) in the world can be found at http://www.pvresources.com/en/top50pv.php

name / site	system	status	operator	operation from … to / starting up	power	physical work	system description	references / sources
Juelich (Jülich)	solar tower	prototype	Stadtwerke Jülich / DLR / FH Aachen	end of 2008	P el = 1,5 MW	0	In [150] we find the following information about the test-facility in Juelich / Germany: total area of the site: 20 000 m², size of receiver: 22 m², porous ceramic receiver: in 55 m height, heat transfer: air in the surrounding of the receiver is channelled through the ceramic receiver and as a result heated up to 700 °C. The heat is transferred on a water-steam cycle via a waste heat boiler. The steam expands into a turbine system which drives a generator. The system also includes heat storage to resist temporary clouds. Electrical output (nominal value) 1,5 MW	[150], [151], [152]
Almeria	Fresnel	prototype	MAN-Ferrostaal, DLR	july 2007	P th = 1 MW	0	In [153] the following information about the site is given: Absorber-tube is flown through by water that evaporates by 100 bar and can be superheatet over 400°C. In a steam-turbine the energy is transferred to electricity. The thermal power of the test-facility is round about one MW by 100 meter of length and 20 meters of width.	[153]
Almeria / PSA DISS test facility	parabolic trough	prototype		1997 to 1998		operated for 3000 h	tracking axis orientation: N-S	[113], [154], [135]
"PS 10" Sanlucar la Mayor near Sevilla	solar tower	commercial	SOLUCAR-ABENGOA	april 2007	P el = 10-11 MW	19-23 GWh/a (forecast)	624 heliostats (glass-metal), each of 120 m² (provided data differ: [26] states that 1000 heliostats of 90 m² are planned), 170 m² receiver size (receiver of wire-weave or even SOLAIR-technology), heat at a temperature level of over 1000°C have already been provided. Storage in ceramic medium for one hour of pure solar operation;	[155], [71] p. 2-3, [26], [1] p.15

several sites in Arizona, California and Nevada	dish stirling	prototype	Science Applications International Corp. (SAIC), STM Corp., Boeing with Stirling Energy Systems	?	P = 5 x 25 kW			[89] pp.18
two systems in New Mexico	dish stirling	prototype	WG Associates with Sunfire Corporation	?	P = 2 x 10 kW			[89] p.20
?	dish / free-piston- stirling engine	prototype	Cummins engine Company	early 1990s to 1996	P el = 5 to 25 kW	?		[89] p.20
Boulder City, Nevada	parabolic trough	commercial (?)	Nevada Power and Sierra Pacific Power	2005 (?)	P el = 64 MW		Over 1 km², largest plant since 1990, Solargenix SGX-1 collector, "new aluminium hubbing system developed in partnership with Gossamer Space Frames to create a structure that is 30% lighter, has 50% fewer pieces, and requires substantially fewer fasteners than earlier designs. The aluminium structure provides better corrosion resistance"	[89] p.20, [156], [44]
SEGS I to IX / California, USA	parabolic trough	commercial, connected to grid	SAIC, STM Corp., Boeing with Stirling Energy Systems, WG Associates with sunfire corporation	1985 -	P el = 354 MW (1x14 MW + 6X30 MW + 2x80 MW)	"electricity for 500 000 people" [157]	electricity costs decreased from 25 ct (1984) to 10-14 ct in the Year 1998 [71] A-4, A-5; [1] pp. 34ff., [157]; unfortunately the development of these power plants could not be continued because the responsible company (Luz) went bankrupt e.g. because of dropping gas prices [4]; 10 TWh have been sold for 1,5 billion US$ [26] p.14	[89] p.18f., [71] S. 2-3, [158], [159]
… / Barstow	*SEGS I*			*1985*	*P el = 14 MW*		*synthetic oil, 307°C, 82960 m² aperture of single-axis-tracking collectors, energy storage for 119 MWh (th)*	*[9] p.270*
… / Barstow	*SEGS II*			*1986*	*P el = 30 MW*		*synthetic oil, 315°C, 165376 m² aperture of single-axis-tracking collectors*	*[9] p.270*
… / Kramer Junction	*SEGS III*			*1987*	*P el = 30 MW*		*synthetic oil, 349°C, 230300 m² aperture of single-axis-tracking collectors*	*[9] p.270*
… / Kramer Junction	*SEGS IV*			*1987*	*P el = 30 MW*		*synthetic oil, 349°C, 230300 m² aperture of single-axis-tracking collectors*	*[9] p.270*
… / Kramer Junction	*SEGS V*			*1988*	*P el = 30 MW*		*synthetic oil, 349°C, 250560 m² aperture of single-axis-tracking collectors*	*[9] p.270*

… / Kramer Junction	*SEGS VI*			*1988*	*P el = 30 MW*		*synthetic oil, 390°C, 188000 m² aperture of single-axis-tracking collectors*	*[9] p.270*
… / Kramer Junction	*SEGS VII*			*1989*	*P el = 30 MW*		*synthetic oil, 390°C, 194280 m² aperture of single-axis-tracking collectors*	*[9] p.270*
… / Harper Lake	*SEGS VIII*			*1990*	*P el = 80 MW*		*synthetic oil, 390°C, 464340 m² aperture of single-axis-tracking collectors*	*[9] p.270*
… / Harper Lake	*SEGS IX*			*1991*	*P el = 80 MW*		*synthetic oil, 390°C, 483960 m² aperture of single-axis-tracking collectors*	*[9] p.270*
ISCCS / Kuraymat 100 km south of Cairo	parabolic trough	planned / feasibility study / in execution	NREA, Cairo (New and Renewable Energy Authority, Egypt), Flagsol GmbH	2009 (?)	P (total) = 50-180 MW; P el (solar field) = 33 MW	up to 1000 GWh per year; up to 10% solar share [160]	"(…) Lahmeyer International (performed) a feasibility study for an Integrated Solar Combined Cycle System (ISCCS) Power Plant (…) result was a candidate ISCCS configuration of 120 to 140 MW total rated capacity using the operation mode 'solar boosting' and supplementary firing during maximum demand at evening hours. (…) Cost range US$ 140-170 million" [160] (but total invest volume of 250 million € [161] (?); According to [160] execution should have started in 2000 but now start-up is predicted for 2009 [162];	[26] pp. 113ff, [163], [160], [162], [164];
INRST solar power plant / Borj-Cedria, southern suburbs of Tunis City	solar flat plate / parabolic trough	prototype / experimental	INRST	1984 -	P el = 12 kW	7,6 MWh per year (1997) [165] p.479	The plant was installed by the INRST (Institut National de Recherche Scientifique et Technique) on the Mediterrean coast in Tunisia. The plant uses a Tetrachloro-ethylene in a Rankine cycle, a 45-m³ hot-water-storage tank and 800m² of flat-plate collectors. [165] p.473 talks about "15 years of successful operation" of the whole plant. In contrast to this the parabolic concentrator unit did not work very well because of high wind speeds. [165] p.477	[165]
Amonix CPV in Torrance / California	Acrylic Fresnal lenses concentrating light on PV	prototype			P = 547 kW, additional 10-20 MW planned in Spain		average annual efficiency of 15,5 % [71] p. A-12	[71]
SSPS CRS/ Almeria, Spain	solar tower	prototype		1981-1986	P el = 0,5 MW		heat transfer medium: liquid sodium; 2-h-storage: sodium, 3655 m² Heliostat field aperture; 43 m tower height;	[26] p.23, [9] p.274,

								[154], [135]
SSPS DCS / Spain	parabolic trough	prototype		1981-1986	P el = 0,5 MW		collector field: 4940 m² two-axis-tracking, 2674 m² single-axis-tracking; heat transfer medium: Mineral Oil 295°C; storage: Oil for 5 MWh and Oil/Cast iron for 4 MWh	[9] p.270
Liddell solar project / Liddell, Australia	Fresnel: CLFR	Prototype – commercial (?)		2007	P th = 95 MW, P el = 35 MW	4,4 MWh (planned)	Reflected solar energy from a Compact Linear Fresnel Reflector CLFR) will be used to heat feedwater in a coal-fired power station	[166], [167]
EURELIOS (AURELIOS) / Adrano, Sicily, Italy	solar tower	prototype		1981-1984	P el = 1 MW		steam turbine; heat transfer medium: steam; 6216 m² Heliostat field aperture; 0,5-h-storage: nitrate salt / water; 55 m tower height	[26] p.23, [9] p.274
SUNSHINE / Nio Town, Japan	solar tower	prototype		1981-1986	P el = 1 MW		steam turbine; heat transfer medium: steam; 12912 m² Heliostat field aperture; 3-h-storage: nitrate salt / water; 69 m tower height	[26] p.23
Solar One / Barstow, CA, USA	solar tower	prototype		1982 to 1988	P el = 10 MW	38 GWh	steam directly produced in receiver, steam turbine; heat transfer medium: steam; 3-h-storage: oil/rock; 71447 m² Heliostat field aperture; 90 m tower height	[26] p.23, [9] p.274
MSEE Cat B / Albuquerque, USA	solar tower	prototype		1983	P el = 0,75 - 1 MW		steam turbine; heat transfer medium: nitrate salt; storage: nitrate salt	[26] p.23
THEMIS / Targasonne, France	solar tower	prototype		1984 [9]: 1982-1986	P el = 2 - 2,5 MW		heat transfer medium: molten salt; steam turbine; 5-h-storage Hitec salt; 10794 m² Heliostat field aperture; 106 m tower height	[26] p.23
SPP-5 / Ukraine	solar tower	prototype		1986	P el = 5 MW		steam turbine; heat transfer medium: steam; storage: water/steam	[26] p.23
TSA Spain	solar tower	prototype		1993	P el = 1 MW		steam turbine; heat transfer medium: air; storage: ceramic static bed	[26] p.23

Solar Two / Barstow, CA, USA	solar tower	prototype		1996 - 1999	P el = 10 MW		steam turbine; molten salt receiver; heat transfer medium: molten salt; 3-h-storage: molten salt; 81400 m² Heliostat field aperture; 90 m tower height; many technical malfunctions occurred. It seems that these problems can be solved easily by using corrosion-resistant materials and wet-pit-pumps [26]. Apart from this many difficulties resulted from the use of the old Solar-One-heliostats.	[26] p.23, [89] pp.18ff, [9], [146] p.118
Solar Tres / near Cordoba	solar tower	planned prototype	Consortium (Spanish / American)		P el = 15 MW		energy storage for 16 hours; solar field will exceed Solar Two by a factor of three.	[26] p.27, [44]
/ Upington, South Africa	Solar tower	planned	ESKOM	end of 2002	P = 100 MW		210 m receiver, working fluid: molten salt,	[26] p. 27, [99], p.2-3, [168]
/ Australia	parabolic PV, dish concentrator	commercial, additional power installation planned	Solar Systems Pty, Ltd	2003	P = 220 kW, additional 720 kW planned		the site has a 15-16% efficiency [71] p. A-12	[71]
Australia / White Cliffs in north-western New South Wales	solar dish	prototype connected to grid	Australian National University (ANU)	1982 - 1992	P el = 25 kW		diesel hybrid system using an array of 14 parabolic dishes with 20 m² each, direct steam generation; storage: Lead acid battery; in contrast to [127] [129] states that this plant worked from 1983 to 1989.	[127], [9] p.273
Molokai, Hawai	solar dish	prototype	Australian National University (ANU)	1985 - 1987	P el = 50 kW		295 m² Square-Dish (design by Power Kinetics Inc., USA), direct steam generation	[127]
ANU's campus	solar dish	prototype, connected to grid	Australian National University (ANU)	1994	P el = 56 kW		400 m² solar dish with a hexagonal shape, direct steam generation	[127]

Tennant Creek in Northern Territory / AUS	solar dish	put on hold	Australian National University (ANU)		P = 2 MW, 4 MW natural gas back-up			[129], [127]
Shiraz / Iran	parabolic trough	under construction			250 kW			[145]
CESA 1 / Almeria, Spain	solar tower	prototype		1983-1984	P el = 1 MW		steam turbine; heat transfer medium: steam; 11880 m² Heliostat field aperture; 3,5-h-storage: nitrate salt; 60 m tower height	[9] p.274, [154], [135], [26] p.23, [46]
PHOEBUS / Jordan		planned, stopped and continued	Fichtner Engineering Development and other German, Spanish, Swiss and US companies		P el = 30 MW		heat transfer medium: air; air leaves receiver at 700°C and produces steam; in case of too little insolation steam is produced by gas; Gulf War II stopped the realisation but a 3-MW volumetric air receiver was refined in Almeria; from 1993 on.	[4] pp. 172f, [146] p.117
Arizona / USA, next to Saguaro power plant, 30 miles northwest of Tucson	parabolic trough	commercial, under construction	Arizona Public Service (APS), Solargenix / Ormat	2005 or 2006 (?)	P el = 1 MW		construction began during 2004, first power plant to be constructed since 1991, organic Rankine cycle (ORC), plant developed by Solargenix Energy, Inc., of Raleigh, North Carolina and Ormat International of Reno, Nevada; over 10 000 m² parabolic trough area, "expected to cost $5-6 million"	[169] pp.1ff, [156], [89] p.18 f
Odeillo in the Pyrenees / France	solar furnace using heliostats directed on parabolic reflector	in use	Centre National de la Recherche Scientifique (CNRS) (National Center for Scientific Research)	1970	P th = 1 MW		Located at an altitude of 1500 m, 3000 hours of sunshine /yr, very dry atmosphere, concentrator is capable of providing a peak flux at its focus on the order of 1000W/cm^2, field of 63 flat heliostats installed on 8 terraces;	[111], [170]

/ Beit Ha'Arava, IL	solar pond (non-concentrating!)			1984	P el = 5 MW		Rankine cycles; The overall annual solar to electric conversion efficiency is about 0,9%	[9] p. 267
/ Alice Springs, Australia	solar pond (non-concentrating!)			1985-1989	P el = 15 kW		Rankine cycles; The overall annual solar to electric conversion efficiency is about 0,9%	[9] p. 267
El Paso, USA	solar pond (non-concentrating!)			1986	P el = 70 kW, P th = 300 kW		Rankine cycles; The overall annual solar to electric conversion efficiency is about 0,9%	[9] p. 267
Manzanares / Spain	Solar chimney (non-concentrating!)	decommissioned	SBP Schlaich Bergmann and Partner, Stuttgart, Germany	1986 - 1989	P el = 50 kW			[9] p. 268
SES-5 / C3C-5 / Shchelkino, Crimera, Russia	solar tower	?		1985 - ?	P el = 5 MW		heat transfer medium: steam; 0,3-h-storage; 40584 m² Heliostat field aperture; 80 m tower height	[9] p.274
Sulaibyah / Kuwait	solar dish			1984 -	P el = 153 kW; P th = 400 kW		56 dishes; 1025 m² aperture; heat transfer medium: Synthetic oil; ORC-engine; thermal storage for 700 kWh;	[9] p.273
Shenandoah, USA	solar dish			1985 -	P el = 400 kW, P th = 2000 kW		114 dishes, Polymer film concentrator, 4332 m² aperture, steam turbine; heat transfer medium: Synthetic oil, thermal storage: 1600 kWh;	[9] p. 273
Solarplant 1 / USA	solar dish			1985-1990	P el = 4920 kW		steam-turbine-engine, no storage, 700 dishes; polymer film concentrator; 30590 m² concentrator aperture;	[9] p.273
Vanguard 1 / Rancho Mirage, CA, USA	solar dish		Vanguard	1984-1985	P el = 25 kW		Glass mirror facets - dish; Stirling- engine; Tubular direct irradiation - receiver; 91 m² concentrator aperture;	[9] p.273
MDA / Los Angeles, CA, USA	solar dish		McDonnell Douglas	1984-1988	P el = 625 kW		Glass mirror facets - dish; Stirling- engine; Tubular direct irradiation - receiver; 91 m² concentrator aperture;	[9] p.273

Riyadh, Saudi Arabia	solar dish		SBP Schlaich Bergmann and Partner, Stuttgart, Germany	1984-1988	P el = 53 kW		Stretched membrane - dish; Stirling- engine; Tubular direct irradiation - receiver; 227 m² concentrator aperture;	[9] p.273
Almeria, Spain	solar dish			1991-1998	P el = 9 kW		Stretched steel membrane, glas mirror tiles - dish; Stirling- engine; Tubular direct irradiation - receiver; 44 m² concentrator aperture;	[9] p.273, [154], [135]
Ft.Huachuka, AZ, USA	solar dish		Cummins Power Generation	1992-	P el = 7,5 kW		Aluminized plastic film modules - dish; Stirling- engine; Sodium heat pipe - receiver; 42 m² concentrator aperture;	[9] p.273
Golden, CO, USA	solar dish		SAIC, STM, USA	1995-	P el = 25 kW		Stretched membrane faceted glas mirrors - dish; Stirling- engine; Tubular direct irradiation - receiver; 118 m² concentrator aperture;	[9] p.273
SOLGAS, Huelva, Spain	solar tower						The SOLGAS project was investigated under an EU-supported feasibility study. Evaporation is supported by solar receiver whereas the gas turbine is just run by energy from natural gas. "the system can't work in a 'solar-only-mode' therefore (…) solar share is restricted to about 7%" [146]	[146] p.118f
REFOS	solar tower		DLR, Weizman-Institute				compressed air (15 bar, 400°C) for a gas-turbine-process is preheated in a closed volumetric receiver (up to 800°C) and heated further by gas.	[146] p.119
/ Hassi R'mel, Algeria	parabolic trough	in construction	New Energy Algeria (NEAL)	start-up in 2010 (prediction)	P total = 150 MW, P solar = 25 MW		Gas-Solar Hybrid system, 180.000 m² solar field erected by Abener, Spain	[171], [172]
Ain Beni Mathar Solar thermal Power Station Project / Morocco	parabolic trough	?	National Electricity Authority (ONE)	construction will start soon (?) according to [115] start up will be 2008 (??)	P el total = 470 MW, P el = 140 MW [173]		planned collector area of 226.000 m², east-west oriented	[115]

Yazd Solar Power Plant / Iran	planned				P el = 400 MW		ISCC - integrated solar combined cycle	[173] p.4
/ Iran				on grid in 2010 (prediction)	P Gas = 159 MW, P steam = 132 MW Psolar = 17 MW			[162] p.3
/ near Tripolis					P = 12 MW		solar thermal including desalination plant.	[162] p.3
SOLIN-1 / Mathania, India	parabolic trough	planned	GEF, Fichtner		P el = 140 MW [173]p.4 (P el = 30-80 MW, [173]p.9)		Hybrid Solar Fossil Combined Cycle Plant, collector field of 220.000 m²,	[173] p.3
Theseus / south of Crete, Greece	parabolic trough	planned	Theseus S.A.		P el = 50 MW		collector field of 300.000 m²	[173] p.3
AndaSol 1 / Aldeire, Guadix, Grenada province, Spain	parabolic trough	in construction		7.2008 (prediction)	P = 3 x 50 MW	3 x 176 GWh/yr	12%-Gas-share, collector field of 510.000 m², Solar millennium collector, Schott HCEs	[44], [174], [175] p.6
AndaSol 2 / Spain		planned, financed and permitted						[175] p.6
Jordan Solar	parabolic trough	planned (?)		2000 (?)	P el = 150 MW		Rankine cycle	[173] p.9
SOLGATE / Italy	solar tower	under construction			P el = 2 x 200 kW		hybrid power plant, pressurised air receiver (REFOS), 343 heliostats, no storage, combined cycle, 800°C, "The system was operated in the project for 500h under solar conditions"	[1] p.15, 72,

/ Castilla-La Mancha Province, Spain	Concentrating PV	under construction	ISFOC - Instituto de Sistemas Fotovoltaicos de Concentración, Institute for concentrating Photovoltaic systems	2008	P el = 3 MW		CPV array principle: many small concentrating parabolic dishes, each having a PV-cell in its focus point, are arranged on a sun-tracking frame	[69]
HCPV / north-west Victoria, Australia	Concentrating PV (solar tower)	under construction	Solar Systems	2010, full commissioning expected 2013	P el = 154 MW	270 GWh	The plant will consist of 19.250 Heliostats and 246 receivers. The system will concentrate the sun by 500 times on high performance solar cells; erection costs are estimated at 450 million AUS$	[74], [75], [76], [77]
RRPGP / Coober Pedy, Australia	Solar dish concentrating on PV receiver (CPV)	planned	Solar Systems		P el = 910 kW		The plant will consist of 26 solar dishes is 14 metres in diameter focussed on a PV receiver. Erection costs are estimated at 7,1 million AUS$	[176]

Table 3: Examples for CSP sites and their relevant characteristics;

10 CSP construction - and specific electricity costs.

10.1 Construction costs and CSP energy price

Unfortunately most authors just give results of calculations and estimations and it is hard to find proper information about long-term specific electricity costs or investment costs. In addition most CSP-plants with considerable energy production are either rather old (sites in California which are responsible for main share of CSP-energy are dated back to the 1980's) or just under construction. For this reason we either talk about aged data or uncertain cost projections.

[4] e.g. cites that "calculations have been carried out for 13 different types of solar thermal plants under various insolation conditions" The data are dated for the early 1990s. Costs are given in US$-ct/kWh in a range depending on the specific site as follows:

- Parabolic trough, solar only, 100 MW: 29,9-32,5
- Parabolic trough, hybrid, 30 MW: 23,8-24,8
- Solar tower, solar only, 100 MW: 29,9-32,5
- Solar tower, hybrid, 30 MW: 23,0-23,6
- Dish, solar only, 1 MW: 86,2-93,6

Up to now the CSP's electricity costs have been reduced significantly and according to relevant studies this trend will last.

The most comprehensive cost projections and comparison between basic systems and specific components can be found in [1] pp. 129ff. They are mainly based on the Spanish situation but also include cost analysis for other sites. Additionally the three basic systems (solar tower, trough and dish) are analysed with respect to cost share of parts of the plants (power block, mirrors, control system etc.). The authors of [1] conclude: "The most mature technology today is the parabolic trough system that uses thermal oil as a heat transfer medium. Several 50 MWel units using thermal energy storage based on molten salt are currently planned in Spain. The present ECOSTAR evaluation estimates levelized electricity cost of 17-18 €-ct/kWh for these initial systems (…) The other technologies analyzed are currently planned in significantly smaller pilot scale of up to 15 MWel (…) ranging from 19 to 28 €-ct/kWh. (…) One significant exception is the integration of solar energy into a gas turbine / combined cycle, which at the current status of technology can only provide a solar capacity factor of 11% and needs significant fossil fuel (20% -25 % annual solar share depending on load curve) but offers LEC of below 9 €-ct/kWh for the hybrid operation[17] (equivalent to 14 €-ct/kWh for the solar LEC)." Unfortunately the question which basic concept is really best cannot be answered from the current point of view, as the authors state: "Since the absolute cost data for each of the reference systems are relatively close and are based on a different level of maturity, choosing technologies for R&D prioritization (e.g. troughs vs. towers) doesn't appear feasible." With regard to future price development the authors estimate: "(…) an overall cost reduction of 55 – 65% (…) can be estimated in the next 15 years. This would lead to levelized cost of electricity in Southern Spain of around 6.5 €-ct/kWh and down to 5 €-ct/kWh in high insolation areas." [1] p.129. Efforts were made to compare the estimated cost reduction potential of several receiver systems (molten salt, saturated steam, atmospheric air, pressurized air etc.). The results are shown in [1] p.130.

Geyer, M. states that parabolic troughs stand for the most reliable solar concentrating technology in commercial use. He states that this technique is still the benchmark for other solar thermal concentrating systems and gives total electricity production for the SEGS I – IX parabolic trough site at 10 TWh at total cost of 1,5 billion dollars for the sold electricity which would result in average costs of 0,15 US$ per kWh of electricity.

The American National Renewable Energy Laboratory (NREL) published levelled cost of electricity- predictions. Prices of electric energy for the year 2003 was predicted at 11,3 for parabolic trough, 12,0 for solar towers and 40 for Dish/engine systems. ($-ct per kWh of electric energy - hopefully these figures are considered as being $-ct (1/100 $) and not $ as mentioned in [89] p.20)

In [115] information on the "Ain Beni Mathar Solar thermal Power Station Project" in Morocco is given. It includes an "environmental and social management plan", detailed

[17] At a fuel price of 15 €/MWh

project costs (especially a calculation for rates of return from 2005 to 2027) and an accurate project implementation schedule.

For detailed cost estimation a software tool has been created by the DLR with Quaschning, V., FHTW Berlin (Fachhochschule für Technik und Wirtschaft Berlin - University of Applied Sciences). A free test-version can be downloaded at

http://www.f1.fhtw-berlin.de/studiengang/ut/downloads/greenius/index.html

This tool includes the possibility to evaluate both economical and technical feasibility of solar concentrating systems as well as several other plants running by renewable energy. Further information can be found in [177].

Location of CSP's is also a relevant factor for costs of electricity production: [121] p.25 compares several sites with different normal irradiation over the year. If we define a site in Las Vegas (2600 kWh/(m²*a)) at 100% production costs decrease to 96% for 2636 kWh (Tucson), to 91% for 2850 kWh (Northern Africa) to 87% for the Kramer Junction site with 2900 kWh. On the other hand specific production cost would increase by 18% if we take Southern Spain (2200 kWh) instead of Las Vegas.

[178] and [179] give a comparison of economic competitiveness of photovoltaic systems and CSP systems. The authors conclude that under consideration of an assumed future price development in the photovoltaic market photovoltaic is – from an economic view – the better technique north of the 47th latitude while CSP shall dominate in regions south of the 47th latitude.

Far-range transportation costs

Eisenbeiß, G. gives 2 €-ct costs for transporting 1 kWh from Morocco to Germany. [26] p.9., Trib, F. estimates 1 €-ct for transportation in [26] p.41. Apart from techno-economical matters one should not forget that every energy-transporting line leads to political addiction that have very often lead to diplomatic or military conflicts in the past. So from a political point of view one should prefer de-central solutions as the back-bone of a region's energy supply. Even though import of electric energy from southern countries will probably play an important role in the future, especially for economic reasons.

Further cost trends are given in [13] pp. 18ff.

10.2 Cost projections

Principal considerations on cost predictions and potential studies

The past has shown that it is very difficult or even impossible to give serious forecasts, whether in the economic or technical sector.

In the economical sector several "experts" have published misleading predictions for energy prices in the past. The third biggest bank in Austria that operates an own research institute, was – as most economic experts – not able to find proper oil-price-data for the future. They proposed a wrong price, even for a very short period of time, which can be seen in Figure 21. So information about future developments given by experts is useless more often than not.

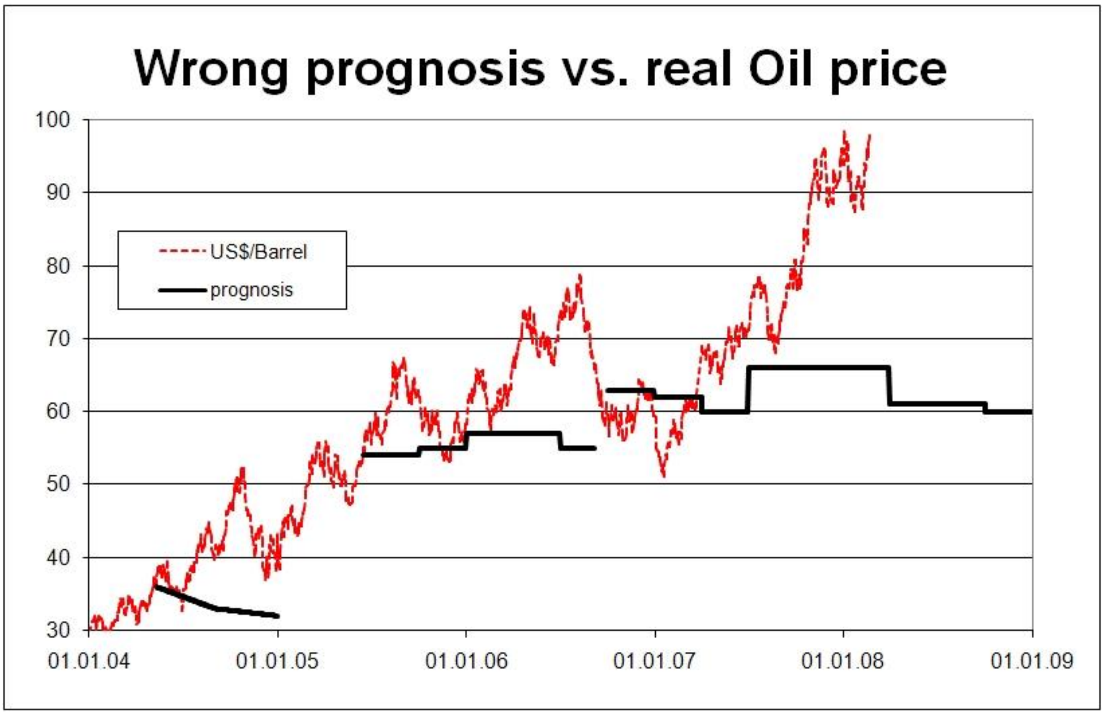


Figure 21: Misleading prediction of crude-oil-price. As long as energy prices can't be predicted for several decades, profitability calculations in advance remain valueless.

But even in the technical sector where projections do not depend on psychological or political factors, forecasts have caused more disadvantages than advantages mostly. Examples for misleading prognoses in the sector of technical sciences are studies of potential of electricity production by wind in Austria. One of them was even published by the Vienna University of Technology. While the predicted amount of annually produced energy ranged between 470 and 568 GWh of electric energy for the investigated province (theoretical/technical potential), the annual production has already exceeded 775 GWh in the year 2007 [180].

So studies about future prices and future energy quantities are ideas of one author copied by many other authors most often. Technicians are no prophets – as well as everyone else, also in the scientific sector. From a technical point of view society should use solar energy with no respect to the specific energy price. But this is a political question that has to be discussed by society.

Apart from these entire facts one should consider that all kinds of electricity-production have always been strongly influenced by national or local politicians. (Large Hydro plants, electricity production by coal or nuclear energy etc.) It depends on political influences first of all if CSP will play an important role in the future and if it will become more attractive for companies to do research on this topic. The chapter "Public Policies Around Solar Economics Make the Difference" in [19] p. 35 deals with this problem.

Additionally the authors of [41] p.96 have revealed an important aspect of renewable-energy financing: "An energy policy with a long-term strategy of reducing dependence on fossil fuels should not tie the revenues of renewable electricity to current prices for fossil fuels. Instead, such a policy should provide incentives that will generate sufficient revenues for emerging renewable technologies, to ensure that such technologies can enter the marketplace regardless of the price levels of fossil fuels. If an energy policy does not proactively work to encourage renewable technologies and instead relies on tying renewable revenues to fossil fuel prices, the price signals from fossil fuels will only attract investment in renewable power when it is too late. With low fossil fuel prices, the demand for fossil fuel will increase, which in turn might accelerate the fossil fuel price, in some cases rapidly. The time is then too short to construct renewable technology to use instead of the now expensive fossil fuel. An example is the low natural gas prices of the late 1990s, which attracted hundreds of thousands of megawatts of natural gas-fired generation, which then resulted in increased demand for this commodity, and finally the natural gas price spikes seen in 2001."

CSP cost projections

Experts say that specific costs for electricity produced by CSP systems will drop to 6 $-ct/kWh within the next 15 years ([140] p.214) if capacity of electric power will grow up to 5 GW. 80% of total costs are investment costs, just 20% remain during operation. Operational costs of actual sites are at 3 ct/kWh.

A study published by the German Federal Ministry for Environment (BMU) together with DLR headed "Concentrating Solar Power Now" [14] says: "Advanced technologies, mass production, economies of scale and improved operation will allow reducing the solar electricity cost to a competitive level within the next 10 - 15 years. This will reduce the dependency on fossil fuels and thus, the risk of future electricity cost escalation. Hybrid solar-and-fuel plants, at favourable sites, making use of special schemes of finance, can already deliver competitively priced electricity today." Further recent cost projections can be found in [181] and in the study [33] that was published in 2005 and which also contains detailed cost analysis for single components: "For economic analysis, an emerging market for solar tower plants is assumed with concentrator costs of 132 €/m^2 (for 120 m^2 glass-metal heliostat). The receiver costs are 16 k€/m^2, 33k€/m^2 and 37.5 k€/m^2 for the low-, medium- and high-temperature receiver. The investment costs for the conventional part (power block, fuel system, cooling system, generator, grid connection) are 1520 €/kW for the Heron system, 560 €/kW for the Mercury system and 510 €/kW for the PGT10 combined cycle system[18]. For effective energy-costs the authors conclude: "The cost analysis showed total plant investment costs from 7000 €/kW down to below 1800 €/kW, depending on power level and solar share. Solar LEC between about 0,13 €/kWh up to 0,90 €/kWh were calculated. Using the cost reduction potential that lies in combined design, construction and operation of multiple distributed plants leads to solar LEC of below 10 €-ct/kWh for an electric power level of 16.1 MW. So, the solar-hybrid gas turbine power technology shows interestingly low cost for solar produced bulk electricity at a moderate power level."

Electricity costs of CSP-systems given by [182] are also in the same range: For the sun-belt in the northern hemisphere a study published in 2005 is cited which gives specific electricity

[18] Heron H1—intercooled recuperated two-shaft engine with reheat. ISO rating 1400 MW, thermal efficiency 42.9%; Solar Mercury 50—recuperated single shaft gas turbine. ISO rating 4200 MW, thermal efficiency 40.3%; PGT 10—simple gas turbine with bottom cycle. ISO rating 11100 MW (gas turbine) respectively 16100 MW (combined cycle), thermal efficiency 31.3% (gas turbine) respectively 44.6% (combined cycle).

costs of 0,15 to 0,20 €/kWh for commercial (not for R&D) plants. The authors assume a cost reduction of 50 percent up to 2020. They state a cost level of 0,11-0,15 €/kWh in the year 2010 and of 0,05-0,09 €/kWh in 2020.

Trieb, F. and Müller-Steinhagen, H., the authors of article [140] p. 209 investigated the role of sustainable energy in the energy sector of the future with respect to the situation of Northern Africa, Middle East and Europe. For concentrating solar thermal power they give a technical electricity potential of 630.000 TWh per year. They state that "concentrating solar collectors are efficient fuel savers, today producing heat at a cost equivalent to US$50/barrel of fuel oil, with the perspective to achieve a level below US$25/barrel within a decade" (until 2015). If we consider that price of crude oil of 50$/barrel in 2005 has doubled meanwhile (1st January 2008) solar concentrating power should already be very attractive. In respect of future electricity prices the authors state: "New CSP plants in Spain with up to 50 MW capacity receive a feed-in tariff of about € 0.22/kWh today. Installing CSP plants worldwide, a reduction of the solar electricity cost due to economies of scale can be achieved with a progress ratio of about 90% *(doubling of production capacity leads to a 10%-reduction of investment costs, author's note).* As an example, a first 10-MW plant in Jordan could produce electricity at about US$ 0,18/kWh. In the period up to 2010, the cost of solar electricity of newly installed plants will drop to less than US$ 0,10/kWh, in 2020 to US$ 0,06/kWh and in 2030 to US$ 0,05/kWh."

Detailed predictions for trough, tower and hybrid CSP-plants are given in the NREL's study "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts" [22]. Consisting of 344 pages, this study is the most comprehensive source with respect to predictions of CSP-system's future.

Horn, M. et al. analysed the economic feasibility of an ISCCS power plant for Egypt and also got energy-cost predictions in the range of 10 $-ct per kWh of electric energy [183] p.944.

Economies of scale

As already mentioned, extending the size of concentrating solar power plants normally reduces specific costs of produced electricity. [121] p.14 shows that cost level of a kWh electric energy produced in a 200-MW plant is just 77% and in a 100-MW plant just 86% compared to a 50-MW plant. A Reduction of size from 50 MW to 25 MW would even lead to an increase of price of 23%. But "economies of scale" also matter if we regard the size of single components of a solar plant: On the analogy to other technical fields it is also the case for the solar tower and solar dish principle that specific costs decrease when sizes of its components increase. For this reason "dishes as large as 400 m² have been made" according to [1] p.79. Compared to former heliostats the size of these items has been expanded, too: "Also the size and geometry of the optical surface influences the costs. Nowadays heliostats up to a size of 150 m² are the commercial reference for CRS[19]. The so-called Megahelio concept emerges as a very-large-area heliostat concept above 200 m² with the target of 30% cost reduction within less than 5 years time for full development and commercial implementation." [1] p.88.

So it is not easy to find a proper way for cost- and price-forecasts of electricity from CSP systems but even not for energy prices at all. On the other hand companies have to make a decision if they invest in solar technology or not. From the current point of view the following statement can be made: If oil price keeps as high as it is now (90-100$ per barrel) or if it will even rise any more, investment in CSP is very reasonable. Unfortunately such decisions always have to be made with respect to political developments in world and national politics. So a general recommendation can be made for national economies but not for private companies. For national governments investment in renewable energy is absolutely necessary and CSP is one of the most cost-effective options for countries with high direct normal irradiation. For companies the decision depends on the political circumstances.

10.3 CSP potential

Czisch, G. in [20] gives – as many other authors - a rough orientation for potential of CSP: "At state-of-the-art technology 0,1 to 0,15 TWh electric energy can be generated per square-km and year in suitable desert regions." [20] p.7.

As already stated before, DNI is the most relevant factor for CSP systems and does depend very strongly on the altitude of a site but it does almost not depend on the distance to equator (degree of latitude), as shown in Table 4: Cologne is located on almost the same line

[19] CRS – Central Receiver System

of latitude as Glasgow (MT, USA). Even though Glasgow approximately has double DNI of Cologne.

site	latitude (°N)	DNI [kWh/(m²*a)]
Daggett, CA, USA	34,87	2700
Jodhpur, India	26,3	2240
Los Angeles, CA, USA	33,93	1750
Glasgow, MT, USA	48,22	1606
Dubai, United Arab Emirates	25,23	1590
Cologne, Germany	50,85	780

Table 4: Correlation of several sites with different distances to the equator; source: [9] p.278;

This is caused by the fact that DNI does mainly depend on air quality, relative humidity in the air, altitude above sea level, share of cloudy weather conditions during one year etc.. China is also a very good example to show this: Tibet region has approximately four times more energy per square meter than the region near the Yangtze Kiang River. Both regions are near the 30° of northern latitude. Tibet e.g. has a high altitude and the light has to pass just little distance through the atmosphere. The longer the way through the atmosphere the higher the mitigation of sunlight is. China's CSP potential is analysed in [184] p.7. This article also underlines the high amount of direct normal irradiation during one average day in Tibet region.

The global situation of areas with high and low DNI values is illustrated in Figure 5 in chapter 4.2.

Several studies exist which analyse the potential of CSP on the electricity market, most of them regarding the western states of the USA. Most times maps of climate data are available for this purpose. Some of the studies also compare regions in respect to their favourability to all kinds of renewable energy, e.g. photovoltaic, biomass, wind and geothermal energy. [185]

11 Ecological and social effects, effect on carbon dioxide emissions

11.1 Ecological analysis and CSP potential, CO_2/kWh

11.1.1 Energy required for CSP construction

In [26] pp. 10ff a comparison between a solar trough and solar tower power plant (air receiver) is given: To get 1 MWh of electric energy during one year the trough system needs 7,14 MWh of solar irradiation hitting on 3 m² collector. 3,36 MWh are losses on the solar field, 2,68 MWh result from the thermal cycle, 0,11 MWh are needed for internal power consumption and 1 MWh of electricity remain. For the solar tower system only 2,16 m² of collector (5,14 MWh) are needed at the beginning of the cycle. 2,07 MWh are spent on collector-losses, 0,61 MWh are lost on the receiver, 1,36 on the thermal cycle and 0,11 MWh are needed for internal power consumption.

Compared to conventional power-plants, CSP plants have positive effect on the environment: article [108], p.41 says: "The energy payback time[20] of a solar thermal power plant is in the order of 0.5 year, while the economic lifetime is at least 25 years. Life cycle emissions of greenhouse gases amount to 0,01- 0,015 kg/kWh, which is very low in comparison to those of gas fired combined cycles (0,500 kg/kWh) or steam/coal power plants (0,900 kg/kWh)." [14] gives the same information: "The energy payback time of the concentrating solar power systems is in the order of only 5 months. This compares very favourably with their life span of approximately 25-30 years. Most of the collector materials can be recycled and used again for further plants." Also [121] p. 21 gives a energy payback time of 5 months for CSP in Morocco. Even compared to established renewable energy production (wind power: 4-7 month, hydro: 9-13 month) this is a very short time. One

[20] The energy payback time is defined as the energy need for the construction of a plant divided by its (renewable) energy output per time unit. The lower the energy payback time the higher the positive effect on environment.

should consider that payback time for fossil plants is always infinite because of fuel consumption during operation.

11.1.2 Environmental pollution?

Apart from effects of process-media (especially thermo-oil etc., dependent on the used technology.), environmental pollution caused by necessary transportation and other effects that also occur in conventional plants, the problem of weed control is named in literature with respect to CSP plants. [41] p.100 for example states: "Nevertheless, because of fire hazards, the land on which the collectors of a parabolic trough plant are located needs to be kept clear of vegetation at all times; this may cause problems under the Endangered Species Act or state wildlife protection laws. The small footprints of PV *(Photovoltaic, author's comment)* and the pedestal of dish Stirling cause a small impact on the land." So both PV and CSP are environmentally friendly because of their small occupation of area.

11.1.3 Social effects

Apart from their advantages for environment, CSP systems also have positive effects on the employment rate of the region. In a chapter headed "Benefits to Ratepayers and Society at Large" in the "Solar Task Force Report" ([19] p. 18) the authors explain why CSP systems are superior to conventional power plants. "The social benefits accruing to all taxpayers are broad in scope. Construction and operation of CSP plants would bring significant economic impacts to the southwest States. (...) Direct economic impacts are the dollars directly spent by the project in the region for materials, equipment and wages. Indirect economic impacts are also referred to as the 'multiplier' impacts of each dollar spent in the region. When a dollar is spent in the region, a portion of that dollar goes to pay employees' salaries (earnings). Those dollars are then re-spent in the region to purchase goods and services."

Effects on national economy and employment

The authors of [14] also cite a study that estimates the economic benefits on California as follows:

Deployment level	2 GW	4 GW
Increase in Gross State Output	$11.7 billion	$22.2 billion
Creation of construction jobs	6,800	12,800
Creation of permanent operations jobs	500	1,100
Increase in State Tax Revenues	$1 billion	$2 billion

Table 5: economic key figures of CSP plants of different sizes; source: [14];

In addition to that the study gives estimations for avoided emissions for additional CSP systems erected in California.

The chapter "Benefits of Using Solar Power" in [41] pp.95ff describes such side effects, namely the stabilisation or reduction of fossil energy prices, too: "Over two-thirds of western energy depends on the price of two fuels. (…) in our view, future volatility of natural gas prices may be higher than has been experienced historically due to the increasing competition for natural gas to fuel generating units. If western states want to hedge against fuel price volatility, then a diversification of energy sources is essential. Renewable energies with no fuel cost, such as wind and solar, can play a fundamental role in hedging against volatility. Portfolio theory clearly shows that even higher cost resources such as renewables can result in lower long-run energy costs at the same risk level."
Several scenarios for CSP sites in Nevada starting with the year 2004 and ranging up to 2035 have been made by Schwer, R.K. and Riddle, M. and have been published in 2004. The three examined CSP plants vary from 100 MW to 1000 MW of electric power. [186] The authors give detailed predictions in tabular form for direct construction costs, O&M-costs, effects on employment, personal income for employees, results on the Gross state product etc. of each alternative. In their conclusion the authors state: "(…) the economic benefits can be significant, particularly if multiple plants are considered. In the most conservative one-plant Scenario A, total personal income in Nevada attributable to the construction phase (2004 through 2006) and the O&M phase (2007 through 2035) is estimated to be $1.15 billion. GSP[21] will be boosted by $1.14 billion. If approximately 2/3 of the Nevada RPS[22] is met with CSP generation, the state can expect additional personal income and GSP of $3.41 and $3.47, respectively. At the largest investment level, Scenario B, ten 100-MWe plants would

[21] GSP - Gross State Product
[22] RPS - Renewable Portfolio Standard

be constructed. Direct, induced, and indirect benefits in terms of personal income and GSP would reach $9.37 and $9.85, respectively."

But apart from the shift of employment caused by CSP construction it is also relevant to say that jobs are created where they are strongly needed – in rural areas: "The CSP-generation industry could support sustainable economic development in places that are currently seeking opportunities for economic development. New jobs in the relatively highly paid utility industry could provide a core of income for counties that are fast losing traditional income sources such as mining." [186] p.22.

Additionally general positive effects of CSP e.g. on environment are not considered here. So benefits would be even higher. Certainly Nevada's situation described in the article is comparable to many other sites that fit for solar concentration.

12 Most relevant suppliers for CSP systems on the international market

It is not easy to give a comprehensive summary about companies that provide CSP systems. Companies are often founded for single CSP projects and unfortunately many enterprises also became bankrupted soon after they have been established. Apart from this most projects are managed by a consortium of companies from several technical fields (turbine producers, glass industry, solar industry etc.). So the CSP sector is not yet a firm market, compared to other businesses.

For this reason just a rough overview of companies that work or worked in the CSP sector shall be given here.

- **Abengoa Solar**, Spain
- **Able Engineering**, Phoenix, Arizona, USA
- **Acurex,** Cambridge, Massachusetts, USA
- **Boeing**, Chicago, Illinois
- **Cobra**
- **CSIRO** (Commonwealth Scientific and Industrial Research Organisation), Australia
- **CIEMAT** (Centro de Investigaciones Energéticas Medioambientales), Madrid, Spain; CIEMAT Almeria, Tabernas (Almería), Spain
- **DLR** (Deutsches Zentrum für Luft- und Raumfahrt e. V.), Cologne, Germany
- **Duke Solar** see Solargenix
- **Eskom**, Johannesburg
- **Fichtner** GmbH & Co. KG, Stuttgart, Germany
- **Flabeg** Holding GmbH, Nürnberg, Germany
- **Flagsol** GmbH, Köln, Germany
- **Iberdrola**, Bilbao, Spain
- **ISFOC** (Instituto de Sistemas Fotovoltaicos de Concentración - Institute for concentrating Photovoltaic systems), Puertollano (C. Real), Spain

- **KAM** – Kraftanlagen Anlagentechnik München, Munich
- **Lahmeyer International** GmbH, Bad Vilbel, Germany
- **MAN** AG, Munich
- **Nexant** San Francisco, California, San Francisco, California, USA
- **NREL** - National Renewable Energy Laboratory (US Department of Energy) Cole Blvd., Golden, Colorado, USA
- **Phoenix Solar** AG, Sulzemoos, Germany
- **Sandia** National Laboratories (SunLab), Aschaffenburg, Germany
- **Sargent & Lundy** LLC, Chicago, Illinois, USA
- **Schott** Solar GmbH, Alzenau, Germany
- **SENER** Ingeniería y Sistemas, S.A., Spain
- **Schlaich Bergermann und Partner**, Stuttgart, Germany
- **SMAG** see Solar Millennium AG, Germany
- **SB&P** see Schlaich Bergermann und Partner
- **Solaq**, Groningen, Netherlands
- **Solar Millennium** AG, Erlangen, Germany
- **Solar Power Group** GmbH, Essen, Germany
- **Solar Systems**, Australia
- **Solel Solar Systems** Ltd., Beit Shemesh, Israel
- **SolFocus**, California, USA
- **Solucar**, Lakewood, Colorado, USA
- **Solargenix**, formerly Duke Solar Energy, Sanford
- **Spectrolab** Inc. (subsidiary of Boeing, also see Boeing) Spectrolab, Sylmar, California, USA
- **Steinbach & Vollmann** (STUV), Heiligenhaus, Germany
- **Züblin** AG, Stuttgart, Germany

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