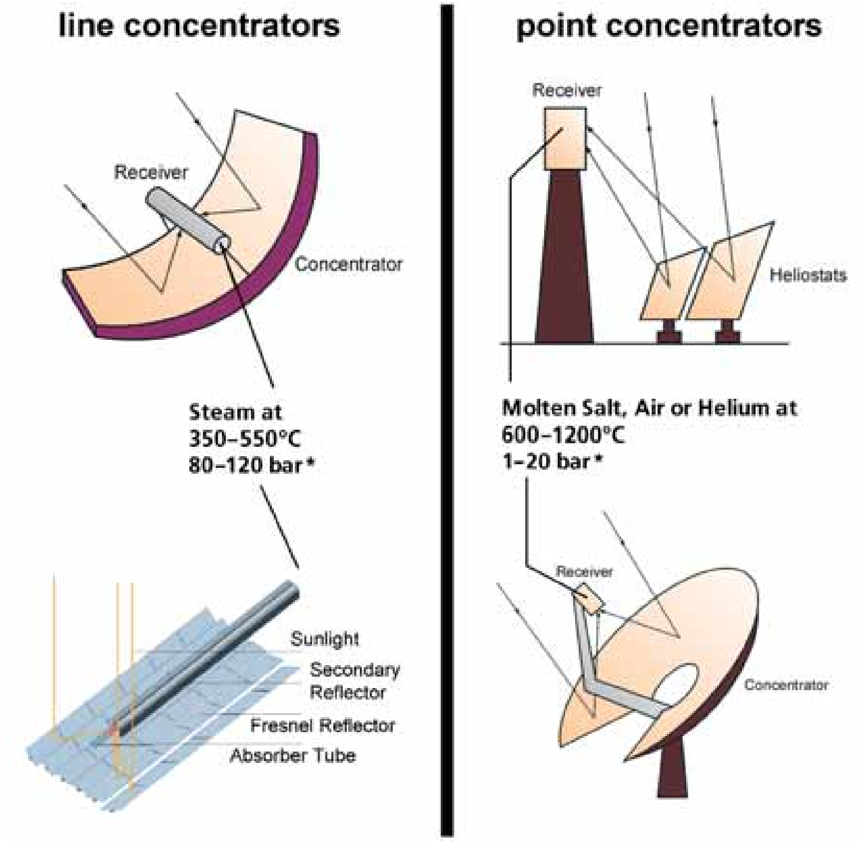


Figure 1 Technologies for concentrating solar radiation: left side parabolic and linear Fresnel troughs, right side central solar tower receiver and parabolic dish (Source: DLR)

Technical principles

In general, solar thermal technologies are based on the concept of concentrating solar radiation to produce steam or hot air, which can then be used for electricity generation using conventional power cycles. Collecting the solar energy, which has relatively low density, is one of the main engineering tasks in solar thermal power plant development. For concentration, most systems use glass mirrors because of their very high reflectivity. Other materials are under development to meet the needs of solar thermal power systems. Point focusing and line focusing systems are used, as depicted in Figure 1. These systems can use only direct radiation, and not the diffuse part of sunlight because this cannot be concentrated. Line focusing systems are easier to handle, but have a lower concentration factor and hence achieve lower temperatures than point focusing systems.

Table 1 gives an overview of some of the technical parameters of the different concentrating solar power concepts. Parabolic troughs, linear Fresnel systems and power towers can be coupled to steam cycles of 10 to 200 MW of electric capacity, with thermal cycle efficiencies of 30–40%. The values for parabolic troughs, by far the most mature technology, have been demonstrated in the field. Today, these systems achieve annual solar-to-electricity efficiencies of about 10–15%, with the aim that they should reach about 18% in the medium term. The values for other systems are, in general, projections based on component and prototype system test data, and the assumption of mature development of current technology. Overall solar-electric efficiencies are lower than the conversion efficiencies of conventional steam or combined cycles, as they include the conversion of solar radiative energy to heat within the collector and the conversion of the heat to electricity in the power block. The conversion efficiency of the power block remains essentially the same as in fuel fired power plants.

Because of their thermal nature, each of these technologies can be ‘hybridised’, or operated with fossil fuel as well as solar energy. Hybridisation has the potential to improve dramatically the value of CSP technology by increasing its power availability and dispatchability, decreasing its cost (by making more effective use of the power block equipment), and reducing the technological risk by allowing conventional fuel use if, for example, the collector has to be repaired. Solar heat collected during the daytime can be stored in concrete, molten salt, ceramics

Table 1 Performance data for various concentrating solar power (CSP) technologies

	Capacity unit MW	Concentration	Peak solar efficiency	Annual solar efficiency	Thermal cycle efficiency	Capacity factor (solar)	Land use m² MWh⁻¹ y⁻¹
Trough	10–200	70–80	21% (d)	10–15% (d) 17–18% (p)	30–40% ST	24% (d) 25–70% (p)	6–8
Fresnel	10–200	25–100	20% (p)	9–11% (p)	30–40% ST	25–70% (p)	4–6
Power tower	10–150	300–1000	20% (d) 35% (p)	8–10% (d) 15–25% (p)	30–40% ST 45–55% CC	25–70% (p)	8–12
Dish-Stirling	0.01–0.4	1000–3000	29% (d)	16–18% (d) 18–23% (p)	30–40% Stirl. 20–30% GT	25% (p)	8–12

(d) = demonstrated; (p) = projected; ST steam turbine; GT gas turbine; CC combined cycle.

$$\text{Solar efficiency} = \frac{\text{net power generation}}{\text{incident beam radiation}} \qquad \text{Capacity factor} = \frac{\text{solar operating hours per year}}{\text{8760 hours per year}}$$

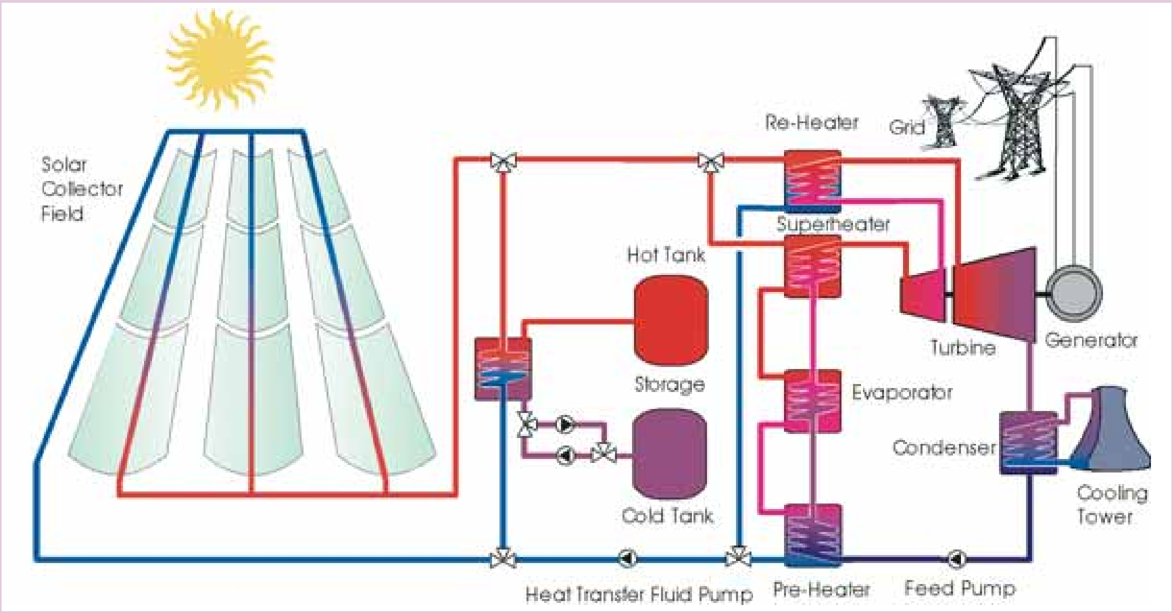


Figure 2 **Schematic diagram of a steam cycle power plant with a parabolic trough collector and a thermal energy storage (Source: DLR)**

or phase-change media. At night, it can be extracted from storage to run the power block. Fossil and renewable fuels such as oil, gas, coal and biomass can be used for co-firing the plant, thus providing power capacity whenever required.

Moreover, solar energy can be used for co-generation of electricity and heat. In this case, the high value solar energy input is used with the best possible efficiencies of up to 85%. Possible applications include the combined production of electricity, industrial process heat, district cooling and sea water desalination.

It is generally assumed that solar concentrating systems are economic only for locations with direct incidence radiation above 1800 kWh m^{-2} year^{-1}. Typical examples are Barstow, USA, with 2500–2700 kWh m^{-2} year^{-1} and Almeria, Spain, with 1850–2000 kWh m^{-2} year^{-1}. Today, all installations would have capacity factors of 25%, equivalent to about 2000 full load operating hours per year, with the aim of using solar operation for base load with thermal energy storage and larger collector fields. To generate 1 MWh of solar electricity per year with CSP, a land area of only 4–12 m^2 is required. This means, that 1 km^2 of arid land can continuously and indefinitely generate as much electricity as any conventional 50 MW coal- or gas-fired power station.

Line focusing systems

As schematically shown in Figure 1, line focusing systems use a trough-like mirror and a specially coated steel absorber tube to convert sunlight into useful heat. The troughs are usually designed to track the Sun along one axis, predominantly north–south. The first parabolic trough systems were installed in 1912 near Cairo (Egypt), to generate steam for a 73 kW pump that delivered 2000 m^3/h of water for irrigation (see Figure 3). At the time, this plant was competitive with coal-fired installations in regions, where the cost of coal exceeded 10 German Marks per tonne (Stinnesbeck, 1914[11]).

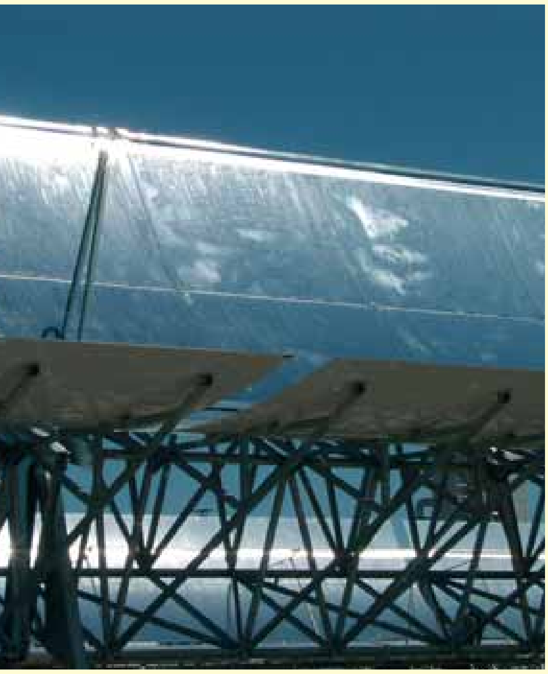
To generate electricity, the fluid flowing through the absorber tube – usually synthetic oil or water/steam – transfers the heat to a conventional steam turbine power cycle (Figure 2). With the sunlight concentrated by about 70–100 times, the operating temperatures achieved are in the range of 350 to 550°C.

With 354 MW of parabolic trough power plants (about 2 million m^2 of mirror area) connected to the grid in southern California, parabolic troughs represent the most mature CSP technology. In the solar electricity generating systems (SEGS) plants developed since the 1980s in California, a synthetic thermal oil is used for operating temperatures up to 400°C. In a steam generator, this heat-transfer oil is used to produce slightly superheated steam at 5–10 MPa pressure, which then feeds a steam turbine connected to a generator to produce electricity. No new plants have been built since 1991, because declining fossil-fuel prices in the United States resulted in unattractive economic predictions for future plants. However, the performance of these power plants has been continuously improved. For example, the Kramer Junction site (see Figure 4) has achieved

Figure 3 **First parabolic trough plant in Egypt (Source: Stinnesbeck, 1914)[11]**

Figure 4 Parabolic trough concentrating solar collector field of the 150 MW (5 × 30 MW) steam cycle solar electricity generating systems at Kramer Junction, California (Source: KJC)

Direct steam generating parabolic trough of the DISS project at Plataforma Solar de Almeria, Spain



Enhanced parabolic trough structure of the EUROTOUGH project facility at Plataforma Solar de Almeria, Spain

Linear Fresnel collector at the Solarmundo test facility in Liege, Belgium

Figure 5 Highlights of line concentrating systems development in Europe (Source: DLR, Flagsol, Solarmundo)

a 30% reduction in operation and maintenance costs during the last five years. In addition, trough component manufacturing companies have made significant advances in improving absorber tubes, process know-how and system integration. It is estimated that new plants, using current technology with these proven enhancements, will produce electrical power today for about 10 to 12 US cents/kWh in solar only operation mode. Performance data for the nine SEGS plants are given in Table 2.

Despite the promising technology, the initiator of these plants, LUZ International Ltd, did not succeed. There were several reasons for LUZ's failure:

- Energy prices did not increase as projected in the mid 1980s.
- The value of the environmental benefits was not recompensed.
- A changing undefined tax status did not allow for the necessary profit to be realised.

However, three operating companies took over the plants and are delivering 800–900 million kWh of electricity to the Californian grid every year, reaching today a total accumulated solar electricity production of almost 9 billion kWh (12 billion kWh including natural gas operation), which is roughly half of the solar electricity generated world wide to date. The plants had a total turnover of over US$1.5 billion.

While the plants in California use a synthetic oil as a heat transfer fluid within the collectors, and a separate heat exchanger for steam generation, efforts to achieve direct steam generation within the absorber tubes are underway in the DISS and INDITEP projects sponsored by the European Commission, with the aim of reducing costs and enhancing efficiency by 15–20% each. Direct solar steam generation has recently been demonstrated by CIEMAT and DLR on the Plataforma Solar in Almeria, Spain, in a 500 m long test loop with an aperture of 5.78 m (Figure 5, top), providing superheated steam at 400°C and 10 MPa. Two-phase, steam-water flow in a large number of long, parallel and horizontal absorber tubes is a major technical challenge. Constant turbine inlet conditions must be maintained and flow instabilities must be avoided, even in times of spatially and temporally changing insolation. Control strategies have been developed based on extensive experimentation and modelling of two-phase flow phenomena (*Eck*, 2001[4]; *Steinmann*, 2002[10])

A European industrial consortium has developed the EURO-TROUGH collector, which aims to achieve better performance and cost by enhancing the mechanical structure, and the optical and thermal properties of the parabolic troughs (Figure 5, middle). A prototype was successfully tested in summer 2003 under real operating conditions at the Californian solar thermal power plants within the PARASOL project funded by the German Federal Ministry for the Environment.

Another European consortium has developed a collector with segmented flat mirrors following the principle of Fresnel (Figure 5). The linear Fresnel system also shows a good potential for low cost steam generation, and provides a semi-shaded space below, which may be particularly useful in desert climates. Acting like a large, segmented blind, it could shade crops, pasture and water sheds to protect them from excessive evaporation and provide shelter from the cold desert sky at night. However, the performance of the linear Fresnel system has so far only been tested in a 50 m installation in Belgium; further modelling and experimental work will be required to determine under what conditions it may be more cost-effective than the parabolic trough system with direct steam generation.

Figure 6 The EURO-DISH parabolic dish concentrator with a Stirling motor-generator in the focal point at the CIEMAT solarthermal test centre Plataforma Solar de Almeria, Spain (Source: SBP)

Point focusing systems

Dish/Stirling systems

Parabolic dish concentrators are relatively small units that have a motor-generator mounted at the focal point of the reflector. The motor-generator unit can be based on a Stirling engine or a small gas turbine. Several dish/engine prototypes have successfully operated over the last 10 years, ranging from 10 kW (Schlaich, Bergermann and Partner design), 25 kW (SAIC) to the 400 m^2, 100 kW 'big dish' of the Australian National University. Like all concentrating systems, they can additionally be powered by fossil fuel or biomass, providing firm capacity at any time. Because of their size, they are particularly well suited for decentralised power supply and remote, stand-alone power systems. Within the European project EURO-DISH, a cost-effective 10 kW Dish-Stirling engine for decentralised electric power generation has been developed by a European consortium with partners from industry and research (Figure 6).

Central receiver systems

Central receiver (or power tower) systems use a field of distributed mirrors – heliostats – that individually track the sun and focus the sunlight on the top of a tower. By concentrating the sunlight 600–1000 times, they achieve temperatures from 800°C to well over 1000°C. The solar

Name	SEGS I-II	SEGS II-VII	SEGS VIII-IX
Site	Dagget	Kramer Junction	Harper Lake
Capacity	14 + 30 MW	5 × 30 MW	2 × 80 MW
Commissioning year	1985–1986	1987–1989	1990–1991
Annual solar-electric efficiency	9.5–10.5%	11.0–12.5%	13.8%
Maximum working temperature	307–350°C	370°C–390 °C	390°C
Investment	3800–4500 $/kWel	3200–3800 $/kWel	2890 $/kWel
Electricity cost	0.27–0.18 $/kWh	0.18–0.12 $/kWh	0.14–0.11 $/kWh
Annual output	30 GWh/y + 80 GWh/y	5 × 92 GWh/y	2 × 250 GWh/y

Table 2 Data for the nine commercial solar electricity generating systems in California, USA

Figure 7 Solar II central receiver plant in Barstow, California (Source: SNL)

energy is absorbed by a working fluid and then used to generate steam to power a conventional turbine. In over 15 years of experiments worldwide, power tower plants have proven to be technically feasible in projects using different heat transfer media (steam, air and molten salts) in the thermal cycle and with different heliostat designs. At Barstow, California (see Figure 7), a 10 MW pilot plant operating with steam from 1982 to 1988, and subsequently with molten salt as the heat transfer and energy storage medium, has now several thousand hours of operating experience delivering power to the electricity grid on a regular basis.

Early approaches with central receivers used bundles of steel tubes on top of the tower to absorb the concentrated solar heat coming from the heliostat field. The Californian 10 MW test plant Solar II used molten salt as heat transfer fluid and as the thermal storage medium for night time operation. In Europe, air was preferred as the heat transfer medium, but the 20 MW air cooled central receiver project GAST in the early 1980s showed that tube receivers where not appropriate for that purpose, because of an inadequate heat transfer and local overheating of the tubes. Thus, the concept of the volumetric receiver was developed in the 1990s within the PHOEBUS project, using a wire mesh directly exposed to the incident radiation and cooled by air flowing through that mesh (Figure 8). This receiver easily achieved 800°C and was used to operate a 1 MW steam cycle. A ceramic thermal heat storage was used for night time operation. This concept has been validated at 2.5 MW (thermal) level in tests conducted at the Plataforma Solar in Almería. In this installation, the solar energy is harvested by 350 heliostats of 40 m^2 area each. For even higher temperatures, the wire mesh screens are replaced by porous SiC or Al_2O_3 structures.

The high temperatures available in solar towers can be used not only to drive steam cycles, but also for gas turbines and combined cycle systems. Since such systems promise up to 35% peak and 25% annual solar-electric efficiency when coupled with a combined cycle power plant, a solar receiver was developed within the

Figure 8 Volumetric receiver (Source: DLR)

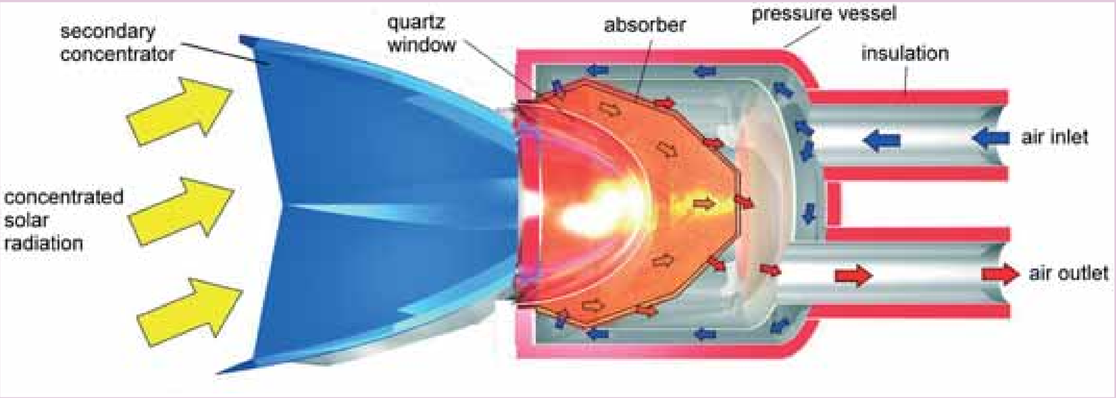


Figure 9 **REFOS pressurised receiver concept (Source: DLR)**

European SOLGATE project for heating pressurised air by placing the volumetric absorber into a pressure vessel with a parabolic quartz window for solar radiation incidence. This design is shown in Figure 9.

Since December 2002, this absorber has been successfully used to operate a 250 kW gas turbine at over 800°C. Combined cycle power plants using this method will require 30% less collector area than plants using equivalent steam cycles (Figure 10). Ceramic volumetric absorbers with an operating temperature of over 1200°C are under development for this purpose.

Conclusions

Concentrating solar power technology for electricity generation is ready for the market. Various types of single- and dual-purpose plants have been analysed and tested in the field. In addition, experience has been gained from the first commercial installations in use worldwide since the beginning of the 1980s. Solar thermal power plants will, within the next decade, provide a significant contribution to an efficient, economical and environmentally benign energy supply both in large-scale grid-connected dispatchable markets and remote or modular distributed markets. Parabolic and Fresnel troughs, central receivers and parabolic dishes will be installed for solar/fossil hybrid and solar-only power plant operation. In parallel, decentralised process heat for industrial applications will be provided by low-cost concentrated collectors.

Following a subsidised introduction phase in green markets, electricity costs will decrease from 14 to 18 Euro cents per kilowatt hour presently in Southern Europe towards 5 to 6 Euro cents per kilowatt hour in the near future at good sites in the countries of the Earth's sunbelt. After that, there will be no further additional cost in the emission reduction by CSP. This, and the vast potential for bulk electricity

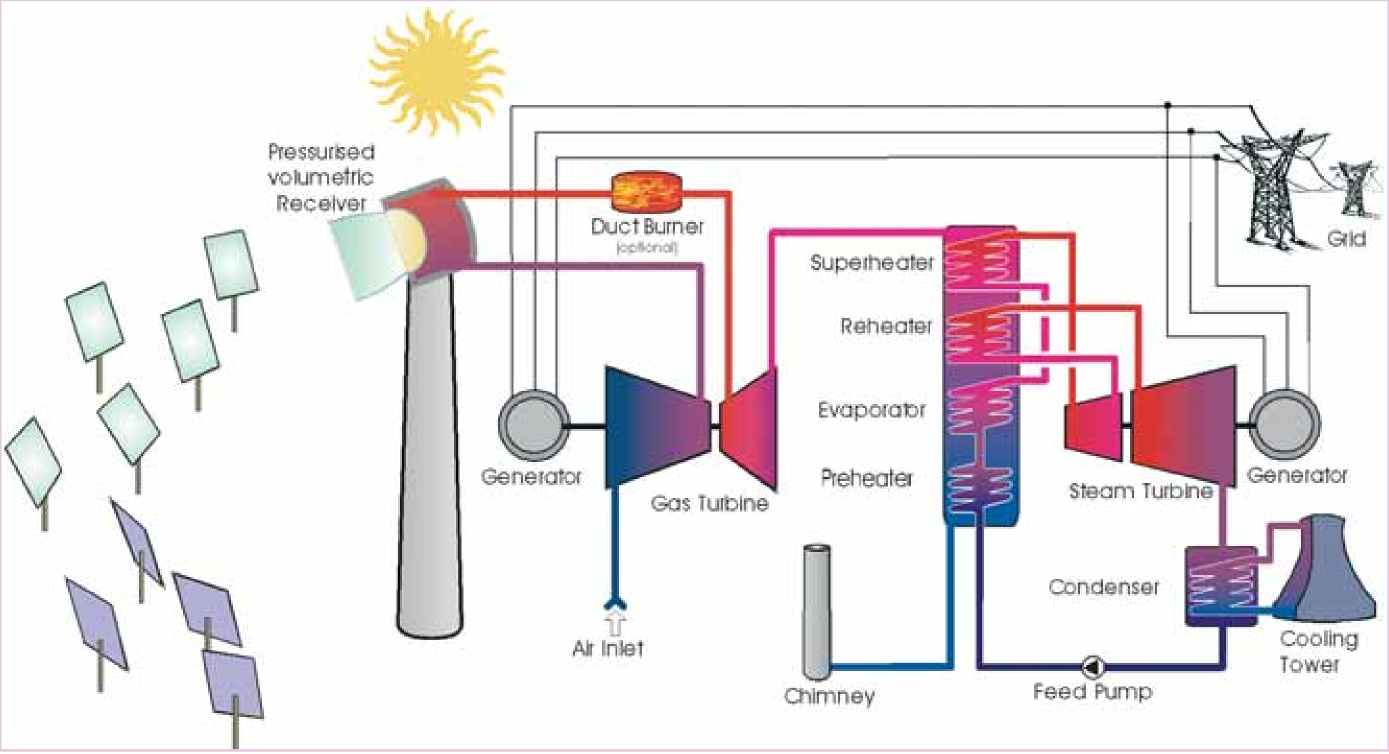


Figure 10 **Schematic of a combined cycle system powered by a volumetric central receiver using pressurised air as heat transfer fluid (Source: DLR)**

generation, moves the goal of long-term stabilisation of the global climate into a realistic range. Moreover, the problem of sustainable water resources and development in arid regions is addressed in an excellent way, making use of highly efficient, solar powered co-generation systems. However, during the introduction phase, strong political and financial support from the responsible authorities is still required, and many barriers must be overcome. These topics will be addressed in the second article. ■

References and additional reading

1. Bockamp, S., Griestop, T., Fruth, M., Ewert, M., Lerchenmüller, H., Mertins, M., Morin, G., Häberle, A., Dersch, J. (2003) *Solar Thermal Power Generation (Fresnel)*, PowerGen
2. Buck, R., Bräuning, T., Denk, T., Pfänder, M., Schwarzbözl, P., Tellez, F. (2002) '*Solar-hybrid gas turbine-based power tower systems* (REFOS)', *J. Solar Energy Engineering*, 124, 2–9
3. Becker, M. *et al.* (2002) *The Future for Renewable Energy 2*, EUREC Agency, James & James (Science Publishers) London
4. Eck, M. (2001) 'Die Dynamik der solaren Direktverdampfung und Überhitzung in Parabolrinnenkollektoren', *VDI Fortschrittsberichte*, Vol. 6, No. 464.
5. Geyer, M., Lüpfert, E., Osuna, R., Esteban, A., Schiel, W., Schweitzer, A., Zara, E., Nava, P., Langenkamp, J., Mandelberg, E. (2002) 'EuroTrough – parabolic trough collector developed for cost efficient solar power generation', *Proceedings of 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies*. Sept. 4–6, Zurich
6. Keck, T., Schiel, W., Reinalter, W., Heller, P. (2002) 'EuroDish – an innovative dish/stirling system', *Proceedings of 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies*. Sept. 4–6, Zurich.
7. León, J., Zarza, E., Valenzuela, L., Hennecke, K., Weyers, D., Eickhoff, M. (2002) 'Direct steam generation – three years of operation of DISS Project', *Proceedings of 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies*. Sept. 4–6, Zurich.
8. Price, H., Lüpfert, E., Kearney, D., Zarza, E., Cohen, G., Gee, R., Mahoney, R. (2002) 'Advances in parabolic trough solar power technology', *ASME Journal of Solar Energy Engineering,* 124, 109–125.
9. Romero, M., Marcos, M.J., Osuna, R., Fernández, V. (2000) 'Design and implementation of a 10 MW solar tower power plant based on volumetric air technology in Seville (Spain)', *Proceedings of the Solar 2000, Solar Powers Life–Share the Energy*, June 17–22, Madison, Wisconsin.
10. Steinmann, W.D. (2002) 'Dynamik solarer Dampferzeuger', *VDI Fortschrittsberichte*, Vol. 6, No. 467.
11. Stinnesbeck, L. (1914/1915) 'Sonnenkraftmaschinen', *Keller's Monatsblätter*, Bergstadtverlag, Vol. 3, No. 1
12. Sugarmen, C., Ring, A., Buck, R., Uhlig, R., Beuter, M., Marcos, M.J., Fernandez, V. (2002) 'Solar-hybrid gas turbine power system', *Proceedings of 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies*, September 4–6, Zurich, Switzerland
13. SUN-LAB Snapshot (2000) *Solar Two Demonstrates Clean Power for the Future*, US Department of Energy

Useful Internet sites

http://www.kjcsolar.com
http://www.eurotrough.com
http://www.solarmundo.be
http://www.dlr.de/TT/solartherm/solargasturbine
http://www.klst.com/projekte/eurodish
http://www.solarpaces.org
http://www.energylan.sandia.gov/sunlab/

Prof. Hans Müller-Steinhagen, FREng, is the director of the Institute of Technical Thermodynamics of the German Aerospace Centre and of the Institute for Thermodynamics and Thermal Engineering of the University of Stuttgart, Germany. Previously, he had been Head of School in the University of Surrey, Associate Professor in the University of Auckland and Research Fellow in the University of British Columbia. For his work on multiphase/multicomponent heat and mass transfer, he has been awarded doctorates by the Universities of Karlsruhe, Auckland and Nuremberg-Erlangen. Present research activities are focussed on efficient and environmentally benign energy conversion processes.

Franz Trieb has worked in the field of renewable energies since 1983. After the implementation of hydrogen storage for an autonomous renewable energy system at the University of Oldenburg, Germany, he taught a two-year postgraduate course 'Renewable Energy' at the National University of Tacna, Peru. Since 1994, he has been project manager at the Institute of Technical Thermodynamics of the German Aerospace Centre (DLR), working on solar energy resource assessment by satellite remote sensing, market strategies for concentrating solar power and renewable energy scenarios.