# Solar Thermal Power Plants

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## 1 Introduction, Potential and Strategic Summary

In solar thermal power plants the incoming radiation is tracked by large mirror fields which concentrate the energy towards absorbers. They, in turn, receive the concentrated radiation and transfer it thermally to the working medium. The heated fluid operates as in conventional power stations directly (if steam or air is used as medium) or indirectly through a heat exchanging steam generator on the turbine unit which then drives the generator.

To make solar high flux, with high energetic value originating from processes occurring at the sun's surface at black-body-equivalent temperatures of approximately 5800 K usable for technical processes and commercial applications, different concentrating technologies have been developed or are currently under development for various commercial applications. Such solar thermal concentrating systems will undoubtedly provide within the next decade a significant contribution to efficient and economical, renewable and clean energy supply.

This paper deals with three different technologies for solar thermal power plants making use of concentrating solar energy systems (Figure 1), namely by

- parabolic troughs,
- central receivers (towers) and
- parabolic dishes.

The White Paper of the European Commission for a community strategy and action plan on renewable energies of 1997 foresees at least 1 GWe of those systems implemented in Europe by the year 2010. This objective can be achieved by a scenario of a number of 25 to 30 commercial solar thermal power plants with 30 to 50 MWe unit size each and distributed along the South of Europe.

These solar thermal technologies comply with the prime objectives and key research, technology, and demonstration actions of the Fifth Framework Programme of the European Commission, because

- their developments will enhance the deployment of solar energy systems for bulk electricity production and the conservation of fossil energy, consequently preserving the environment in particular with respect to their high potential to contribute to the reduction of the $CO_2$ emissions,
- they reduce the generating costs of solar power plants, and thus contribute to ensure durable and reliable energy services at affordable costs in the medium- to long-term range,

* DLR; Köln, Stuttgart and Almería
** CIEMAT; Madrid and Almería
*** CNRS; Odeillo

- they will provide the European industry with a privileged technological position, thus opening industrial growth possibilities not only to the internal market of southern European countries but also to the export of equipment and services in the field of solar plant installations; in some respect, the solar specific technology required in most cases is also accessible to the local industries; the opportunity to create links with developing countries and their markets is self-evident,
- they have the potential to contribute to the social objectives of the European Union as to the quality of life, health, safety (including working conditions) and job creation; the erection of such plants at undeveloped areas in southern Europe can create new opportunities of industrial fabrication, of assembling and of operation and maintenance.

So, solar thermal power plant technologies are important candidates for providing a major share of the clean and renewable energy needed in the future, because

- solar thermal power stations are among the most cost-effective renewable power technologies; they promise to become competitive with fossil-fuel plants within the next decade,
- solar thermal power stations are already today of well-proven and demonstrated technology; since 1985 nine parabolic trough-type solar thermal power plants in California have fed more than 8 billion kWh of solar-based electricity into the Southern Californian grid, demonstrating the soundness of the concept,
- solar thermal power stations are now ready for more intensified market penetration; accelerated grid-connected applications will lead to further innovation and cost reduction.

However, no new commercial solar thermal power plants have been built since the last two 80 MWe parabolic trough plants (SEGS VIII and IX) were connected to the Southern California grid in 1991 and 1992 respectively, due to the following main reasons:

- financial uncertainties caused by delayed renewal of favourable tax provisions for solar systems in California
- financial problems and subsequent bankruptcy of the U.S./Israeli LUZ group, the first commercial developer of private solar power projects
- rapid drop of fossil energy prices and following stable energy prices at low levels since years world-wide
- required large unit capacities of solar thermal power stations to meet competitive conditions for the generation of bulk electricity, resulting in financing constraints due to the inherently large share of capital costs for solar installations
- rapidly decreasing depreciation times of capital investments for power plants due to the deregulation of the electricity market and the shift to private investor ownership of new plant projects world-wide
- dropping specific prices and enhanced efficiencies of installed conventional power plant installations, particularly of combined cycle power plants
- missing favourable financial and political environments for new initiatives for the development of solar thermal power plant projects in sunbelt countries.

Fortunately, the chances for solar thermal projects in the next decade have increased in the meantime significantly, because

- interest rates and capital costs have fallen drastically in Europe with the introduction of the Euro for the benefit of capital-intensive projects such as solar thermal power plants,
- the EU policy firmly supports an 8 % reduction in gas emissions by doubling the share of renewable energies of the EU energy balance from 6 to 12 % by the year 2010,
- a recent expertise of the World Bank predicts solar thermal cost reductions below 6 US cents/kWh after the year 2010, convincing the Global Environment Facility (GEF) to support barrier removal and market introduction of solar thermal power in developing

countries. India, Egypt, Morocco and Mexico have now applied within the GEF Operational Programme for about 50 million US-Dollar GEF grant for each project to cover their incremental costs of solar thermal power projects.

With positive experiences in construction and operation of the first European demonstration power plant projects being under development (50 MWe THESEUS on the Crete island in Greece; 10 MWe Planta Solar (PS 10) in Southern Spain), other projects are expected to follow. Until the year 2015, the market potential for solar thermal power plants is estimated at least with 7 GWe in southern Europe, representing a $CO_2$ reduction potential of up to 12 million tons per year.

These projects represent a cost reduction potential of 20 % compared to the last built 80 MWe SEGS IX plant in California. Projected electricity production costs can then come down to 14 Euro cents/kWh (in pure solar mode, without any grant). However, electricity costs of solar power plants operating in the solar/fossil hybrid mode (as encouraged by the EU Fifth Framework Programme) could fall to as low as to 8 Euro cents/kWh in the short-term period. Research and development programmes in Europe and in the USA are aimed at reducing the electricity costs furthermore in the long-term run.

The Mediterranean Member States of the European Union will surely be counting on solar thermal power plants as an excellent option for achieving the mentioned goals in their national policies. This is the case in Spain, where solar energy has been given special priority. It is expected that the new Spanish legislation on renewable electricity generation will allow solar thermal power plants to earn an additional 18 Euro cents/kWh on top of the conventional electricity price, which will undoubtedly favour the short-term construction of commercial solar thermal power plants in Spain.

## 2 Achievements, Present Situation, Main Barriers and Vision on the Way Forward

### 2.1 Parabolic Trough Systems

Trough systems use linear concentrators of parabolic shape with highly reflective surfaces, which can be turned in angular movements towards the sun position and concentrate the radiation onto a long-line receiving absorber tube (see Figure 1). The absorbed solar energy is transferred by a working fluid, which is then piped to a conventional power conversion system.

The used power conversion systems are based on the conventional Rankine-cycle/steam turbine generator or on the combined cycle (gas turbine with bottoming steam turbine). Trough power plants are highly modular and are already applied up to 80 MWe unit capacity using a thermal oil heat transfer system. Total power plant capacities of above 100 MWe are actually projected for solar/fossil “hybrid” integrated solar combined cycle systems (ISCCS) with equivalent solar field capacities of 30 to 40 MWe in order to help introduce the systems on the energy market of sunny countries in the near to medium term, e. g. in the countries with GEF support mentioned above.

*Energy Service Sector and Role of Technology:*
Parabolic trough power plants represent today the most mature solar power plants with 354 MWe of commercial solar electric generating systems (SEGS) parabolic trough power plants connected to the Southern California grid since the 1980’s (Figure 2). These plants have unit capacities of 14 MWe (SEGS I), 30 MWe (SEGS II to VII) and 80 MWe (SEGS VIII and IX). With more than two million square meter of total glass mirror area of current trough technology they have generated more than 8 TWh of electricity since 1985. The 30 MW SEGS plants of Kramer Junction with an annual insolation of over 2700 kWh/m²a have verified generating costs of 15 US cents/kWh during high-priced daytime slots (mainly for

peak-load demand by air conditioning), with allowance to generate up to 25% of the annual output by supplementary natural gas-firing. (The equivalent pure solar costs would be 20 US cents/kWh); the 80 MW SEGS plants of Harper Lake with the same annual insolation have verified generating costs of 12 US cents/kWh, also with allowance to generate up to 25% of the annual output by supplementary natural gas firing. (The equivalent pure solar costs would be 16 US cents/kWh). They have gained record values of an annual plant efficiency of 14 % and of a daily solar-to-electric efficiency near 20 % as well as peak efficiencies up to 21.5 %. The annual plant availability exceeded 98 % and the collector field availability more than 99 %. The performance of the plants have been improved continually during the operation time. The five plants at the Kramer Junction site (SEGS III to VII) have during the last five years achieved a 30 % reduction in operation and maintenance costs. In addition, key trough-component manufacturing companies in Europe and its associated partners have made considerable advances.

Parabolic trough plants may be designed as quasi-solar-only plants for peak-load (as the SEGS plants with about 2,000 equivalent solar full-load hours per year and with 25 % supplementary fossil firing) or in the future on an annual average up to 100 % solar share, applying thermal energy storage systems. Plant concepts favourable for the market introduction are hybrid ISCCS plants for mid-load or base-load operation, with solar shares between 10 and 50%.

*Technology Shortages:*
Parabolic trough systems have the following technology shortages:

- The upper process temperature is currently limited by the heat transfer thermal oil to 400°C.
- The heat transfer thermal oil adds extra costs of investment and of operating and maintenance.
- Depending on national regulations, environmental constraints from ground pollution by spillage of thermal oil could occur.
- Some absorber tubes are still object of early degradation; reasons are the risk of breakage of absorber envelope glass tubes with loss of vacuum insulation and degradation of the absorber tube selective coating.
- High winds may break mirror reflectors at field corners.
- Low-cost and efficient energy storage systems have not been demonstrated up to now.
- The direct steam generation trough technology is still in a developmental stage.

*Current Projects:*
While the European Commission supports only pure solar plants, the World Bank/GEF focus on the integration of parabolic troughs into combined-cycle plants (ISCCS) in sunny developing countries. On the above mentioned background, various commercial power plant development projects with unit outputs of 50 to 310 MWe and large solar fields of parabolic trough collectors are currently promoted or are in a progressive planning stage by European and U.S. project developers with grants of the World Bank/GEF or other co-funds world-wide, namely in:

- <u>Greece:</u> 50 MWe solar thermal power plant THESEUS on the Crete island; promoted by German and Greece companies; solar field of approximately 300,000 $m^{2;}$, 112 GWh of pure solar electricity per year
- <u>Spain:</u> Various 50 MWe plants group in southern Spain; promoted by international industrial group; based on the new Royal Decree on the support of renewable electricity generation
- <u>Egypt:</u> 135 MWe natural-gas-fired ISCCS plant in Kuraymat at the Nile river; 30 MWe equivalent solar capacity; promoted by industrial groups; with allocated 40 to 50 million US-Dollar GEF grant

- Morocco: 150 MWe natural-gas-fired ISCCS plant project; 30 to 50 MWe equivalent solar capacity; promoted by industrial groups; with allocated 40 to 50 million US-Dollar GEF grant
- India: 140 MWe naphta-fired ISCCS plant in Mathania/Rajasthan; 35 MWe equivalent solar capacity; promoted by industrial groups; with allocated 49 million US-Dollar GEF grant and 100 million US-Dollar loan of the German KfW-bank
- Iran: Feasibility study for the implementation of a 100 MW natural gas fired combined cycle plant with a 200 000 – 400 000m² parabolic trough field in the desert of Yazd contracted with its own national funds.
- Mexico: 310 MWe natural-gas-fired ISCCS plant in the Northern Mexican desert; 40 MWe equivalent solar capacity; promoted by industrial groups; with allocated 40 to 50 million US-Dollar GEF grant.

The German/Spanish R&D project generates direct steam using LS 3-trough collectors at the PSA in southern Spain (DISS project, schedule 1996 – 2001, Figure 3). This new concept is expected to produce a cost reduction over the SEGS plants of between 20 and 30 percent. Future solar-only solar thermal power plants are planned with potential use of solar energy storage systems in order to enlarge the solar capacity or solar share and to ultimately minimize the $CO_2$ emissions. The EuroTrough R&D project of an European group under Spanish industrial leadership is in progress with EU co-funds since 1998 with the goal to reduce the costs of an advanced European trough collector on the basis of the proven LS 3-collector type.

*Competitors, Cost Situation and Vision of Cost Range:*
Competitors are the current conventional grid-connected fossil fuel-fired power plants, particularly the modern natural gas-fired combined cycle plants in mid-load or base-load operation mode.

Installed plant capital costs of the Californian SEGS Rankine-cycle trough systems with on-peak power operation fell from 4,000 US Dollar/kWe to under 3,000 US Dollar/kWe between 1984 to 1991, mainly due to scaling-up effects from 30 to 80 MWe units and due to series effects. The 50 MWe THESEUS plant will already meet the near-to-mid-term cost targets set forth in the EU Fifth Framework Programme for solar power systems with 2,500 Euro/kWe installed. Projected electricity production costs for a next 50 MW parabolic trough plant at a Southern European site with 2400 kWh/m²a like on the Island of Crete are then at 14 Euro cents/kWh (in pure solar mode without any grant), or at 18 Euro cents/kWh at a site with 2000 kWh/m²a like in Southern Spain. However, in hybrid mode with up to 49 % fossil-based power production, the electricity costs could drop to as low as 8 Euro cents/kWh.

Installed trough field costs have dropped to 210 Euro/m² of current or near-term installed collector technology (based on the LS-3 type). They are expected to fall below 200 Euro/m² for enhanced collectors and larger production rates in the medium-term and to 130 to 110 Euro/m² for high production rates in the long-term. 15 % discount on the U.S./European price level of solar installations may be projected for developing countries due to lower labour costs.

As analyzed by the above mentioned World Bank expertise on solar thermal power plants, installed plant capital costs of near-term trough plants are expected in the range of 3,500 to 2,440 Euro/kWe for 30 to 200 MWe Rankine-cycle (SEGS type) plants and of about 1,080 Euro/kWe for 130 MWe hybrid ISCCS plants with 30 MWe equivalent solar capacity for U.S./European construction price scenario. The projected total plant electricity costs range from 10 to 7 Euro cents/kWh for SEGS type plants and less than 7 Euro cents/kWh for ISCCS plants, which however are not assessed to have lower electricity costs than conventional gas-fired combined cycle pants.

The expected drop of the installed capital costs of grid-connected ISCCS trough plants will result in electricity costs of 6 Euro cents/kWh in the medium-term period and of 5 Euro cents/kWh in the long-term run (200 MWe Rankine-cycle plant without and with storage). There is the promising long-term potential of Rankine-cycle trough plants to compete with conventional peaking Rankine-cycle plants (coal-fired, oil-fired) at good solar sites. The long-term application of direct steam generation trough technology has even higher expectance in the future due to its promising cost reduction potential.

## 2.2 Central Receiver Systems

Central receiver systems use heliostats to track the sun by two axes mechanisms following the azimuth and elevation angles with the purpose to reflect the sunlight from many heliostats oriented around a tower and concentrate it towards a central receiver situated atop the tower (see Figure 1). This technology has the advantage of transferring solar energy very efficiently by optical means and of delivering highly concentrated sunlight to one central receiver unit, serving as energy input to the power conversion system.

In spite of the elegant design concept and in spite of the future prospects of high concentration and high efficiencies, the central receiver technology needs still more research and development efforts and demonstration of up-scaled plant operation to come up to commercial use. Its main attraction consists in the prospect of high process temperatures generated by highly concentrated solar radiation to supply energy to the topping cycle of any power conversion system and to feed effective energy storage systems able to cover the demand of modern power conversion systems.

The solar thermal output of central receiver systems can be converted to electric energy in highly efficient Rankine-cycle/steam turbine generators, in Brayton-cycle/gas turbine generators or in combined cycle (gas turbine with bottoming steam turbine) generators. Grid-connected tower power plants are applicable up to about 200 MWe solar-only unit capacity. Conceptual designs of power plant units of above 100 MWe have been analyzed for ISCCS plants.

*Energy Service Sector and Role of Technology:*
The technical feasibility of the central receiver (tower) technology has been proven world-wide between 1981 and 1986 by operation of six research or proof-of-concept solar power plant units ranging from 1 to 5 MWe capacities and by one pilot demonstration plant (SOLAR ONE with water/steam receiver) connected to the Southern California grid, totaling to a net electric capacity of 21.5 MWe with an installed heliostat mirror area of about 160,000 m². However, the central receiver technology has not been used commercially up to now.

The 10 MWe SOLAR ONE pilot demonstration plant was operated in California from 1982 to 1988 with steam as the heat transfer medium. Rebuilt to the 10 MWe SOLAR TWO plant, it was successfully operated with a molten salt-in-tube receiver system and a two-tank molten salt storage system from 1997 to 1999 (Figure 4), accumulating several thousand hours of operating experience and delivering power to the grid on a regular basis. Solar Two has successfully demonstrated grid-connected operation and successful tests of dispatching the generated energy as designed. This concept is the basis for the U.S. efforts for tower plant commercialization; it has the potential of more than 15 % annual solar-to-electric plant efficiency and of annual plant availability of over 90 %.

Different receiver heat transfer media have been successfully researched (water/steam, liquid sodium, molten salt, ambient air). Two of the proof-of-concept power plants have been converted to central receiver test bed facilities on the largest European solar test center, the Plataforma Solar de Almería (PSA) in Spain (Figure 5), and two further large test facilities are actually available for R&D activities in the USA and in Israel. Today, promising advanced systems refer to the European volumetric air receiver technology and to the U.S. molten salt-in-tube receiver technology; both concepts are assessed to be the most mature and promising central receiver technologies for mid- to long-term grid-connected power plant applications. The heliostat technology, which is available at near-to-commercial conditions in Europe (Germany, Spain) and in USA already today, comprises glass-metal and stretched membrane heliostat types of 70 to 150 m² reflective surface area.

More recent European activities have demonstrated that high-flux characteristics are maximized in high-intensity/high-efficiency volumetric air receivers in either open or closed cycles, in which the concentrated solar energy irradiates fine wire mesh or ceramic foam structures, transferring the energy by convection directly to air in the attractive temperature range of 700 to 1,200°C. Tests conducted at the PSA in a joint German/Spanish project between 1993 and 1995 within the PHOEBUS Technology Programme Solar Air (TSA) with the German 2.5 MWth pilot experimental plant showed the feasibility and prospects of the volumetric air receiver system concept with ceramic energy storage system.

Plants may be designed as solar-only plants for peak-load (with about 2000 equivalent full-load hours per year) or in the future up to 100 % solar share on an annual average. Hybrid plant concepts, which are favourable for the phase of market awareness and expansion, are ISCCS plants for mid-load or base-load operation.

Future solar-only solar tower plants have the good long-term perspective for high conversion efficiencies and for use of very efficient energy storage systems by utilization of high temperatures in order to enlarge the solar capacity or solar share. In addition, they have the potential to be applied to other high-temperature heat processes (e.g. process heat, solar-chemical processes).

In 1999 the World Bank expertise assessed the central receiver power plants to be currently less favourable for the start of commercialization and market introduction versus Parabolic trough systems due to less advanced plant maturity and lack of demonstration of commercial operation of up-scaled unit size. Consequently, new up-scaled demonstration central receiver projects are required before these systems can be considered to be commercially ready.

*Technology Shortages:*
Central receiver systems have the following technology shortages:

- No successful scaled-up central receiver plants are available for commercial demonstration up to now, although more than six experimental and pilot demonstration central receiver plants were successfully operated world-wide since 1981.
- Currently promising technologies (the molten salt-in-tube receiver technology in USA and the volumetric air receiver technology in Europe, both with energy storage system) are proven only by one pilot demonstration unit (10 MWe SOLAR TWO) with two years of operating experience and by one pilot experimental unit (2.5 MWth PHOEBUS-TSA) with some years of operating experience.
- Not yet verified is the good potential projected for the improvement of solar system performance and for cost reductions.
- Not yet verified are projections of the installed plant capital costs, operation and maintenance costs, electricity costs, solar subsystem performance, operational characteristics and of the annual plant availability.
- The industrial demonstration of volume production of heliostat components is still missing.

*Current Projects:*
European activities related to the technical and economic feasibility of central receiver demonstration power plants have already started. Two 10 MWe projects are currently under development to take credit of the Spanish Royal Decree of December 1998 with special legal

classifications of premium payments for renewable or solar electricity and of subsidies of the solar investment from the EC Fifth Framework ENERGY Programme in its 1999 call for proposals. The projects are namely in:

- Spain: Two EU funded central receiver projects SOLGAS and Colón Solar for European demonstration of hybrid solar tower power plants (ISCCS) for integration of 20 MW of solar saturated steam into a conventional combined-cycle power plant; terminated due to budgetary reasons after the detailed engineering phase in 1998
- Spain: 10 MWe solar-only power plant project Planta Solar (PS10) at Sanlúcar near Sevilla promoted by Spanish and German companies; application of German PHOEBUS volumetric air receiver/energy storage technology; use of Spanish 90 $m^2$ glass-metal heliostats (Figure 6)
- Spain: 10 MWe solar-only power plant project at Córdoba promoted by Spanish and U.S. companies; application of U. S. molten-salt technologies for receiver and energy storage; use of new Spanish low-cost heliostats with reduced dimensions.

In addition, the following R&D projects concerning central receiver components or systems are being promoted or are in progress, namely in:

- Spain: SOLAIR project with 3 MWth high-temperature volumetric air receiver system at the PSA proposed by European group under Spanish industrial leadership; application for next central receiver projects after PS 10; with co-funds of the EC Fifth Framework Programme
- Spain: REFOS project with a 1 MWth cluster of three closed pressurized volumetric air receivers at the PSA proposed by DLR together with CIEMAT (Figure 7); application for solar preheating of gas turbine combustion air in combined-cycle plants
- Spain: SIREC project led by CIEMAT and IAER together with Spanish company; new low-cost heliostats with advanced technologies
- Israel: DIAPR project by Israeli industry with German and U.S. co-operation at central receiver facility of Weizmann Institute of Science (WIS) with tower reflector; for solar thermal or thermal-chemical applications
- Israel: SOLASYS project by Israeli company with German co-operation at WIS central receiver test facility; application for synthetic gas production by solar reforming of natural gas; use of 400 kWth high-temperature volumetric air receiver (DLR).

*Competitors, Cost Situation and Vision of Cost Range:*
Competitors are the current conventional grid-connected fossil fuel-fired power plant technologies, particularly the modern natural gas-fired combined cycle plants in mid- or base-load operation mode.

Specific installed capital costs of built central receiver pilot plants are yet too high. There are no electricity costs of commercial scaled-up plants available today. Economic analyses show more cost uncertainties versus trough plants due to less mature technology. Central receiver plants, however, will take credit from their potential of favourable application of high temperature and energy storage systems. But the addition of a long-time energy storage system is not reducing the electricity costs, it is increasing the plant performance and the capacity factor.

As analyzed by the above mentioned World Bank expertise, installed plant capital costs of near-term central receiver plants are expected in the range of 4,300 Euro/kWe (next 130 MWe ISCCS plant with 30 MWe solar-generated capacity with storage) to 3,300 Euro/kWe (next 100 MWe Rankine-cycle plant with storage) for U.S./European construction price level, with the range of predicted total plant electricity costs of about 14 to 12 Euro cents/kWh.

In Europe, new near-term tower project developments in Spain have indicated the validation of installed plant capital costs in the order of 2,700 Euro/kWe by central receiver power plant with Rankine-cycle and small energy storage system, with the range of predicted total plant electricity costs of 20 to 14 Euro cents/kWh.

The actual range of installed heliostat field costs is 180 to 250 Euro/m² for small production rates in the USA, and 140 to 220 Euro/m² in Europe. 15 % discount on the U.S/European price level may be projected for developing countries due to lower labour costs. Heliostat field costs are expected to drop below 100 Euro/m² at high production rates in the long-term period.

Central receiver plant projects will benefit from similar future cost reduction effects as mentioned for parabolic trough plants. By the expected evolution of total plant costs of grid-connected central receiver plants, the total plant electricity costs will drop to 8 to 7 Euro cents/kWh in the medium-term period (100 MWe Rankine-cycle plant or 100 MWe ISCCS, both with storage) and to 5 Euro cents/kWh in the long-term period (200 MWe Rankine-cycle plant with storage), as has been analyzed by the mentioned World Bank expertise. Long-term central receiver plants are expected to produce electricity at approximately 25% lower electricity costs than similar sized trough plants. There is the promising long-term potential of Rankine-cycle central receiver systems to compete with conventional peaking Rankine-cycle plants (coal-fired, oil-fired) at good solar sites. As mentioned above for ISCCS trough plants, also ISCCS central receiver plants are not expected to have lower electricity costs than conventional gas-fired combined cycle plants.

## 2.3 Parabolic Dish Systems

Dish systems use parabolic reflectors in the shape of a dish to focus the sun's rays onto a dish-mounted receiver at its focal point (see Figure 1). In the receiver a heat-transfer medium takes over the solar energy and transfers it to the power conversion system, which may be mounted in one unit together with the receiver (e. g. receiver/Stirling engine generator unit) or at the ground. Due to its ideal optical parabolic configuration and its two axes control for tracking the sun, dish collectors achieve the highest solar flux concentration, and therefore the highest performance of all concentrator types in terms of peak solar concentration and of system efficiency. These collector systems are restricted to unit capacities of some 10 kWe for geometrical and physical reasons.

The dish technology is applicable to off-the-grid power generation, i. e. at remote places or at island situations. Dish systems may optionally be arranged in large dish arrays in order to accumulate the power output from the kWe capacity up to the MWe range. It requires some more continued R&D activities and demonstration before start of market introduction.

The power conversion subsystem of dish systems is mainly based on the Stirling engine generator system, but also on the water/steam powered turbine or piston engine generator system or on the gas turbine generator system. Peak-load by solar-only operation or by solar/fossil "hybrid" operation with solar shares may range from 50 to 100 % on an annual average.

Short-/medium-term turn-key dish/Stirling systems are projected with the option of hybrid dish/Stirling operation, i. e. with supplementary combustion of natural gas integrated into the receiver component. Such systems are currently under development and are expected to be available for first demonstration projects in the near-term run.

*Energy Service Sector and Role of Technology:*
Several small power systems for off-the-grid solar thermal electricity generation with parabolic dish unit sizes in the range of 5 to 25 kWe have been proven their technical feasibility in several experimental, prototype and demonstration projects world-wide since the end of the seventies. Dish/Stirling systems have excellent possibilities for high conversion efficiencies due to their potential of high process temperatures in the Stirling engine. The record energy yield was experienced by a 25 kWe U.S. dish/Stirling system with a solar-to-electric system efficiency of 30 %. The current advanced dish/Stirling technology development is performed mainly by European (German) and U.S. industries and institutions, developing the most promising unit capacities of 10 kWe (German units) and 25 kWe (U.S. units). These systems are under proof-of-reliability operation in the USA and in southern Spain. The concept of stretched-membrane dish concentrators, currently under proof-of-reliability testing mainly on the PSA using German advanced technologies, holds great promise for further reduced cost in order to make them competitive with Diesel stations in remote areas or on islands. The tools required for a small-series production of 100 units per year are also being developed.

*Technology Shortages:*
Parabolic dish systems have the following technology shortages:

- The electricity output of single dish/Stirling unit is limited to small ratings of e. g. 25 kWe due to geometric and physic reasons (exception: Australian big dish designed for use of a 50 kWe steam engine or turbine generator).
- Large-scale deployment has not yet occurred.
- No commercial demonstration has been performed up to date.
- Not yet demonstrated or verified are projections of capital costs, operation and maintenance costs, electricity costs, system performance and of the annual plant availability over the long run.
- The predicted potential for improvements of solar system performance and of cost reductions is still to be verified.
- Hybrid systems have inherent low-efficient combustion and have to be proven.
- No adequate energy storage system is applicable or available.
- The establishment of industrial large volume production of dish components and Stirling engines is needed for entry into appropriate market segments.

*Current Projects:*
The following R&D and demonstration projects concerning dish/Stirling systems are being promoted or are in a progressive stage of development or demonstration, namely in:

- <u>Europe:</u> First ongoing industrial dish/Stirling demonstration programme under successful operation for proof of continuous operation of six German dish/Stirling pre-commercial units with 9 to 10 kWe ratings of Schlaich, Bergermann & Partner (SBP) at the PSA (three DISTAL I-systems since 1992 and three DISTAL II-systems since 1997, Figure 8); over 30,000 operating hours accumulated by the DISTAL I-systems up to now; promising advanced heat pipe receiver types and Stirling engines currently under development and testing for proof of system reliability; new 9 to 10 kWe dish/Stirling units under way for testing on the PSA within the EuroDish R&D programme with EU co-funds since 1998 (goal: cost reductions by advanced structures for commercialized European dish/Stirling systems)
- <u>Spain:</u> Feasibility study and a small demonstration project promoted by a Spanish group in collaboration with Stirling Energy Systems (SES) consortium using a 25 kWe Dish/Stirling unit of McDonnell Douglas (MDAC) for erection in the South-east of Spain

- <u>USA</u>: First industrial series of five 25 kWe U.S. dish/Stirling 2nd generation prototype systems for extended testing in the South-west USA; projects will possibly be shortened or stopped due to dropping public R&D funds in the short term run
- <u>Australia:</u> First 400 $m^2$ pilot experimental “big dish” project with capacity of up to 150 kWth under scientific testing at the Australian National University (ANU) since 1994; designed for power generation using a 50 kWe steam engine generator or for co-generation applications by solar steam production; alternative to the small-unit philosophy described above.

The Australian government is presently funding a 2.6 MWth solar power plant project consisting of eighteen 400 $m^2$ “big dish” units which will inject solar generated steam directly into the steam turbine of an existing coal-fired power station. Another 400 $m^2$ dish collector unit was recently sold to the Israeli solar test center in the Negev desert for solar R&D test bed purposes.

*Competitors, Cost Situation and Vision of Cost Range:*
Competitors for dish/Stirling systems are conventional small-scale off-grid generation systems with unit ratings of the kWe-range up to about 10 MWe in peak- or mid-load operation at remote places, i. e. the gas oil- or heavy fuel oil-powered Diesel engine generators, particularly in developing sunbelt countries and on islands with relatively high fuel costs.

Experienced dish cost trends show a drastic reduction of installed dish collector costs: 1,250 Euro/m² (40 m² Shenandoah, USA, 1982), 300 Euro/m² (91 m² MDAC, USA, 1985), 200 Euro/m² (44 m² LaJet, USA, 1986) and 150 Euro/m² (44 m² German SBP stretched-membrane dish, 1992).

The today’s installed plant capital costs of a first stand-alone 9 to 10 kWe dish/Stirling unit is 10,000 to 14,000 Euro/kWe and of actual near-term units 7,100 Euro/kWe (at 100 units/year production rate). The most attainable near-term goal of electricity costs is less than 15 Euro cents/kWh. In the medium- to long-term run, dish/Stirling systems are expected to have drastically decreasing installed system costs, which are projected with growing number of dish units produced in series. The goal of the European EuroDish project: drop from 7,100 Euro/kWe (100 units/year) to 3,700 Euro/kWe (1,000 units/year) to 2,400 Euro/kWe (3,000 units/year) and to 1,600 Euro/kWe (10,000 units/year), but not below that price level due to the inherently very high modular technology. Medium- to long-term installed dish collector costs are predicted in the range of 125 to 105 Euro/m² for high-production rates. Advanced dish/Stirling systems have the promising medium- to long-term potential to compete with similar sized Diesel generator units at sunny remote places or islands.

## 3 Goals for Research, Development and Demonstration (RD&D)

There are the following main goals for solar thermal power plants:

- Of highest importance is the erection of <u>large solar thermal power plants</u> having at least units of equivalent solar capacities of 10 MWe or even more favourable 100 MWe in the Mediterranean area to ensure a significant contribution to the environmentally benign electricity production in Europe. In this respect, Spanish and Greek initiatives will play a decisive role, enjoying the support of the European Union.
- Essential objectives of R&D activities concern <u>the development of improved and optimized components and subsystems</u>. These activities are in progress as described above. In essence, the most important features and cost-reducing items considered are the qualification and demonstration of direct steam generation for parabolic troughs, the reliable utilization of volumetric air and molten salt receiver techniques for central receiver

systems, the hybrid operation of saturated steam central receiver systems and of the hybrid operation of dish/Stirling systems.
- The integrated hybrid solar/fossil solutions (ISCCS plants) have to be followed up. They link proven solar thermal and conventional technologies through optimized integration of solar thermal energy into fossil-fired power plants, particularly into combined cycle power stations. Such applications are not only door openers for solar applications, but in fact represent a most realistic strategy.
- Finally, an effective answer to the problematic issue of energy storage systems is obligatory. As a short-term goal, guaranteed electricity delivery from a buffer storage or short-period storage capacity is advisable, and as a long-term objective solar-only operation from large storage capacities.

## 4 Roads to the Market

Solar thermal power plants have the potential to generate well-priced bulk electric power together with hydro power stations and with large wind energy converter arrays. They have, therefore, the potential to effectively contribute to the international efforts to reduce climatic gas emissions from fossil-fired electricity generation. They also can take profit from the already proven high-voltage direct current transmission system in order to link good solar sites of the Mediterranean area by grid-connection with consumers of high electricity demand at less sunny locations.

All three solar thermal power plant technologies are approaching readiness for the market introduction, although with different technological and commercial availability:

- the parabolic trough technology already today and still more improved with the direct steam generation technique in the near-term period,
- the central receiver technology and the dish/Stirling technology in the near-term to medium-term run.

Figures 9 and 10 show the status of international developments and the evolution of the levelized energy costs of parabolic trough and central receiver power plant projects.

The GEF’s Operational Programme provides financial support for specific solar thermal power applications in sunbelt countries, as mentioned above.

It is recommended that the roads to the market be pursued step-by-step, implying speedy market introduction of proven SEGS-type parabolic trough plants, the implementation of a first limited series of commercial central receiver power plants and the consequent use of dish/Stirling applications in appropriate market segments.

After the first step of identifying the most probable market segments through market analysis, awareness and acceptance, all solar thermal power technologies have to be demonstrated by stages until finally ensuring commercial introduction within the next decade. As for solar/fossil hybrid solutions, solar systems should be demonstrated by coupling to conventional power plants in order to optimally combine the technical concepts and their economies, particularly during the market introductory phase. However, these recommendations should be taken with a certain measure of flexibility so that they remain adaptable to circumstances and do not become intolerant of local requirements. Recent national and regional experiences like in Spain, in the USA and in Australia do demonstrate the open-minded strategies required for a successful implementation of solar thermal power plants. In a world in which recognition of differences is more patent and more important every day, the only viable strategies for introducing a new technology are those which integrate the user or receiver of the technology in the definition of the strategy itself and are respectful of social circumstances and the expectations of those to whom the solution is proposed.

## 4.1 Roads to the Market of Parabolic Trough Systems

Parabolic trough systems will proceed the following main items on their road to the market:

- Projection on the success of current parabolic trough collector system experience and on the low-risk approach to advance the state of the trough technology by several steps during the next decade, in order to reach the necessary synergy of technology development and market awareness/expansion/acceptance
- Hybrid ISCCS plants using current trough technology; hybrid plant design optimization and optimized linkage to conventional power plants or to co-generation plants
- Improvements of trough collector key elements by optimized design, e.g. optimized steel structures, absorber tubes of increased lifetime and better maintainability; special operation and maintenance tools and equipment; improvement of procedures
- Standardized designs of hybrid ISCCS cycles with equivalent solar unit capacities of 30 to 50 MWe and of solar Rankine-cycles with more than 30 MWe up to 200 MWe
- Advanced trough collector/reflector design concepts, e. g. mirror facets with front surface or film reflectors of high reflectivity, lighter and strengthened mirror panels
- Application of direct steam generation trough technology ready for commercialization
- Development and application of efficient energy storage systems in future solar thermal power plants in order to enlarge the solar capacity of mid-load or near base-load plants with solar shares up to 100 % on an annual average.

## 4.2 Roads to the Market of Central Receiver Systems

Central receiver systems will proceed by the following main items on their road to the market:

- Projection on the success of current central receiver experience and on the low-risk approach to advance the state of the central receiver technology by several steps during the next decades, in order to reach the necessary synergy of technology development and market awareness/expansion/acceptance
- Hybrid ISCCS plants using current central receiver technology; hybrid plant design optimization and optimized linkage to conventional power plants or to co-generation plants and to bio-mass plants
- Heliostat field and receiver improvements by better optical and thermal properties, lighter mirrors and optimized heliostat structures, better heliostat/field controls
- Proof of solar system performance and reliability during representative operating times
- Process improvements by further advances in selected heat transfer media and receiver concepts for commercial power generation (European technology of volumetric air receiver, U.S. technology of advanced molten salt-in-tube receiver)
- Improvements in the system integration by reduced parasitic loads, optimized start-up procedures, better control strategies, automatic heliostat field control
- Development and application of low-cost/very efficient energy storage systems in future central receiver power plants in order to enlarge the solar capacity of mid-load or near base-load plants with solar shares up to 100% on an annual average.

## 4.3 Roads to the Market of Parabolic Dish Systems

Parabolic dish systems will proceed by the following main items on their road to the market:

- Improvements of dish reflector and receiver, including better optical properties of the mirrors; lighter mirrors and structures, better system control characteristics; development of an automatic control system for remote operation and for long-distance control

- System improvements using Stirling and Brayton (gas turbine) engines adapted to solar processes with advanced heat-pipe and volumetric air receivers
- Proof-of-reliable operation of advanced Stirling engine/receiver units over the long run
- Improvements in system integration by reduction of parasitic loads, optimization of start-up procedures, better control strategies and hybrid operation of Stirling or Brayton engines.

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**List of Abbreviations**

| | |
|---|---|
| CESA 1 | 1 MWe Central Electrosolar Uno at the PSA, Tabernas, Spain |
| Colon Solar | Co-generation project using central receiver technology at Colon, Spain |
| DIAPR | Directly irradiated annular pressurised receiver |
| DISS | Direct Solar Steam Project |
| DISTAL | Dish/Stirling Almeria, R&D project at the Plataforma Solar de Almeria, Spain |
| EuroDish | European dish/Stirling R&D programme |
| EuroTrough | European parabolic trough R&D programme |
| ISCCS | Integrated solar combined cycle system |
| KfW | Kreditanstalt für Wiederaufbau, Germany |
| LEC | Levelized electricity costs |
| LS-3 | LUZ System, parabolic trough system model No.3 of LUZ |
| PHOEBUS-TSA | PHOEBUS technology programme solar air receiver |
| PS 10 | 10 MWe central receiver power plant project Planta Solar 10 near Sevilla, Spain |
| REFOS | Modular pressurised volumetric air receiver, R&D project for solar preheating of combustion air of fossil-fired gas turbines and combined cycle power plants |
| SEGS | Solar electric generating systems |
| SIREC | Sistemas de receptor central (systems for central receiver) project, involving CIEMAT and IAER for heliostat and receiver development, Spain |
| SOLAIR | Advanced solar volumetric air receiver for commercial solar tower power plants, European R&D project |
| SOLASYS | Novel solar assisted fuel driven power system |
| SOLAR ONE | 10 MWe central receiver power plant No. 1, Barstow, CA., USA |
| SOLAR TWO | 10 MWe central receiver power plant No. 2, Barstow, CA., USA |
| SOLGAS | Solar/gas-fired hybrid co-generation plant project using central receiver technology in Andalusia, Spain |
| THESEUS | 50 MWe parabolic trough power plant project, Frangocastello on Crete, Greece |

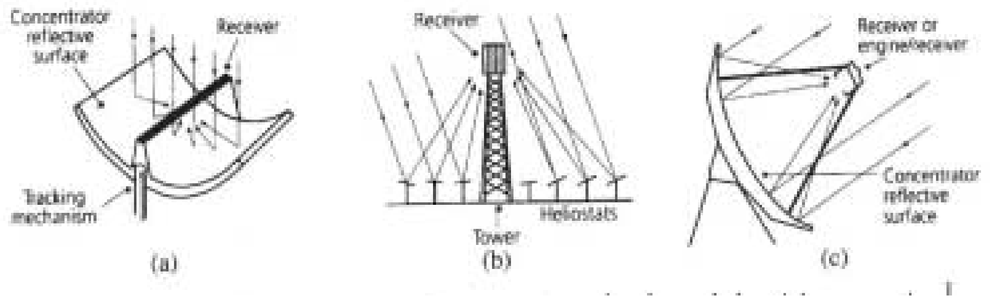



Figure 1: Schematic diagrams of the three main concepts of concentrating solar thermal electricity generation:
a) Parabolic trough, b) Central receiver (tower), c) Parabolic dish
(Source: DLR-Köln)

Figure 2: The parabolic trough field arrays of five SEGS plants at Kramer Junction, CA./USA
(Source: Pilkington Solar International, Germany)

Figure 3: The direct solar steam generation test facility using LS-3 trough collectors on the Plataforma Solar de Almería
(Source: PSA, Spain)

Figure 4: The 10 MWe central receiver power plant SOLAR TWO at Barstow, CA./USA
(Source: Sandia National Laboratory, Albuquerque, USA)

Figure 5: The CESA 1 tower test facility on the Plataforma Solar de Almería
(Source: PSA, Spain)

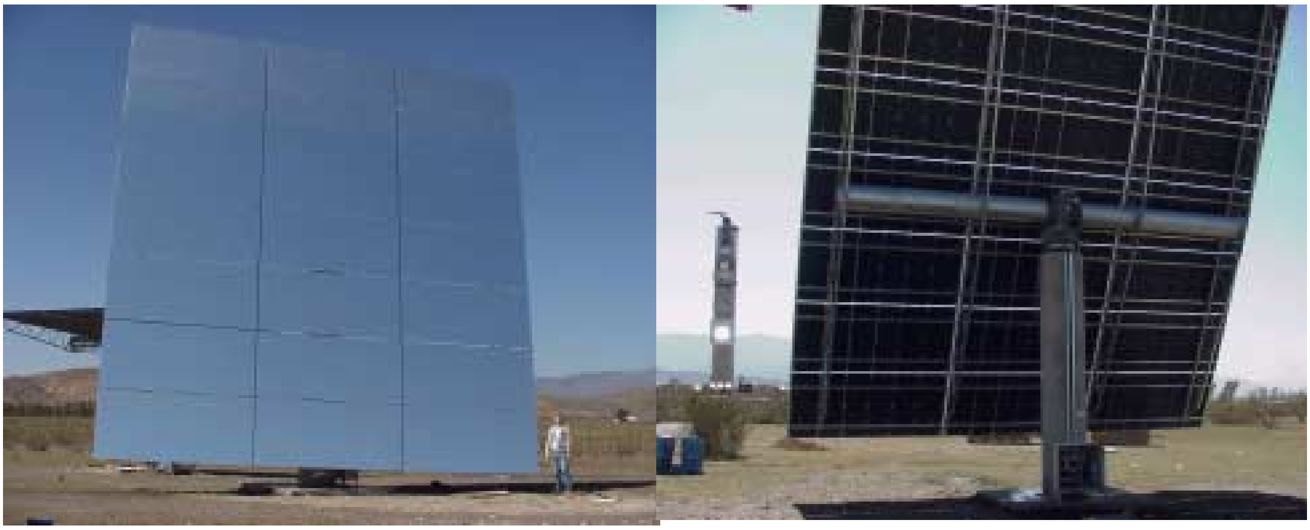


Figure 6: The Spanish 90 m² glass-metal heliostat Sanlucar-90
(Source: CIEMAT, Spain)

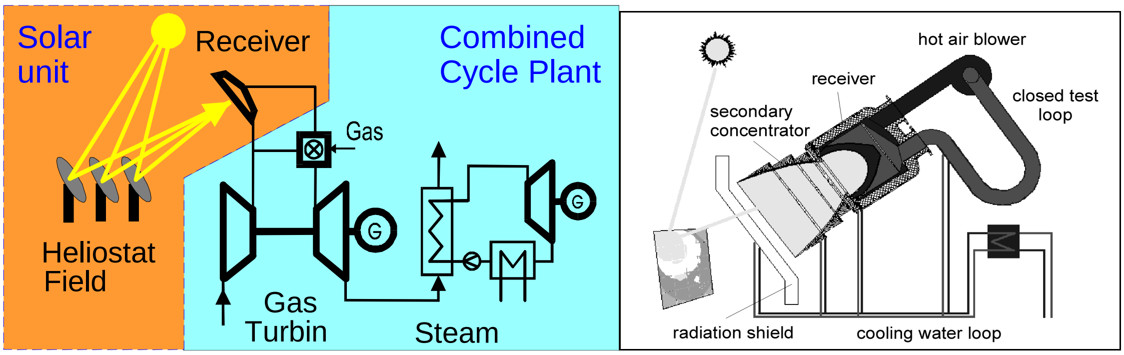
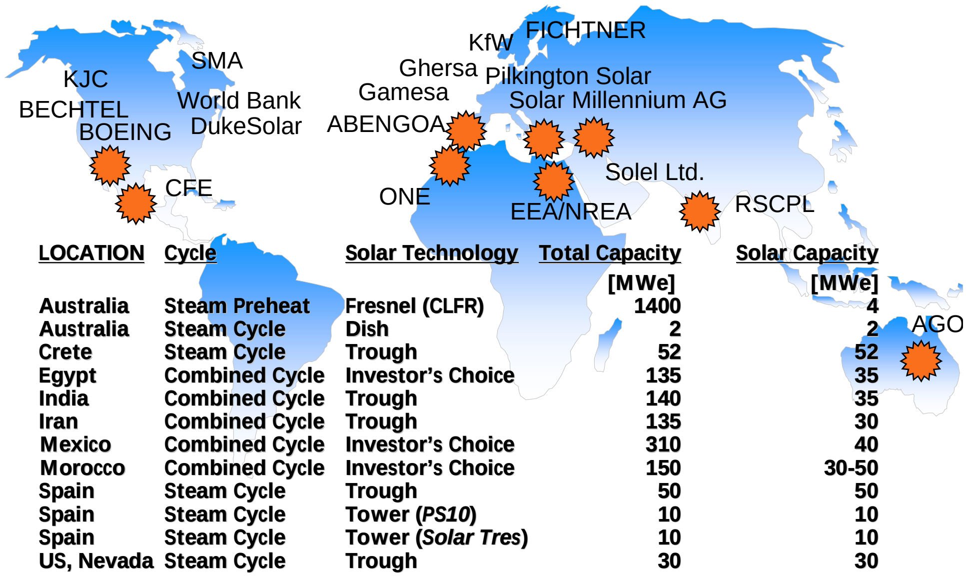



Figure 7: The REFOS-receiver for testing at the Plataforma Solar de Almería
(Source: DLR-Stuttgart)

Figure 8: The six 9 kWe dish/Stirling units (projects DISTAL I and DISTAL II) under continuous proof-of-reliability operation on the Plataforma Solar de Almería (Source: PSA, Spain)




| LOCATION | Cycle | Solar Technology | Total Capacity [MWe] | Solar Capacity [MWe] |
|---|---|---|---|---|
| Australia | Steam Preheat | Fresnel (CLFR) | 1400 | 4 |
| Australia | Steam Cycle | Dish | 2 | 2 |
| Crete | Steam Cycle | Trough | 52 | 52 |
| Egypt | Combined Cycle | Investor's Choice | 135 | 35 |
| India | Combined Cycle | Trough | 140 | 35 |
| Iran | Combined Cycle | Trough | 135 | 30 |
| Mexico | Combined Cycle | Investor's Choice | 310 | 40 |
| Morocco | Combined Cycle | Investor's Choice | 150 | 30-50 |
| Spain | Steam Cycle | Trough | 50 | 50 |
| Spain | Steam Cycle | Tower (*PS10*) | 10 | 10 |
| Spain | Steam Cycle | Tower (*Solar Tres*) | 10 | 10 |
| US, Nevada | Steam Cycle | Trough | 30 | 30 |

Figure 9: The status of international developments of solar thermal power plant projects (Source: DLR-Almería)

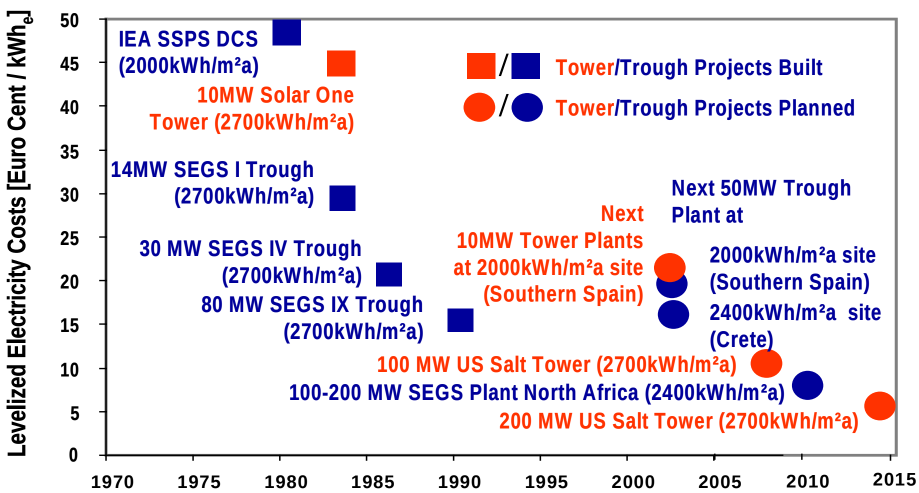



Figure 10: Evolution of levelized electricity costs for solar thermal power plants referred to solar-only production for sites with different insolation
(Source: DLR-Almeria)